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Socio-ecological sustainability of cotton farming systems in central India

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ABSTRACT

Agricultural land covers 38% of the total world's land surface area. These are man-made ecosystems which provide Ecosystem Services of food, fibre and fuel to human society. With the world population predicted to reach 8.9 billion by 2050, one of the most important challenges the world is facing today is to increase its agricultural production in ways that is sustainable. To work towards a more sustainable world, 17 Sustainable Development Goals (SDGs) have been adopted by the world leaders. There have been many studies looking at the ecology of food production but not on cotton production. Cotton is the most important fibre in the world: it is also the most polluting cash crop in the world. India is responsible for 26% of global cotton production of which more than 95% is genetically modified Bt-cotton. As well as being a major conventional producer, India is also the largest country producer of organic cotton. Despite this leading role, India has one of the lowest yields per hectare in the world which is attributable to challenges in soil fertility and inadequate plant protection. Focusing on the impact of agricultural management on biodiversity is essential to ensure that cotton productivity is ecologically sustainable in the long-term. In this study, the functional biodiversity above and below ground was evaluated on plot-scale and farm-scale systems using bio-indicators to evaluate the potential ecological sustainability of four cotton farming systems (CFS) practiced in India: conventional; Bt-conventional; organic and biodynamic. The long-term comparison study showed that Bt-cotton had no further significant effect on the above and below ground biota in comparison to the non Bt-conventional cotton systems. Both organic systems showed a significant higher biodiversity in comparison to both conventional systems. In the above ground diversity, the predator: pest ratio was higher in both organic systems. In the below ground diversity, the earthworm biomass and abundance were higher in both organic systems. The fungi Trichoderma sp. was significantly more abundant in Biodynamic systems in comparison to other systems.

The aim of this thesis was to assess the socio-ecological sustainability of cotton farming in Central India. To evaluate the socio-ecological sustainability, this study assessed farm-scale systems using working cotton farms (12 farms: 6 pairs of Bt-conventional and organic systems) by modifying an FAO model to develop a context-based assessment tool. The study showed that conventional management had negative effects on the above and below ground functional biodiversity on the plot-scale and farm-scale cotton systems. On the farms, socio-economic indicators showed

that organic systems were significantly more sustainable in comparison to conventional systems, however, there is still need improvement for both farming systems. Adding ecological empirical data to the framework didn’t make a difference in determining which of the two systems were the most sustainable. However, integrated the ecological indicators facilitated insightful understanding of farmers management choices and highlighted the contextual problem that farmers face while growing cotton in Central India.

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ABREVIATIONS

Bt-	Bacillus thuringiensis
CFS	Cotton Farming Systems
ESs	Ecosystem services
FAO	Food and Agriculture Organization
FiBL	Forschungsinstitut für Biologischen Landbau (German: Research Institute of Organic Agriculture).
IPM	Integrated Pest Management
SDG	Sustainable Development Goals

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Chapter 1
Introductory chapter

This chapter purpose is to give an overall introduction of the concept of sustainability, cotton farming systems in India and introduces the chapter of this thesis. Each concept will be developed in the following chapters of the thesis.

1.1. Introduction

Agriculture covers 38% of total land surface area on earth (FAO, 2020). Agricultural lands are man-made ecosystems dedicated to production of food, fibre and fuel for society. Agricultural production depends on ecosystem services (ESs) provided by biodiversity. A combination of unsustainable practices has meant that agricultural lands are increasingly responsible for large-scale loss of biodiversity which is vital for Ess. Converting more land for agricultural use begins with clearing of land which results in habitat fragmentation, soil erosion and most importantly the loss of biodiversity (Conway and Barbier, 2013; Fan et al., 2012). One of the most important challenges the world is facing today is to increase its agricultural production within existing agricultural lands in ways that are sustainable (FAO, 2015; Pretty et al., 2010; Siebrecht, 2020).

1.1.1. What is sustainability?

Sustainable agriculture is an umbrella term which can have different meanings as per specific contexts. The definition of sustainable agriculture is context-specific (Siebrecht, 2020). In this study, I will use the definition provided by the Sustainable Development Goals (SDGs) to define sustainable agriculture:

"A sustainable production system implements agricultural practices that increases productivity and production, that helps maintaining ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters, and that progressively improves land and soil quality" (FAO, 2018, 2015).

In other words, agricultural systems should be able to maintain a healthy rate of productivity while conserving ecosystem health (Doran and Zeiss, 2000; Ikerd, 1993). Sustainable agriculture has three main dimensions: social, economic and environmental, yet spatial and temporal dimensions need to be taken in consideration when assessing sustainability in agriculture (Tomich et al., 2004).

1.1.2. Agriculture and sustainability

During the Green Revolution, crop yields increased due to the introduction of high-yielding varieties and hybrids, introduction of irrigation, fertilizer and pesticides (Chakravarti, 1973; Ramani and Thutupalli, 2015a; Talukder et al., 2020). However, studies have shown evidence that modern agriculture has reached its critical productivity limits while being responsible for the loss of environmental services indispensable to sustain global demands (Lal, 2015; Millennium Ecosystem Assessment, 2005; Talukder et al., 2020). During an historic United Nation Summit, world leaders adopted 17 SDGs (Sustainable Development Goals) to create a more sustainable world with a goal to eradicate poverty while tackling climate change and protecting the earth (FAO, 2015). Several SDGs are deeply rooted within the realm of agricultural activities (Abraham and Pingali, 2020). These are the following SDGs which are linked to agriculture: SDG1: no poverty, SDG 5: gender equality, SDG 6: clean water and sanitation, SDG 7: affordable and clean energy, SDG 8: decent work and economic growth, SDG 12: responsible consumption and production, SDG13: climate change, SDG15: life on earth.

1.1.3. In particular how does this apply to cotton?

Cotton accounts for about 50% of the world’s fibre supply (Wendel et al., 2010). India represents about 41% of global area under cotton growing farming systems and 26% of total cotton grown in the world (CCI, 2017). Despite being the biggest producer of cotton, India has one of the lowest yields per hectare due to glaring weaknesses in plant protection and soil fertility (Ganapathi and Madeti, 2018; Ramasundaram, 2001; Udikeri et al., n.d.). In India, the total area of cultivation for cotton represents 15% of the total agricultural land available. With 5.8 million Indian farmers cultivating it, cotton is coveted and considered the most important cash crop. (Ministry of Textiles, 2018). Focusing on improving Indian cotton productivity while reducing the pollution caused by cotton farms will bring India a step closer to realising the SDGs.

1.2. Assessing sustainability of farming systems

To fulfil the SDGs by 2030, there is a need to evaluate the sustainability of current agricultural systems.

To be able to correctly and comprehensively address sustainability of farming systems, it is important to first assess the level of sustainability of each system (Streimikis and

Baležentis, 2020). There is plenty of literature which has discussed and studied the measurement of sustainability. However, there continues to be a research gap in interlinking the SDGs, agricultural sustainability and developing socio-ecological frameworks for sustainability assessment in agriculture (Streimikis and Baležentis, 2020). Agricultural practices often create trade-offs between functions (e.g. maximizing production vs protecting the ecological system) (MacPherson et al., 2020), which are capable of causing harm to long-term environment and socio-economic sustainability (Power, 2010). Even if a numerous number of indicators have been developed for assessing sustainability, “they do not cover all the issues of SDGs relevant to agriculture in scientific debate on sustainable agriculture” (Streimikis and Baležentis, 2020). The SDGs do not explicitly state the importance of agricultural ecosystem services provided by the biodiversity (MacPherson et al., 2020). This study looks at assessing the socio-ecological sustainability of Indian CFS.

In 2007, the Textile Exchange assessed organic cotton farms in a few countries in Africa, Asia and America using the Sustainability Assessment of Food and Agriculture (SAFA) framework. In many cases, results represented an average or a generalised data set with no data collected at the farm or household level (Textile Exchange, 2015) (for more details, see chapter 2, 2.4.6).

In 2015, the FAO published guidelines based on the SAFA framework(FAO and ICAC, 2015) to specifically evaluate sustainability in cotton farming systems (CFS). To my knowledge, no published studies have used their framework to evaluate sustainability of CFS at the farm-level. This research has assessed the ecological sustainability of Indian cotton farming by first looking at long-term effects of farming systems on biodiversity on a plot-scale level and second, has looked at the wider aspect of sustainability issues through an integrated evaluation done at the whole farm-scale.

1.3. Cotton

1.3.1. Farming cotton in India

India represents a quarter of the total global cotton production (Choudhary and Gaur, 2015) and accounts for 5.8 millions cotton farmers (MinistryOf Textiles, 2018). Cotton production is the single largest consumer of pesticides worldwide, making it one of the most polluting crops (Barbosa, 2016). In India, around 99% of cotton grown is under genetically modified conventional systems, and only 1% of cotton farming is organic.

Still, India is the world leader in growing organic cotton (Lernoud and Willer, 2017). Despite India being the biggest producer of cotton globally, its productivity only averaged around 500 kg per hectare (Kranthi, 2014) whereas the world yield average is 773 kg per hectare (Daisen, 2020).

The main problem in cotton crops is low productivity due to soil fertility and inadequate plant protection (Ganapathi and Madeti, 2018; Ramasundaram, 2001; Udikeri et al., n.d.). Ramasundarum (2001) stated that in India “Plant protection is the weakest link in the production process”. Cotton crops are very sensitive to damage caused by insect pests, they can damage roots, leaves and fruiting bodies (Solangi et al., 2008). To counter these factors, conventional CFS rely heavily on chemical inputs such as fertilizers and pesticides (Pesticide Action Network UK, 2017). Cotton, which covers only 5% of all cropped land area, consumes 50% of the total amount of pesticide used in all Indian crops (Devi et al., 2017). On the other hand, organic farming systems which do not use chemical inputs may lead to lower yields (Seufert et al., 2012).

Soil degradation has been responsible for the decline in agronomic productivity in the global South (Lal, 2006). “Resource poor-farmers” through farming practices contribute to degrading soil quality and to the reduction in cotton productivity threatening the sustainability of productive agriculture (Atis, 2006; Lal, 2006). Improving small farm productivity while promoting sustainable agriculture can reduce rural poverty and thus achieve the SDGs (Abraham and Pingali, 2020).

1.3.2. Bt vs non-Bt

Worldwide, conventional practices such as the use of bioengineered crops have increased rapidly. The introduction of transgenic cotton to India in 2002 started off as a success story, claiming that Bt-cotton cut pesticide use and boosts productivity(Liesl, 2011). However, after the introduction of Bt-cotton, doubts arose about the long-term sustainability of cotton farming due to bollworm resistance and increase of sucking pests (see Chapter 2 for more details). The limited studies done on long-term farming systems have prioritised economic performance and yield of Bt-cotton (Eyhorn et al., 2007; Forster et al., 2013). However, issues with Bt technology do not stem from economic performance or associated indicators, rather it has been about its ecological impact in the long-term (Ramani and Thutupalli, 2015a). Ecological studies have been largely overlooked leaving a gap in our understanding of the ecological impact of Bt-cotton (Ramani and Thutupalli, 2015a).

In the first section of this study, long-term farming trials on plot-scale systems have been used to compare ecological sustainability of Bt-conventional and non-Bt-conventional CFS. To my knowledge, this is the first study to compare the long-term effects of Bt-conventional systems in comparison to non-Bt-conventional systems in India.

Table 1.1: Main differences in the four cotton farming systems studied (for more details for each system, see chapter 3: methodology)

	Conventional		**Organic**	
	Bt-conventional	**Conventional**	**Organic**	**Biodynamic**
Seed treatment	NA	Imidachloprid	Beejamrut +hing, Trichoderma viridae, blue Vitriol	Beejamrut +hing, Trichoderma viridae, blue Vitriol
Fertilizer management	FYM, Urea, SSP, MOP	FYM, Urea, SSP, MOP	compost, neem seed cake	compost, neem seed cake, BD500, BD501, CPP
Pest management	Imidachloprid, Monochrotophos, Acephate		neem oil, Garlic-Onion-Chilli, TopTen after emergence	
Other differences	treated Bt-seeds	non Bt-seeds	non Bt-seeds	non Bt-seeds

After having introduced the key concepts used in this thesis to the reader, the following part gives the reader a summary of each chapter and introduce the aim and objectives of the study.

1.4. Outline of the thesis

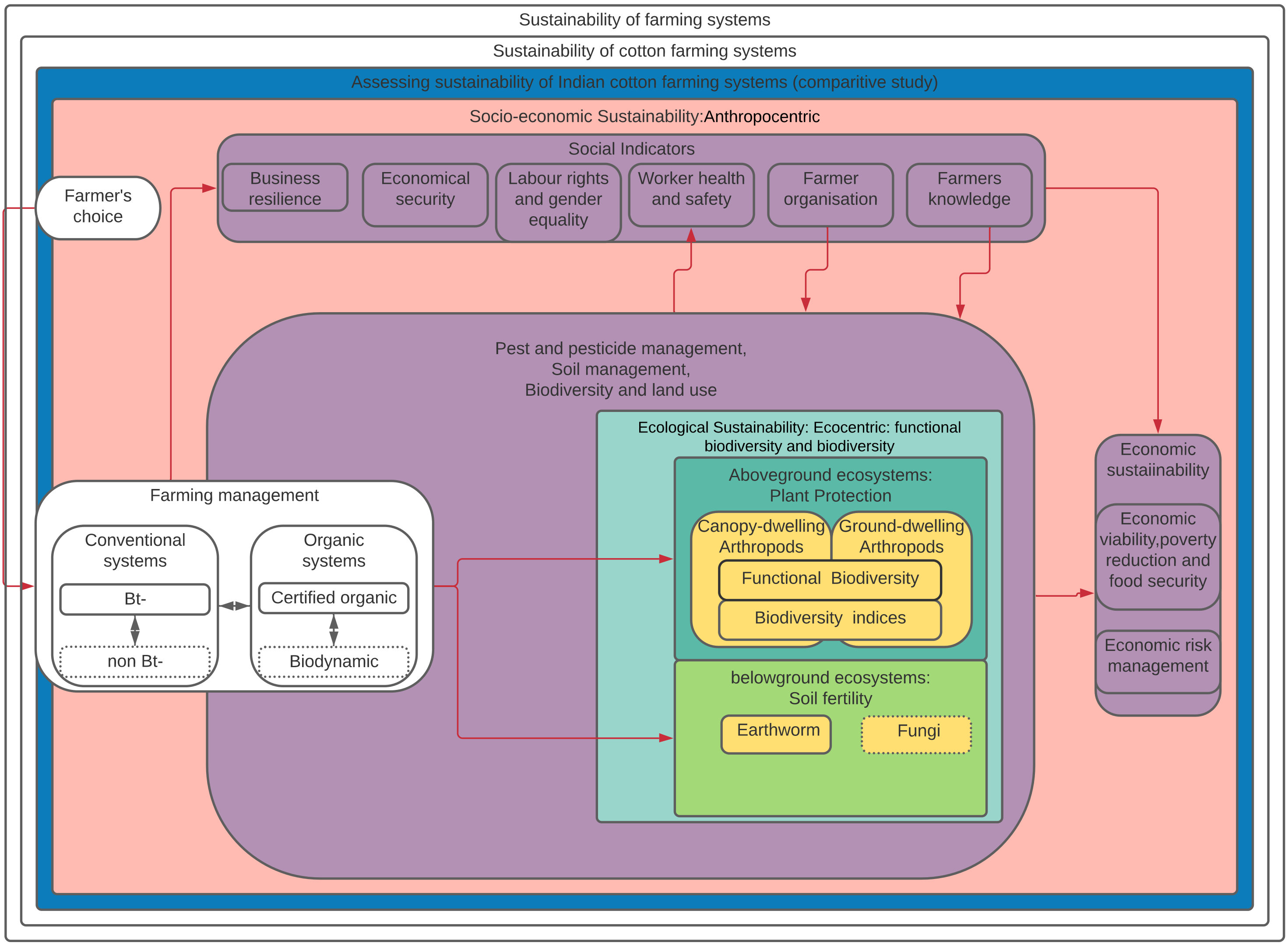


Figure 1.1: Summary of the thesis

1.5. Chapter 2 and 3: Literature review and methodology

The literature review on assessing sustainability and cotton farming in India has been provided and developed in Chapter 2. More information about the general methodology can be found in Chapter 3.

1.6. Chapter 4 and 5: Ecological process leading to sustainability

Understanding and valuing ecological functions provided by biodiversity is the first step towards evaluating ecological sustainability (Swinton et al., 2007). Biodiversity within farming management plays an important role in providing ESs. Previous studies and research has focussed on the importance of diversity in farming systems (Tscharntke et al., 2005). However, there remains a research gap around the complexity of ecological processes in farming systems (Valiente-Banuet et al., 2015).

In the first two result chapters of this study, using the study of ecology, agronomy, soil science and entomology, I have looked at the above and below-ground functional biodiversity using invertebrates as bio-indicators to evaluate the impact of agricultural practices (Paoletti et al., 1991).

The first result chapter is focussed on studying the biodiversity above-ground with a focus on supporting services like plant protection. In India CFS, inadequate plant protection is the main cause for low productivity (CICR, 2018a). Research in cotton crops has mainly focussed on insect pests (Ambrose and Claver, 1999; Khalil et al., 2017; Men et al., 2005). During this study, I have focused on secondary pests responsible for reducing the yield of cotton systems and their natural enemies. There have been doubts about the effect of BT-cotton on the secondary pests, which may increase and become primary pest themselves (Zhao et al., 2011). I have not surveyed the main pest Lepidoptera larvae which have already been the focus of much research (CICR, 2018b; Naranjo, 2009).

The second results chapter examined below-ground biodiversity with special attention to soil health. Soil health is generally used in reference to sustainable agriculture (Frac et al., 2018). More than just fertility, soil is dynamic and the most complex and diverse ecosystem on earth (Gunstone et al., 2021). In this thesis, the terminology of soil health has been used rather than soil quality or soil fertility as it includes biotic and abiotic factors. This study looked at earthworm biomass and density as well as the fungal community. To my knowledge, this was also the first study to compare long-term effects of CFS on earthworm biomass and density as well as on fungi communities.

1.7. Chapter 6: From ecological sustainability to socio-ecological sustainability

Agriculture is a unique system which includes human and ecological systems. Farming systems both benefit from and influence ESs through biodiversity (Lescourret et al., 2015). Although focusing on the impact of agricultural management on biodiversity is essential to ensure that productivity is ecologically sustainable, there are also other essential factors which affect sustainability (Wittman et al., 2016). There is a need to go deeper into the assessment of sustainability by looking at socio-economic variables which play an interconnected role in managing cotton systems. Sustainable agriculture provides a set of visible social and economic benefits (Marsden, 2012). Irrespective of the type of agricultural management, socio-economic aspects provide indicators that cannot be ignored while evaluating the sustainability of CFS (FAO and ICAC, 2015). In this study, I have used the guidance framework "measuring sustainability in cotton farming systems" developed by the FAO (FAO and ICAC, 2015) model to develop and design a context-based assessment tool. The assessment tool was created by using the same model as the "public goods tool" developed by the Organic Research Centre and Natural England (Gerrard et al., 2011). The socio-ecological sustainability assessment was done on farmers' agro-systems. It was important to include the ecological indicators in the framework to be able to make an integrated evaluation of CFS. Most sustainability assessment tools have not involved ecological approaches (Lescourret et al., 2015). Empirical data used to assess the ecological sustainability of the farming systems studied were integrated into the assessment tool to evaluate the socio-ecological sustainability of CFS of 6 pairs of organic and Bt-conventional farmers. In the last result chapter, I have combined this empirical data with data obtained through farmer interviews to assess sustainability of the two farming systems: Organic and Bt-conventional systems.

1.8. Aim and objectives of the study

The main aim of this thesis is to assess the socio-ecological sustainability of cotton farming in Central India.

The objectives of this thesis are the following:

(1) To develop a methodological approach to explore sustainability in Indian cotton systems (Chapter 2 and 3)

(2) To compare the long-term impact of four plot-scale cotton farming systems and two farm-scale farming systems on functional biodiversity with a focus on crop protection (chapter 4)

(3) To compare the long-term impact of four plot-scale cotton farming systems and two farm-scale farming systems on functional biodiversity with a focus on soil health (chapter 5)

(4) To investigate if Bt-transgenic cotton crops have a long-term impact on biodiversity (Chapter 4 and 5).

(5) To integrate the measurement of functional biodiversity into whole farm sustainability assessments and compare the two major farming systems currently practised in India (Chapter 6)

Chapter 2 Understanding Sustainable Agriculture

2.1. Agriculture and its challenges

Thirty eight per cent of the total land surface in the world is agricultural (FAO, 2020). By 2050, this agricultural land will need to feed an additional two billion people, while at the same time, the climate crisis is expected to negatively affect the yield of crops (Challinor et al., 2014). These agricultural lands are man-made ecosystems which provide food, fibre and fuel to society. With the world population predicted to reach 9.9 billion by 2050, one of the most important challenges the world is facing today is to increase agricultural production in sustainable ways (Pretty et al., 2010; Tahat et al., 2020).

Since the early ‘60s, agricultural land has increased by 21% in developing countries (Pretty, 2008). The Green Revolution (also called the third agricultural revolution) has played a very important role in preventing famine in the developing world, especially in India (Nelson et al., 2019). During the Green Revolution (GR), crop yields increased due to the introduction of high-yielding varieties and hybrids, but primarily thanks to the effective implementation of irrigation schemes as well as increased fertilizer and pesticide usage (Chakravarti, 1973; Ramani and Thutupalli, 2015b; Talukder et al., 2020). Thanks to the GR, Asia and sub-Saharan Africa have drastically reduced rural poverty (Abraham and Pingali, 2020). The GR saved vast acreages from being converted into agricultural land (Renkow et al., 2011). Since the GR, world food production has grown by 145% (Pretty, 2008). Without it, food production may have been 20% lower in some developing countries (Renkow et al., 2011). However, there is a need to recognize the limits of the GR and transit towards alternative solutions. There is a need to consider sustaining production gains while adapting to climate change, conserving biodiversity and making agriculture sustainable over the long-term (Murgai et al., 2001; Pingali, 2012).

In 2019, agriculture was responsible for 26% of employment in the world, while in India, the figure was closer to 43% of total employment (World Bank, 2020a). Likewise, 20% of the Gross Domestic Product (GDP) comes from the agricultural sector in India which is much higher than the global average (of 4%) (World Bank, 2020b). This makes the agriculture sector an integral and crucial part of the Indian economy. Even though productivity of agricultural crops has increased in the last 50 years, thanks to the development of better technology and practices, it is likely that it will not increase as significantly going forward (IAASTD, 2009). As the population is forecast to reach 9.9

billion by 2050, the challenge is to increase production without converting more land, as this would result in land clearing, habitat fragmentation, soil erosion and loss of biodiversity (Conway and Barbier, 2013; Fan et al., 2012). Therefore, there is a need to close the yield gap while ensuring crop sustainability to be able to generate enough on existing agricultural land (Talukder et al., 2020).

2.1. Sustainability and the SDGs

The word sustainable comes from the German nachhaltigkeit which means “sustained yield”. The term sustainability in agriculture started coming into use in the ‘50s-‘60s (Pretty et al., 2008). Sustainability comprises fundamentally connected concerns which are economic, environmental and social (Brundtland, 1987). Addressing them in a comprehensive and decisive way is essential for long-term sustainability in agriculture.

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

(Brundtland, 1987)

There is still an urgent need to shift the world onto a sustainable path. In 2015, the United Nations created 17 Sustainable Development Goals (SDGs). The focus of the SDGs has been to improve human lives and protect the environment with “**agriculture** being the common thread which holds the 17 **SDGs** together“ (UN, 2015). One of the main goals of the SDGs is to promote sustainable agriculture by finding universal, holistic and measurable solutions (Stephenson and Carbone, 2020). By 2030, the SDGs have an objective to “ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters, and that progressively improve land and soil quality” (FAO, 2018, 2015)

Sustainable agriculture seeks to use the best technologies and practices to improve productivity without damaging the environment. Sustainable agriculture integrates the principles of both resilience and persistence (Pretty et al., 2008). Scientific knowledge about agricultural sustainability comes from a wide range of disciplines such as ecology, agronomy, climate science, economics and social sciences.

There is a need for multidisciplinary research to fill the knowledge gaps in both the scientist's as well as the practitioner's perspectives (Dicks et al., 2013). Sustainable agriculture has three main dimensions: Social, economic and environment. Yet, spatial and temporal dimensions need to be taken into consideration when assessing sustainability in agriculture (Tomich et al., 2004). Sustainable agriculture is an umbrella term which has different meanings for different people (Smith and Mcdonald, 1998) and should be considered in a case-specific manner (Streimikis and Baležentis, 2020). There are plenty of assessment tools and frameworks which have been created to enable achieving sustainability (de Olde et al., 2018; Hayati, 2017; Weber et al., 2020) but there are a series of obstacles that hinder the implementation of sustainable agriculture (Siebrecht, 2020).

Sustainable agriculture has various goals according to respective contexts (Siebrecht, 2020). To be able to reach a sustainable agricultural model, all these goals have to be achieved which can be challenging (Kropff et al., 2001). Therefore, it is a complex and lengthy process (Van Passel and Meul, 2012). According to Siebrecht (2020), there are four types of obstacles which makes it difficult to ensure sustainability in agriculture: Theoretical, methodological, personal and practical obstacles (Siebrecht, 2020). To surmount these, it is important to first define sustainable agriculture in the specific context of the study and to focus on the goals which are "highly case-specific" (Siebrecht, 2020).

2.2. Cotton farming

"India was famed for its cotton textiles in the past, that cotton cloth in India dates from the Harappan civilization, and that India made the finest cloth in the world, the Dacca muslin" (Uzramma and Menon, 2017)

Cotton is grown on approximately 2.5% of the world's arable land, generating 350 million jobs (Barbosa, 2016). In 2014/2015, 26 million tonnes of cotton were produced in the world. India alone represents a quarter of the total global cotton production (Choudhary and Gaur, 2015). The farming population in India is estimated to be a total of 100-150 million (Damodaran, 2020), among which 5.8 million are cotton farmers (MinistryOfTextiles, 2018). While cotton is an economically important crop, it also relies heavily on chemical inputs. Hence, it is one of the most polluting crops in the world (EJF (Environmental Justice Foundation), 2007). In addition to excess pesticide and fertilizer use, cotton farming uses significant amounts of fossil fuels and water as well. Cotton production is the single largest consumer of pesticides in the world (Barbosa, 2016; EJF (Environmental Justice Foundation), 2007). In total, 5% of total pesticides and a staggering 14% of total insecticides sold in the world are used in cotton systems alone (Pesticide Action Network UK, 2017).

Worldwide, conventional practices, including the use of bioengineered crops, have increased significantly. Biotech crops have been used to increase productivity and reduce the use of pesticides (ISAAA, 2017). In 1996, only six countries had started cropping different types of biotech fields. By 2016, 26 countries were planting biotech crops (ISAAA, 2017). The sustainability of these biotechnologies needs to be questioned constantly and re-evaluated to ensure that they will contribute to solving context-based issues while having a minimum impact on the environment and human health (Falck-zepeda et al., 2002). The sustainability of farming systems depends on the context in which they are being used or applied and the outcomes of genetically-modified crops can vary according to the specific area where it is grown (Cleveland and Soleri, 2005; Rigby and Caceres, 2001).

Bollworm (*Helicoverpa sp.),* which is a Lepidoptera larva, has been a consistent threat to commercial cotton production (Mbaye et al., 2011). Transgenic cotton was originally created by Monsanto (a life science company – recently bought by Bayer) by inserting the gene of the bacterium *Bacillus thuringiensis* in cotton plants. This gene produces a protein which is toxic for the Lepidoptera larva but – according to trials – harmless to other organisms. Monsanto patented this Bt gene technology which was registered under the name Bollgard®. It was first introduced commercially in 1996 in the United States of America (Manjunath, 2004). By 2015, 0.3 billion hectares of biotech cotton were grown worldwide. In 2016, there were around 7.2 million farmers planting Bt cotton (ISAAA, 2018).

In 1998, before the commercialisation of Bt-cotton seeds, Monsanto started field trials in India (Bharathan, 2000). At the end of that year, farmers protested against these trials by burning the crop (Jayaraman, 1998). However, four years later, the Kisan Coordination Committee representatives from all the cotton-growing states in India strongly supported the introduction of Bt-cotton in the country. In 2002, the Indian agricultural ministry officially approved its first genetically-modified (GM) crop

(Unknown, 2002). The majority of cotton farmers shifted to Bt cotton, and by 2014, 95% of the cotton planted in India was GM (Choudhary and Gaur, 2015; Kranthi and Stone, 2020). Farmers were convinced of the benefits based of the considerable increase in net production and profitability (Sadashivappa, 2015). The gains in productivity came largely due to the twin benefits of a reduction in pesticide use for bollworms and higher yields (Manjunath, 2004). However, as shown in Figure 2.2, insecticides used on cotton for bollworms has reduced by more than 90% (from 4,470 metric tonnes in 2002 to 222 metric tonnes in 2011), pesticides used on cotton for sucking pests have increased threefold (from 2,110 metric tonnes in 2002 to 6,372 metric tonnes in 2011), effecting no net change in total pesticide use on cotton (Kranthi, 2012; Peshin et al., 2014).

With the introduction of this technology, doubts arose about the long-term sustainability of cotton farming in the country. One of the main concerns has been the resistance build-up of *Helicoverpa sp.* larvae. As mentioned earlier, the limited studies done on long-term farming systems have prioritised economic performance and yield of Bt-cotton (Eyhorn et al., 2007; Forster et al., 2013) while ecological studies have been largely overlooked, leaving a gap in our understanding of the ecological impact of Bt-cotton (Ramani and Thutupalli, 2015b). Since the dawn of GM crops, there has been a heated debate over whether these have a positive or negative effect on the economy and society over the long-term, especially in developing nations (Cleveland and Soleri, 2005). Often, when this technology is introduced in a new country, the government and seed producers have a tendency to focus research on practices that will enhance the productivity of the introduced biotech crop and do not raise the question of risk management on the assumption that biotech crops can only bring net benefits (Cleveland and Soleri, 2005). However, in India, Bt-cotton seeds were distributed to the farmers without the Genetic Engineering Approval Committee implementing any resistance plan managements (Ramanjaneyulu and Kuruganti, 2006).

Figure 2.2: Insecticides used on cotton crop in India. Insecticides used on cotton for bollworms decreased since the introduction of Bt-cotton in 2002. Insecticides used on cotton for sucking pests has increased since the introduction of Bt-cotton (data source (Kranthi, 2012)*)*

Among the 179 countries worldwide which practise organic agriculture, India is one of 87 to have organic regulations (Lernoud and Willer, 2017). In India, only 1.1% of the total area of cotton farming is organic (Textile Network, 2017). Even with this minuscule percentage cultivated, India retains the top spot in the market, producing 66.9% of the organic cotton worldwide (Lernoud and Willer, 2017). In fact, India is home to the largest number of organic cotton producers in the world (Willer and Lernoud, 2017). As the global demand for organic products is growing, especially in the fashion industry where organic cotton is synonymous with sustainability (Radhakrishnan, 2017); there is an urgent need to improve organic supply. Research which focuses on improving the performance of organic systems is often limited by funding (Forster et al., 2013). However, this type of research is necessary to help achieve socio-ecologically sustainable production.

While cotton farming is of significant economic importance for farmers worldwide as well in India (Uzramma and Menon, 2017), it also raises concerns over its impact on the environment. For this reason, it is necessary to closely examine the socio-ecological sustainability of CFS studies in this field can bring research and industry a step closer towards understanding the complex interlinked concepts of sustainability.

2.3. Biodiversity and its role in Ecological sustainable in agriculture

2.3.1. Role of biodiversity in sustainability

Biodiversity is indispensable for the survival of any agricultural system (Kazemi et al., 2018). Through biodiversity, the health and well-being of the farming community is ensured (Garbach et al., 2014; Millennium Ecosystem Assessment, 2005; Pearce and Moran, 1994). In the last few decades, research has focused on the importance of diversity in farming systems (Tscharntke et al., 2005). However, there remains a research gap around the complexity of functional biodiversity in farming systems. (Valiente-Banuet et al., 2015).

First, the concept of functional biodiversity needs to be defined. Barberi (2013) clearly makes a distinction between agrobiodiversity and functional agrobiodiversity, where the first one has been clearly defined by the Organization for Economic Development and Cooperation (OECD) but the second one has yet to receive a commonly accepted definition (Bàrberi, 2013; Cardona et al., 2021). The classical ecological definition of Pearce and Moran (1994) does not specify the positive or negative functionality of the monitored organisms (Pearce and Moran, 1994), rendering this definition unusable for the agroecosystems which have maximisation of yield as their main objective (Gurr et al., 2003). Functional biodiversity is crucial for the functioning and stability of ecosystems (Korthals and Putten, 2001) consequently leading to improved agricultural production (Pimentel et al., 1997).

Comprehensively measuring and quantifying biodiversity is a complex process, and there is no existing standard to evaluate the health of a system in ecology or to measure biodiversity (OECD, 2001; von Haaren et al., 2012). To assess the biodiversity in agroecosystems, comparative studies are needed. In this research, cotton systems are assessed by comparing two types of systems, organic systems and conventional systems. To assess the ecological sustainability, evaluating the impact of human management on ESs (WHAT IS ESs?) is essential. To evaluate this impact, a range of disciplines need to be consulted, including soil science, entomology, ecology and agronomy. Through empirical data, the complex interaction between living organisms (biotic) and the physio-chemical components (abiotic) of the ecosystem can be understood and evaluated.

In 2019/2020, Indian cotton yield was below 500 kg per hectare (Kranthi, 2014) in comparison to the global yield average which was on average 773 kg per hectare. On the other hand, China's yield was projected to be 1,748 kg per hectare in 2020/2021 (Daisen, 2020). India's low productivity can be attributed to poor soil fertility and inadequate plant protection (Ganapathi and Madeti, 2018; Udikeri et al., n.d.). Therefore, in this study, to assess the ecological sustainability of cotton farming in the Indian context, these two key aspects were taken into consideration.

2.3.2. Assessing biodiversity and ecosystem services

2.3.2.1. Above-ground ecosystems

Through functional groups, biodiversity provides ESs. The United Nations Sustainable Development Solution Network suggested environmental goals which include "protect biodiversity and other ESs in farmlands" (Dicks et al., 2013). With conventional agriculture, the function of the ESs provided by these beneficial organisms has been replaced by chemical and mechanical inputs (Kazemi et al., 2018). For example, pesticides have been part of the most common management practices to prevent pest damage and replace the role of natural enemies (Barbosa, 2016). However, there are many studies that indicate that pesticides have wholesale negative effects on non-targeted biodiversity (K. Birkhofer et al., 2008) and, therefore, could indirectly impact other ecosystems services negatively (Bennett and Gosnell, 2015).

2.3.2.2. Soil ecosystems

Soil is the "essential life-supporting zone" for plants (FAO and ICAC, 2015). Water, mineral nutrients and oxygen are provided to plants from the soil. Healthy soil is crucial for sustainable agriculture. Soil health can be impacted by farming practices, affecting its biodiversity which is essential for soil fertility and crop productivity (Edwards, 1984; Zhang et al., 2007). Understanding the impact of farming systems on this biota can help in evaluating the sustainability of the system. In India, a large majority of cotton producers are using inorganic agricultural inputs "leading to the depletion of soil nutrients and deterioration of soil structure" (Brévault et al., 2007). Soil management is a way to improve soil fertility and consequently increase productivity.

A study has revealed that conventional cotton farmers mistakenly believe that they improve their soil fertility thanks to the chemical fertilizers they use on their farm lands (Riar et al., 2017). Studies have observed a relationship between the application of chemical fertilizers and change in community structure (Donnell et al., 2001). Synthetic fertilizers can have a direct or indirect impact on soil biota by changing the interaction between above-ground and below-ground communities, negatively affecting the internal biological cycles as well as pest control (Thiele-Bruhn et al., 2012). Studies have also shown that the residual concentration of pesticides accumulate in the soil which could have a long-term effect on the biotic and abiotic properties of the soil (Klaus Birkhofer et al., 2008; Brévault et al., 2007). Soil contaminated with pesticides pose a hazard to non-target arthropods and to the ecosystems services they provide (Gunstone et al., 2021).

2.3.2.3. Assessing biodiversity using bio-indicators

To assess the health of ESs, a focus on small invertebrates and key species has been deemed useful (Cardoso et al., 2004; Paoletti, 1999a). The choice of indicators is important and depends mainly on the aims of the investigation (Y. G. Han et al., 2015).

A good bio-indicator according to available literature should: “Have well-known classification and ecology, “cover a wide geological area”, “be cost-efficient and easy to investigate”, “independent from the sample size”, “have speciality as a necessary condition of habitat”, “provide early warning of change”, “be important potentially and economically”, and many other factors. However, it would be very hard to find species or group of species which cover all these requirements(Y. G. Han et al., 2015).

Birds have been considered good indicators to assess the health of the environment they live in. They are generally used for assessing landscape habitats (Roché et al., 2010). For smaller landscapes such as farming systems, bio-indicator-based studies make use of the living components with the highest diversity above soil, generally found to be invertebrates which make them suitable bio-indicators. They are one of the most representative groups for the overall biodiversity of respective ecosystems (Obrist and Duelli, 2010). They are also easy to sample and monitoring them does not require costly equipment, which makes them cost-effective (Obrist and Duelli, 2010). Invertebrates vary significantly around the world and abiotic factors such as humidity, temperature, latitude and longitude influence their populations (Stork and Eggleton, 1992). They have been used to assess and understand the general status of agroecosystems as they provide early warnings of change. They have frequently been the focus in comparative studies of agricultural systems, including system management (Popov et al., 2018; Zhang et al., 2007), pest management (Naranjo and Ellsworth, 2009; Prokopy, 2003) and soil management (Brévault et al., 2007; Thiele-Bruhn et al., 2012).

2.4. Assessing the sustainability of farming systems

2.4.2. Socio-ecological Frameworks

Agriculture is a unique system which operates at the confluence of human and ecological systems. Farming systems both benefit from and influence ESs through biodiversity (Lescourret et al., 2015). Although focussing on the impact of agricultural management on biodiversity is essential to ensure that productivity is ecologically sustainable, there are also other essential factors which affect sustainability (Wittman et al., 2016). Multi-disciplinary approaches are crucial to understanding the sustainability of farming systems as a whole (Lescourret et al., 2015; Zhang et al., 2007). There is a need to go deeper into this examination of sustainability by looking at socio-economic variables which play an all-important role in managing cotton systems. Socio-ecological frameworks have been developed to consider both social and ecological dimensions (Binder et al., 2013). Socio-ecological approaches allow research to concentrate on different focal points, allowing an integrated understanding of the sustainability concept (Bennett and Gosnell, 2015). The question is not which assessment framework is best, but which one is more relevant for the case in question. To be able to evaluate the sustainability of an agricultural system, an integrative framework that takes into consideration the social, ecological and economic factors is needed. Lescourret has developed a conceptual framework focussed on the service-based management of agroecosystems, which looks at the ESs generated by the different agricultural systems and focuses on investigating which systems maximize the most ESs (Lescourret et al., 2015). ESs have been defined by Daily (Daily, 1997) as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life”. A sustainable agricultural system is capable of delivering multi-layered and robust ESs. The ESs conceptual framework is a powerful tool to evaluate and develop the sustainability of agricultural systems (Lescourret et al., 2015), but it is also a challenging framework where ecological and socio-economical dimensions need to be incorporated. The majority of the ESs frameworks are focussed on biophysical mechanisms of ESs provision of the systems without looking at the socio-economic implications of their use (Zhang et al., 2007). However, ESs extend beyond the agricultural field as people are also part of this system. The challenge is the multiple synergies, immeasurable trade-offs and non-linear relationships that exist in and between ecological and socio-economical dimensions (Lescourret et al., 2015). Therefore, the key is to develop a dynamic framework (Binder et al., 2013).

Another major problem of ESs frameworks is the consideration of a particular ecosystem service as more valuable than another one (De Groot et al., 2002). How society values biodiversity and perceives ESs is a key factor to understand the sustainability of a particular agroecosystem (Zhang et al., 2007). How farmers make their choices and understand priorities in the management of a farm can lead to a more holistic, sustainable farming system (Lescourret et al., 2015). While assessing sustainability at a farm-level, the most important factor to keep in mind is that farmers are a sub-cultural group which differs based on varied regional contexts (Kuehne, 2016; Syswerda and Robertson, 2014). Their motivations for adopting a sustainability model are different and should be taken into consideration. Therefore, it is important for research to account for the ways farm managers make decisions accommodating for the ESs that the system provides them. It has been demonstrated that such a complex issue of socio-ecological sustainability cannot be assessed with disciplinary approaches alone (Lescourret et al., 2015).

One of the more common methods of evaluating sustainability is to use indicator-based tools. There are a number of frameworks and analytical tools to assess sustainability (De Olde et al., 2016; Srinivasan et al., 2011). Some frameworks have been created specifically to assess sustainability at the farm-level. The concept of sustainability keeps evolving and assessment tools need to constantly evolve and improve (FAO, 2013a). Many frameworks are oriented toward a particular aspect of the assessment of sustainability in farming systems (Lescourret et al., 2015).

2.4.3. IDEA – *Indicateurs de Durabilite des Exploitations Agricoles* (Sustainability Indicators of farming systems)

Borrowing from the French context, the IDEA method is based on 41 sustainability indicators which is a self-assessment of agricultural sustainability. This method is quantitative with scientifically sound indicators (Zahm et al., 2008). One of the prominent criticisms of this method is that it is limited to its visual presentation (de Olde et al., 2018).

2.4.4. PG – OCIS Public Goods Tool Development

This sustainability assessment tool is specific to farmers living in the United Kingdom. Some aspects of the assessment tools are based on sustainability assessment methods in European countries. This approach relies on asking detailed questions to the farmers as well as using databases that farmers already have available. No further surveys are conducted. The scores of the farms are shown using a radar diagram.

Both of the above methods are closer to a rapid sustainability assessment tool than a full assessment tool such as the following RISE and SAFA methods (de Olde et al., 2018).

2.4.5. RISE – Response-Inducing Sustainability Evaluation

RISE can be defined as a voluntary initiative standard (VIS). VISs aim to enhance and measure the sustainability of agricultural outcomes at different levels of the value chains (FAO and ICAC, 2015). RISE is a framework which looks specifically at sustainability at the farm-level (HAFL, 2017). The model looks at 12 indicators of economic, environmental and social importance (Häni et al., n.d.). In comparison to other assessment tools such as IDEA (Zahm et al., 2008) and PG (Gerrard et al., 2012), RISE has been considered the most time-consuming. This can be a disadvantage while comparing multiple farms; it is also a complex scoring process and it can be difficult to understand how the data reflects in the final results (De Olde et al., 2016). However, this assessment tool has been considered superior in terms of accuracy and relevance in comparison to IDEA or PG. IDEA and PG can be subjective, for example, assuming that organic systems are more sustainable (De Olde et al., 2016). RISE collects data from farm accounts and the primary method of information-gathering is interviews with farmers. There remains a strong possibility that the information collected is not as accurate as physical primary data is collected directly on the farm (Steinke et al., 2017). A lack of training on how to use, conduct and effectively document interviews can lead to lower levels of accuracy in this methodology (Steinke et al., 2017). The level of accuracy of data collection should be clear. In some cases, information collected during the interview is not accurate and does not match the empirical data gathered (Keeffe et al., 2016).

2.4.6. SAFA – Sustainable Assessment of Food and Agriculture systems

The free access to this clear guideline makes it available for anyone to use. The advantage is that SAFA is adaptable and can be used in varied contexts, at different scales and locations. SAFA is constituted like any Life Cycle Assessment the framework follows the ISO 14,044 steps. SAFA also relies mainly on obtaining information through interviews which can be challenging as they generate more qualitative than quantitative data. One of the positives of the SAFA framework is that it appoints an accuracy score according to the quality of the data collected (FAO, 2013b). SAFA is an assessment tool more suitable for smallholder producers and for developing countries. In developed countries, it has been criticized for obtaining results which are too positive (De Olde et al., 2016). This means that the scoring standards are too low to evaluate the sustainability of farms in developed countries fairly.

There is no single approach which serves all purposes to assess agricultural sustainability at the farm-level (Schader et al., 2019). The sustainable assessment choice depends on the location, the type of farming systems assessed, the stakeholder as well as the objectives of the sustainable assessment. In other words, sustainability is context-specific. Studies have assessed the sustainability of farming systems using the above assessment frameworks and tools in both the Global South and Global North. Recent studies have used the SAFA framework in the Global South to assess the sustainability of a range of systems on both the American and African continent. On the American continent, comparative studies have been done in silvo-pastural systems in Mexico (Pérez-Lombardini et al., 2021), coffee systems in Brazil (Winter et al., 2020) and banana systems in Ecuador (Bonisoli et al., 2019). On the African continent, assessment studies have been done in Ghana (Bandanaa et al., 2021), Uganda (Ssebunya et al., 2019) and Ethiopia (Winter et al., 2020). To my knowledge, no assessment using the SAFA framework on CFS has been done on the Asian continent.

Table 2.2: Simple description of RISE, SAFA, PG and IDEA framework source:(De Olde et al., 2016)

	IDEA	PG	RISE	SAFA
Full name	Indicateurs de Durabilité des Exploitations Agricoles	Public Good Tool	Response Inducing Sustainability Evaluation SAFA	Sustainability Assessment of Food and Agriculture Systems
Publication	Zahm (2008)	Gerrard et al. (2012)	Hani et al. (2003)	FAO (2013)
Origin	France (multiple institutes)	United Kingdom (Organic Research Centre)	Switzerland (Bern University of Applied Sciences	Multiple countries and institutes
Number of elements in each tool	Dimension: 3 Theme: 10 SubTheme: 42 Indicators: 126	Theme: 11 SubTheme: 57 Indicators: 185	Theme: 10 SubTheme: 50 Indicators: 156	Dimension: 4 Theme: 21 SubTheme: 58 Indicators: 116
Number of subthemes per dimension	Environmental: 18 Economic: 6 Social: 18	Environmental: 43 Economic: 2 Social: 12	Environmental: 30 Economic: 6 Social: 9 Governance: 5	Environmental: 14 Economic: 14 Social: 16 Governance: 14
Assessment level	Farm	Farm	Farm	Farm,chain

2.5. Summary

Occupying more than 40% of total employment in the country, agriculture is an integral part of the Indian economy. Thanks to the GR and the introduction of fertilizers and pesticides, crop yields have increased. However, we have now reached a stage where we need to go beyond the GR practices and transit toward a greener and more sustainable agriculture to be able to adapt to the climate crisis and improve productivity without damaging the environment. There is an urgent need to transit toward sustainable agricultural practices. Sustainable agriculture includes three main dimensions--social, economic and environmental.

In India, cotton is an important cash crop. Unfortunately, it is a crop that relies heavily on pesticides and fertilizers. To reduce its dependency on pesticides, GM cotton crops have been introduced to the farmers under the name of Bt-cotton. Today, the majority of Indian cotton farmers have shifted to Bt-cotton. With the introduction of this technology, doubts arose about the long-term sustainability of cotton farming systems in the country due to the resistance of bollworm and the increase in secondary pest attacks as well as low yield of cotton crop. There is a need to re-examine the socio-ecological sustainability of different cotton farming systems. For the last few decades, research has focused on biodiversity in farming systems. However, this subject is so complex that it remains a research gap in the ecology of farming systems. Biodiversity plays a crucial role in providing the ecosystem services absolutely necessary for a productive, sustainable agricultural system. Measuring and assessing biodiversity is by itself a complex process with no existing standard. Therefore, comparative studies are needed to assess biodiversity. Through empirical data, the complex interaction between living organisms (biotic) and the physio-chemical components (abiotic) of the ecosystem can be understood and evaluated.

In this comparative study on cotton farming systems, two key aspects were taken into consideration: Plant protection in chapter 4 and soil fertility in chapter 5. To assess the health of ecosystem services provided by biodiversity, the choice of a good bio indicator was important. In this comparative study, invertebrates have been used to assess the health of ecosystems.

Agriculture is a unique system which operates at the confluence of human and ecological systems. Therefore, transdisciplinary approaches to evaluate the sustainability of farming systems are needed. There are many frameworks which have been developed to evaluate sustainability in farming systems. A few of these frameworks such as RISE, SAFA, PG or IDEA have been used to assess the three dimensions of sustainability at the farm-level. These frameworks were indicator-based tools. To develop our framework in chapter 6, we have used the concept of indicator-based tools using the FAO framework guideline which is based on SAFA.

Chapter 3
Methodology

Abstract

This study was conducted in collaboration with the Research Institute of Organic Agriculture (FiBL) and bioRe. FiBL and bioRe have a long-term field trial established since 2007 in India, in and around which this work was conducted. First, a brief description of the two organisations and details of the trial set up and the context of the study are provided. Second, the farm and farmers selection for the in-situ assessment of sustainability is explained. Third, a detailed description of the ecological surveys, laboratory analysis and statistical analysis is given. Finally, the methods for the literature review for the development of the tool to assess the holistic sustainability of farming systems is given.

3.1. Collaborators in this research

3.1.1. FIBL

"The Research Institute of Organic Agriculture (FiBL) is one of the world's leading research institutes in the field of organic agriculture. FiBL is located in Switzerland, Germany, Austria, France and has a representation in Brussels (Belgium) through FiBL Europe. FiBL focuses on interdisciplinary research, on developing innovations with farmers and the food industry, on projects which are solution oriented and on implementing knowledge from research into practice. "FiBL has long been committed to the international development of organic agriculture" and FiBL has been facilitating sustainable agriculture development in Africa, Asia, Latin America and Eastern Europe in collaboration with local partner organisations. In long-term trials, FiBL employees conduct research on local and organic farming systems, offering expertise in market development.

3.1.2. BioRe

BioRe India is a successful enterprise in the production of organic cotton uniting economic benefits with ethical responsibility.

BioRe India works with the farming community in Madhya Pradesh, Central India and aims to achieve sustainable agriculture in CFS. It works with more than 4000 farmers, giving them technical support, facilitating the organic certification and giving the organic farmers access to the market. BioRe assures the cotton quality by supplying organic cotton seeds to the farmers. BioRe India is part of various research activities. They are working on a non-Bt cotton seed breeding programme in collaboration with the University of Agriculture Sciences Dharwad. BioRe India in partnership with FiBL have undertaken numerous research initiatives including a long-term trials experiment (BioRe, 2017). Most of the research and social work is coordinated through BioRe Association, which is a farmers' cooperative working in close collaboration with BioRe India.

3.2. Long term trials as the context for this research

3.2.1. Overview of the international long-term trials

Since 1978, FiBL has started a long-term trial comparison system in Switzerland. For the past 39 years, this long-term trial experiment has been comparing Biodynamic (D), Organic (O) and Conventional (K - in German: "Konventionel") systems. The trial evaluated the different farming systems using crops of wheat, potatoes, maize, soya and grass-clover leys. Since 2007, FiBL has been running the system comparison program in the tropics. The trial is expected to run for a period of twenty years. The three selected countries to establish the system comparison are Kenya, India and Bolivia. This project aims to create a scientific base and records different aspects of the performance of conventional and organic agricultural production systems in the tropics. For each country, a long-term farming system has been launched in tandem with participatory on-farm research. Each country focuses on different crops. In Kenya, the experiments are based on a three-year crop rotation with maize, beans, potatoes and vegetables. They compare two types of system management: organic and conventional. In Bolivia, the long-term experiments are focused on the production of cocoa. Four treatments have been defined: Monoculture, full sun exposure with conventional management, monoculture, full sun exposure with organic management, diversified shaded agroforestry system with conventional management and diversified shaded agroforestry system with organic management. In India, the long-term experiments are focused on a two-year crop rotation with cotton, wheat and soya bean. They compare four systems; biodynamic, organic, conventional and Bt-conventional. This research focuses on the India trials.

3.2.2. Long-term Field trial in India

3.2.2.1. Overview

Long-term experimental trials managed by FiBL in India are located at the BioRe Research farm on the plains of the Narmada river belt in the Nimar Valley, Khargone district, Madhya Pradesh (Figure 3.1). This area is characterized by a hot summer and general dryness except from mid-June to September which is monsoon season. Generally, Khargone district receives an average annual precipitation of 835mm. The temperature in the region is ranging from a normal minimum of 11.1 degrees Celsius during the month of December and rising to a normal maximum of 41.8 degrees Celsius in the month of May (MinistryOfWaterResources, 2013). The local soils are Vertisol soil, which is the predominant soil type found in this region of Madhya Pradesh (Forster et al., 2013).

Figure 3. 3: LTE site location

3.2.2.2. Trial design with its farming systems

The trial compares two organic farming systems (biodynamic (Bd, organic (Org)) (Orgsys) and two conventional farming systems (conventional (Con), conventional using Bt cotton (Bt) (Consys) managed by FiBL since 2007. Management of each system has been kept in line with current best practices, consequently they have been slightly adapted according to the updates in the standardization of these different types of management. The four farming systems mainly differed in the following aspects: Genetic material, type and amounts of fertiliser inputs, green manures, plant protection, the use of biodynamic preparations and crop sequence.

3.2.2.2.1. Biodynamic systems (Bd)

Biodynamic management is a sub-type of organic management with an explicitly holistic approach toward farming. It was developed by Rudolph Steiner in 1924 and looked at the farm as an entity (Turinek et al., 2009). The biodynamic plots in this trial were managed according to the Demeter international standards (Demeter, 2020). The principle way in which it differs from organic practices is by using fermented preparations (Table 1) and the implementation of a planting calendar which is based on the lunar, solar, constellation cycle. This celestial calendar guides all farm activities. 501 preparation which is applied for the purpose of bringing vitality and health to the plant is applied during the ascending moon. As fertilisers, 500 preparation and Cow Pat Pit (CPP) is applied during the descending moon when the moon is opposite Saturn (Chalker-Scott, 2013). In this trial, biodynamic compost and CCP were applied as fertilisers, both made on-site according to biodynamic standards. Two-thirds of the compost was applied before sowing, and one-third of the compost was applied two months after sowing. Seeds were also treated with Beejamrit but instead of using cow dung slurry, Cow Pat Pit was used. Neem seed cake, Jaavamrat, *Beauveria Bassiana* and cow urine were used for crop protection throughout the season.

Table 3.3: Biodynamic preparations, their main ingredients and their potential effects (Chalker-Scott, 2013)

Preparation	Main ingredients	Effect
BD 500	Cow (*Bos taurus*) manure field spray	Soil biological activity
BD 501	Ground silica from quartz or feldspar	Plant resilience
BD 502	arrow blowwoms (*Acchillea millefolium L.*)	K and S processes
BD 503	Chamomille blossoms (*Matricaria recucitata L.*)	Ca and K processes
BD 504	Stinging nettle shoot (*Urtica dioeca L.*)	N management
BD 505	Oak bark (*Quercus robur L.*)	Ca processes
BD 506	Dandelion flowers (*Taraxacum officinale Weber*)	Si management
BD 507	Valerian extract (*Valeriana officinalis L.*)	P and warmth processes

Table 3.4: Biodynamic systems farming management practices (FIBL recommendation for the long-term experiment trial)

	2016	**2017**
Variety	JK Durga (non-Bt)	ANKUR JAI (non-Bt)
Seed Treatment	Beejamrit + Hing, *Trichoderma viridae,* Blue Vitriol (Nila Thota or copper sulphate)	
Fertilizer management	320 kg/plot (5000 kg/acre) of compost in three doses First= 160 kg/plot as basal, prepare ridge on it and sow cotton, Second =80 kg/plot at at square formation, Third =80 kg/plot at at peak flowering stage 10.0 kg/plot (156 kg/acre) of **Neem Seed Cake** in two doses; 5.0 kg at 45 DAS (= 10.0 g per plant) and 5.0 kg at 60 DAS (= 10.0 g per plant) BD-500 (Soil app.before sowing) ; App. of BD-501 at 50 DAS & each moon opp. Saturn CPP+BD-500 twice a month (Soil app.) until boll bursting	
Pest management	Treatment of ring around cotton plants with Hing spray (repellent), if insects persist spray Neem oil Botanical sprays @ 15 days interval: Alternate Hing sprays (5-10 g per pump + 250 mL fermented butter milk mixed with 1 L Jiv Amrit spray) with Neem oil, GOC (Garlic-Onion-Chilli), and Top Ten; First application right after emergence	

3.2.2.2.2. Organic systems (Org)

Organic management is characterized by the prohibition of synthetic pesticides and fertilisers. In this trial, organic systems were managed according to the standards defined by the international Federation of Organic Agriculture Movements (IFOAM)(IFOAM, 2019): Organic compost was used as fertilizer. Pest control was principally products which aim to repel pests by spraying botanical sprays (Table 2.3) which include GOC, TopTen and neem oil. The levels of organic fertiliser inputs reflects practices of local smallholder farmers (Table 3.4). The amount of compost was similar to the one applied in the biodynamic systems. Before sowing, the seeds were treated with Beejamrit and cow dung slurry.

Table 3.5: Names of the organic botanicals, their main and active ingredients

Organic botanicals	Ingredients	Active ingredients
GOC	Allium stivum, Allium cepa, Capsicum s.	Allicin, Suyn-propanethial-S-oxide, Capsaincin
Beejamrit	Cow dung, cow urine, lime powder, bund soil powder	Calcium, Nitrogen, Phosphorus, micronutrients
Neem Seed cake	Azadirachta indica	Azadirachtin
Jaavamrat	Cow dung, cow urine, jaggery, any leguminous powder, bund soil	macro nutirents, micronutrients, vitamins, amino acids
Top Ten	Ricinus communis, Annona squamosa, Vitex neguno, Ipomoea carnea, Nerium indicum, Datura festiosa, Pongmis pinnata, Carica papaya, Calotropis procera	Different alkaoids

Table 3.6: Organic system farming management practices (FIBL recommendation for the long-term experiment trial)

	2016	**2017**
Variety	JK Durga (non-Bt)	ANKUR JAI (non-Bt)
Seed Treatment	Beejamrit + Hing, *Trichoderma viride,* Blue Vitriol (Nila Thota or copper sulphate)	
Fertilizer management	320 kg/plot (5000 kg/acre) of compost in three doses First= 160 kg/plot as basal, prepare ridge on it and sow cotton; Second =80 kg/plot at at square formation, Third =80 kg/plot at at peak flowering stage 10.0 kg/plot (156 kg/acre) of **Neem Seed Cake** in two doses; 5.0 kg at 45 DAS (= 10.0 g per plant) and 5.0 kg at 60 DAS (= 10.0 g per plant)	
Pest management	Treatment of ring around cotton plants with Hing spray (repellent), if insects persist spray Neem oil Botanical sprays @ 15 days interval: Alternate Hing sprays (5-10 g per pump + 250 mL fermented butter milk mixed with 1 L Jiv Amrit spray) with Neem oil, GOC (Garlic-Onion-Chilli), and Top Ten; First application right after emergence	

3.2.2.2.3. Conventional systems (Con)

The conventional plots were managed according to the Indian Council of Agricultural Research (ICAR) guidelines which used synthetic fertilisers and pesticides (as well as organic manure)(ICAR, n.d.)(Table 3.5).

After land preparation and before sowing, Farmyard Manure (FYM) was applied and incorporated to the soil by bullock drawn harrows. FYM was applied before sowing. Seeds were treated with Imidacloprid (Table 3.5).

Table 3.7: Conventional systems farming management practices (FIBL recommendation for the long-term experiment trial)

	2016	2017
Variety	JK Durga (non-Bt)	ANKUR JAI (non-Bt)
Seed Treatment	Imidachloprid 70% SL (Gaucho) @ 3ml/kg seeds.	
Fertilizer management	105 kg/plot (1640 kg/acre) of FYM as basal, prepare ridge on it and sow cotton Urea = 7 kg/plot @ rate of 109 kg/acre in three split doses. 3.5 kg at first shower. 1.75 kg at square formation and 1.75 kg at peak flowering stage. SSP = 11.2 kg/plot as basal @ rate of 175 kg/acre MOP = 1.8 kg/plot as basal @ rate of 28 kg/acre	
Pest management	1) spray 20 days: Imidachloprid @ 100ml/acre. 2) Spray Monochrotophos @ 40ml + Acephate @25gm per pump. Saaf menchozeb + Carbandazim @ 300gm per acre. Thiomethaxam (Actara) @70gm per acre. Acetamiprid. Jassid and aphid: Confidor (Imidachloprid) 10ml per pump or Actara (Thiomethaxam) 7gm per pump or pride (Acetamiprid) 7gm per pump. For thrips: Karate (Lambda-Cyhalothrin) or Polytrin c @40ml per For white fly: polo (Diafenthiuron) @25gm per pump.	

3.2.2.2.4. Bt-conventional systems (Bt)

The Bt-conventional plots were managed according to the Indian Council of Agricultural Research (ICAR) guidelines which used synthetic fertilisers and pesticides (as well as organic manure) (ICAR, n.d.)(Table 3.7).

After land preparation and before sowing, farmyard manure was applied and incorporated to the soil by bullock drawn harrows. Bt-cotton seeds were not treated before sowing as they were already sold coated. According to the recommendations by ICAR, fertiliser and pesticides inputs for the Bt-conventional management were applied at higher rates to the non-Bt conventional management. In the (Con) and (Bt) systems, Confidor, Monocrotophos, Acephate, Triazophos and acetamiprid were used as pest control (Table 3.6).

Table 3.8: Names of the chemical used in conventional and Bt-conventional management practices and their classification

Chemicals	Classification
Imidacloprid Confidor	Systemic insecticide
Single Super Phosphate SPP P_2O_5 16% Phosphorus	Mineral fertiliser
Muriate of Potash K_2O 60% Potassium	Potassium fertiliser
Urea carbamide CH_4N_2O	Nitrogen fertiliser 46-0-0
Monocrotophos	Organophophate insecticide
Triazophos 60% LC	Organophophate insecticide
Acetamiprid	Neonicotinoid insectide
Pendamethalin	Dinitroaniline herbicide

Table 3.9: Bt-conventional systems farming management practices (FIBL recommendation for the long-term experiment trial)

	2016	2017
Variety	JK Durga (Bt)	ANKUR JAI (Bt)
Seed Treatment	No seed treatment (seed already treated)	
Fertilizer management	105 kg/plot (1640 kg/acre) of FYM as basal, prepare ridge on it and sow cotton Urea = 8.1 kg/plot @ rate of 127 kg/acre in three split doses. 4.1 kg at first shower. 2.0 kg at square formation and 2.0 kg at peak flowering stage. SSP = 13.2 kg/plot as basal @ rate of 206 kg/acre MOP = 2.3 kg/plot as basal @ rate of 36 kg/acre	
Pest management	1) spray 20 days: Imidachloprid @ 100ml/acre. 2) Spray Monochrotophos @ 40ml + Acephate @25gm per pump. Saaf menchozeb + Carbandazim @ 300gm per acre. Thiomethaxam (Actara) @70gm per acre. Acetamiprid. Jassid and aphid: Confidor (Imidachloprid) 10ml per pump or Actara (Thiomethaxam) 7gm per pump or pride (Acetamiprid) 7gm per pump. For thrips: Karate (Lambda-Cyhalothrin) or Polytrin c @40ml per For white fly: Polo (Diafenthiuron) @25gm per pump.	

3.2.2.3. Trial crop rotation

The trial incorporated a two-year rotation of cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.) and wheat (*Triticum aestivum* L.) on two strips (Figure 3.1).

In order to obtain data from each crop during each year, the layout was doubled with shifted crop rotation in two strips, resulting in a total of 32 plots, and 16 plots per strip (Fig. 1). Each farming system is replicated four times in a randomized block design in each of the two strips. Plots are sized 16 m by 16 m which represent the gross plot. Data and sampling was collected in the net plot which was sized 12 m by 12 m to avoid border effects. The distance between two plots within a strip and between the two strips was 6 m and 2 m, respectively.

Alternative years, on the first strip, cotton was planted from May to November and wheat was grown from December to March while on the second strip, soybean was planted from June to October and from December to March, wheat was planted.
In the organic farming systems (Orgsys) a green manure was grown from April to June every alternative year. This was not done for the conventional farming systems. On the

second strip, for (Org) and (Bd) systems, green manure was planted from the month of April for two months, but this practice was not followed in the conventional farming systems. Green manure crops were cut at flowering and the biomass was given to the cow. The cow dung from these cows was collected and applied on the organic and biodynamic managed plots.

For cotton, cultivars were selected by referring to the local practice and availability. In cotton, these were Maruti 9632 (2007), Ankur 651 (2008), Ankur AKKA (2009) and JK Durga since 2010 in all farming systems, except in the (Bt) management where Bt JK-Durga were used. The land was prepared with bullock-drawn ploughs, harrows and levelers. Cotton seeds were sown by hand with a spacing of 53 cm plant-to-plant distance and 106.6cm row-to-row distance.

		2016								2017												2018			
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Strip 1	Org	GM	Soybean						Wheat					Cotton							Wheat				GM
	Bio	GM	Soybean						Wheat					Cotton							Wheat				GM
	Con		Soybean						Wheat					Cotton							Wheat				
	Btc		Soybean						Wheat					Cotton							Wheat				
Strip 2	Org	Cotton							Wheat				GM		Soybean						Wheat				
	Bio	Cotton							Wheat				GM		Soybean						Wheat				
	Con	Cotton							Wheat						Soybean						Wheat				
	Btc	Cotton							Wheat						Soybean						Wheat				

Figure 3.4: Sequence of crops in different farming systems of the Long-term experiment trials from 2016 to 2018. GM represents the green manure which was only applied in the organic and biodynamic systems. The two years rotation consisted of cotton (Gossypium hirsutum), soybean (Glycine max) and wheat (Triticum aestivum)

3.2.2.3.1. Water management

The whole trial was irrigated through drip irrigation when necessary and all the plots received similar amounts of irrigation water. During monsoon, there was no irrigation as the amount of water received by rain was sufficient. After the monsoon, the cotton received additional water.

3.2.2.3.2. Weeding

Weeding was carried out in line with the recommendation of FiBL. The first weeding was done 13 days after sowing, using bullock-drawn blades (tine harrow) in all farming systems. After this, weeding was done when necessary. On the day of sowing, Pendamethalin was applied in (Con) and (Bt) plots. After this, no more synthetic herbicides were used (For more details, see Chapter 4, section 4.2.1.1.).

3.3. Farm-scale plots

After two years of ecological survey done on the long-term experiment trials, the study to assess sustainability was taken in-situ at the farmers field.

3.3.1. Farmers

3.3.1.1. Organic Farmers

- The organic farmers were part of the 4000 farmers working with BioRe. Organic farmers receive technical support from BioRe. BioRe are facilitating the organic certification and giving the organic farmers access to the market by buying their organic cotton with a 30% bonus.
- The organic farmers were using certified organic seeds distributed by BioRe.

3.1.1.1. Bt-conventional Farmers

- The Bt-conventional farmers were not part of any organisations and were farming independently.
- The Bt-conventional farmers were using genetically modified seeds.

3.1.2. Farm scale plots selection

In order to compare different farming systems at a farm-scale, farms were selected to be as similar as possible by using the following criteria:

- The 12 farm-scale plots were growing *Gossypium hirsutum*, however, the varieties of the *G. hirsutum* were different.
- Farm-scale plots were less than 2 hectares each. The owners of the plots were classified as small holder farmers.
- The crops monitored were all planted as a summer cotton crops, sowing dates were between the 29th May 2018 to 10th June 2018.
- all soils were vertisol.
- The farms were situated within a maximum radius of 35km to avoid differences in weather patterns.
- The farm-scale plots were selected as pairs. Each pair included one certificated organic farm and one Bt-conventional farm. The pairs were located at a

maximum distance of 200 meters from each other to minimize variation in the type of soil and it was possible to survey the pairs at the same moment.

Farms were selected in a two-stage process. First, a meeting with the BioRe research and extension team was organized to select farm-scale plots that matched the above criteria. Twenty pairs were selected. On-site visits were organized for these twenty pairs and they were evaluated, the six most homogenic pairs were selected and surveyed.

3.4. Evaluating sustainability from the plot-scale to farm-scale

The plot-scale study set in a controlled environment was essential as it accommodated a closer study of the ecology while minimizing other external variables. This was a novel ecological assessment studying the canopy, above ground and below ground biodiversity. The same ecological study was carried out in a living context directly on farmers' fields. In the second part of the study, the wider sustainability of organic and Bt-conventional CFS was evaluated and compared using cotton farmer's systems.

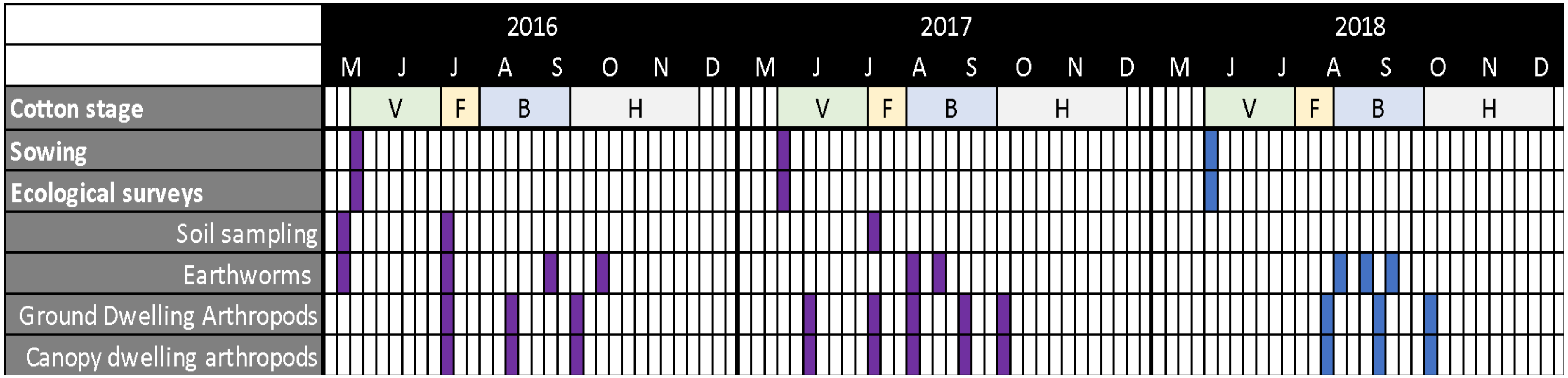
3.5. Sampling methods

3.5.1. General

Ecological surveys were carried out at the plot (2016 and 2017) and farm-scale (2018) using the same methodology at all sites. The survey comprised a soil survey, surveys of earthworms and above ground arthropods.

Above ground arthropods were sampled at the key development stages of cotton growth (vegetative stage, flowering stage, boll formation, harvesting period) at both the soil surface (via pitfall trapping) and the plant canopy (using a suction sampler) both diurnally and nocturnally. Earthworms were used as a bio-indicators to monitor the soil health and sampled on three occasions (*for details refer to Chapter 5, section 5.3.2.)*

Table 3.10: Cotton stages and survey schedule for the year 2016, 2017 and 2018. The purple cells represent the surveys done on the trial-scale plots and the blue cells were done on the farm-scale plots. Four cotton stages have been indicated: V: Vegetative stage, F: Flowering stage, B: Boll formation stage, H: Harvesting period)



3.5.2. Arthropod survey

Arthropod sampling was conducted during the cotton growing season. Arthropods were collected during the key period of the cotton cycles. (*For details methodology see Chapter 4, section 4.1.6.)*

3.5.3. Earthworm survey

Earthworm surveys were conducted using traditional hand sorting collection (*For details methodology see Chapter 5, section 5.3.2.)*

3.5.4. Soil survey

The soil analysis included electric conductivity, soil pH and bulk density, organic carbon, total Nitrogen, Nitrate and Ammonium were analysed. (*For details methodology see Chapter 5, section 5.3.3. and 5.3.4.)*

3.5.5. Fungi survey

Soil samples were taken using a soil core. The obtained soil samples were tested in a laboratory and fungi were then identified. (*For details methodology see Chapter 5, section 5.7.2.)*

Chapter 4 Ecological sustainability: Aboveground Biodiversity

Abstract

Through ecosystem services, biodiversity plays a key role in ecologically sustainable agriculture. One of the challenges that sustainable agriculture faces is balancing low chemical inputs with a sufficiently productive farming system. In Indian cotton farming systems, plant protection is the main cause of low productivity. In this study I investigated above-ground biodiversity with a focus on the functional biodiversity that provides regulating services such as biocontrol. In this study I surveyed the canopy- and ground-dwelling arthropod community on long term plot trials and in commercial fields of different cotton farming systems including: organic, biodynamic and two conventional systems (with and without Bt cotton seeds). To assess the ecological sustainability of different farming systems, the study investigated the arthropods community. The canopy- and ground-dwelling arthropods indicated no significant differences between the conventional and Bt-conventional systems. Jassids (Hemiptera: Cicadellidae), which are the main sucking pests represented more than 50% of the total number of canopy-dwelling arthropods in all the farming systems . Araneae represented the most abundant group of natural enemies. On both the plot-scale and farm-scale systems, Araneae abundance was higher in the organic systems when compared to the Bt-conventional systems for both canopy and ground-dwelling communities.

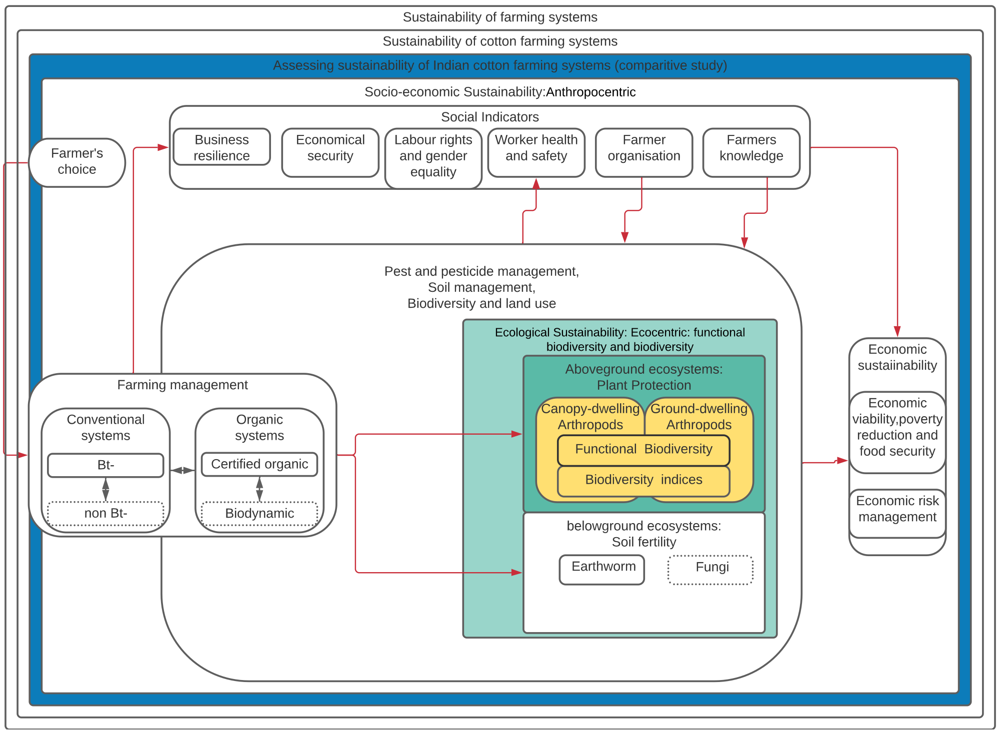


Figure 4.5: Diagram of the thesis summary highlighting this chapter

4.1. Introduction

4.1.1. Invertebrates in agricultural systems

Invertebrates represent no less than 97 per cent of all animal species on Earth (Georgia Tech Biological Sciences, 2019). They play a dominant role in providing ecosystem services (ES) to arable land (Prather et al., 2013). There are several ESs provided by functional biodiversity including supporting services, provisioning services, regulating services and cultural services (Haines-Young and Potschin, 2009). However, the function of these services has been understudied (Soliveres et al., 2016), especially in the tropics (Giller et al., 1997; Sarathchandra et al., 2021). Due to the industrialization and intensification of agriculture (Giller et al., 1997; Krauss et al., 2011), insect biodiversity has declined by an estimated 41% since the beginning of the 20th century (Sánchez-Bayo and Wyckhuys, 2019). It is estimated that from 2000 to 2011, 40% of tropical forest was replaced by commodity crop production (Ordway et al., 2017). Worldwide, the majority of crops are grown using conventional and intensive agriculture methods which include the use of chemical fertilizers and pesticides (Morente et al., 2018). Conventional agriculture is related to negative environmental impacts including a decrease in functional biodiversity, which can lead to an increase in pest damage (Mkenda et al., 2019). The majority of farmland is managed under conventional agriculture whereas only 1.4% of the total farmland in the world is managed organically (FiBL, 2019; Lernoud and Willer, 2017). The main objective of organic production is to establish an agricultural system that contributes to biodiversity and take in consideration nature's systems and cycles (Soldi et al., 2019). Research has shown that organic farming benefits biodiversity (Hole et al., 2005).

In cotton, previous research has mainly focused on insect pests, although other invertebrates play an important role in ecosystem services such as regulating pest control (Ambrose and Claver, 1999; Khalil et al., 2017; Men et al., 2005). The main pest in cotton is moth larvae from the Noctuidae family, *Helicoverpa armigera,* commonly called bollworm. In 2008, gene technology was developed to fight this pest. A gene from the bacterium *Bacillus thuringiensis* was inserted in cotton plants to control *H. armigera* larvae (Ramani and Thutupalli, 2015b; Sharma and Pampapathy, 2006). This transgenic cotton (hereafter referred to Bt cotton), was introduced in order to reduce the amount of pesticides used in crops (Naranjo and Ellsworth, 2009; Vadakattu and Watson, 2004). Thanks to this technology, in some countries the use of pesticides has been reduced (Deguine et al., 2000).

However, in India, since the introduction of transgenic cotton in 2002, the amount of pesticides in cotton crops has increased (Pesticide Action Network UK, 2017) (Figure 4.6). One of the ecological effects of the use of Bt cotton has been the increase of secondary pests, which are sucking pests and are not controlled by Bt (Zhao et al., 2011). This resulted in a surge of sucking pests shortly after the introduction of Bt cotton (Biradar and Vennila, 2008; Sharma and Pampapathy, 2006). Consequently, by 2014, pesticide consumption increased by 16.1% as farmers controlled for major pests like mealy bugs, or sucking pests (Pesticide Action Network UK, 2017). Biotechnology was supposed to target specific pests but with an increase in pesticide usage, it questions the ecological sustainability of addressing the non-target invertebrates of Bt technology in India.

In this study, I consider the secondary pests responsible for reducing the yield of cotton systems but exclude bollworm, as much research has been done on this topic (Dhillon et al., 2011; Tabashnik and Carrière, 2019).

Figure 4.6: Amount of pesticides used in cotton crops in comparison to the total area of BT-cotton plants in India. Source: Kranthi,2014)

4.1.2. Comparative studies in different farming systems

Indicator-based studies have used invertebrates to evaluate the impact of agricultural practices for decades now (Paoletti et al., 1991). They have been frequently employed to compare different types of agricultural systems including Bt-cotton and non-Bt-cotton (Naranjo and Ellsworth, 2001; Wolfenbarger et al., 2008) as well as organic systems and conventional systems (Bengtsson et al., 2005). They have been used to evaluate soil quality (Stork and Eggleton, 1992) or to assess the sustainability of agroecosystems above soil (Cardoso et al., 2004; Paoletti, 1999b). Indicator-based studies have been used to evaluate the influence of crop cover (Olson et al., 2009) as well as the effect of other farming management (Paoletti, 1999a; Paoletti and Hassall, 1999; Rendon et al., 2015). Arthropods are quality indicators as they are easy to sample and monitor and do not require costly equipment (Obrist and Duelli, 2010).
Furthermore, arthropods rapidly respond to changes in environmental drivers (Hooper et al., 2000) and represent the largest percentage of species at any given scale which make them a good indicators of the total biodiversity, more than any other group of organisms (Obrist and Duelli, 2010). They are important economically for farming systems as they provide free ecosystem services (Y. G. Han et al., 2015). There is a need to understand the impact that human activity has on terrestrial arthropods in order to enable the conservation of biodiversity (McGeogh, 1998).

The majority of biodiversity studies in agriculture have focused on the impact of farming systems on a single taxonomic group (Bengtsson et al., 2005; Scharff et al., 2003; Torres and Ruberson, 2005), rather than the whole invertebrate community (Li et al., 2012), overlooking the fact that biodiversity loss occurs across many taxa and that the functional effects of trophic groups have an impact on each other (Naeem et al., 2000). Ecological systems are complex and dynamic; they fluctuate according to the time and location of the survey. Thus, there is difficulty in monitoring and interpreting them (Wolfenbarger and Phifer, 2000). The monitoring of the arthropods community can be time-consuming and a relevant methodology to evaluate the impact of farming systems on the whole invertebrate community has not been established yet (Li et al., 2012; Popov et al., 2018). The choice of indicator species should be selected according to their sensitivity to the studied farming management as well as their economic value for farmers (Popov et al., 2018). Species richness, is linked to ecosystem functioning and is considered useful because researchers suggest that an agro-ecosystem with more species is more productive as well as more sustainable (Mouillot et al., 2011; Tilman et al., 1996). However, biodiversity indices and relative abundance in agroecosystems do not constantly reflect the effect of agro-management on the arthropod community (Morente et al., 2018; Popov et al., 2018). Functional biodiversity studies look at components that help improve productivity and are therefore linked to agricultural sustainability through the ESs they provide (Bàrberi, 2013). This study invested and selected taxa which have been used in previous studies as bio-indicators and that are economically important for the farmers - improving or increasing productivity (Duelli and Obrist, 2003).

With the introduction of Bt-cotton, there has been an increase in sucking pest populations in Indian cotton agriculture such as jassids (*Amrasca biguttula* (Vonzun et al., 2019). It is one of the most damaging sucking pests in cotton and can be found throughout the country (Arora et al., 2006). In this study, I looked at the jassids population in the different farming systems as well as its natural enemies. Natural enemies are often the most sensitive to pesticides and are the most affected, impacting the stability of the ecosystem (Kannan et al., 2004; Solanki and Kumar, 2014). Many studies have looked toward native natural enemies to combat insect pests(Ali et al., 2016; Dhaka and Pareek, 2007).

4.1.3. Aims of the chapter

The aims of this chapter are the following:

(1) To compare the arthropod community at a plot-scale in four farming systems (biodynamic, organic, conventional and Bt-conventional) and a farm- scale in two farming systems (organic and Bt-conventional) by quantifying the relative abundance, species richness and diversity of ground and canopy-dwelling arthropods.

(2) To investigate if Bt transgenic cotton crops have a long-term impact on the arthropod community.

(3) To investigate the functional biodiversity and the ecosystem services potential provided by above ground arthropods with a focus on biological control of pests.

4.2. Methods

4.2.1. Sites

The survey was conducted in the Nimar Valley, Madhya Pradesh, India. The site is located in an area with a semi-arid subtropical climate. The mean annual temperature and precipitation are 27 degrees Celsius and 793mm respectively. The soil at the field site has been categorized as a vertisol with an average pH of 8.7.

4.2.1.1. Long Term Experimentation

Since 2007, FiBL has run a system comparison program in the tropics (Bolivia, Kenya and India). The trial is expected to run for a period of twenty years. In India, the trial is located at the BioRe field station (Khargone district, Madhya Pradesh, India) and consists of a two-year crop rotation which includes cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* L.) and wheat (*Triticum aestivum* L.). The trial compares two organic farming systems (biodynamic and organic) and two conventional farming systems (convention and Bt-conventional). Each farming system has been replicated four times in a fully randomized block design (Forster et al., 2013). To obtain data from each crop during each year, the layout was doubled with shifted crop rotation in two strips, resulting in a total of 32 plots, and 16 plots per strip, net plot were 12x12 m (a detailed experimental design is described in Chapter 3, section 3.2., page29).

Weeding was carried out in line with the recommendation of FiBL. The first weeding was done 13 days after sowing, using bullock-drawn blades (tine harrow) in all farming systems. After this, weeding was done when necessary. On the day of sowing, Pendamethalin was applied in (Con) and (Bt) plots. After this, no more synthetic herbicides were used (Table 4.11).

Table 4.11: Removal of weed schedule for the plot-scale systems in the year 2016 and 2017 (BDW: blade harrow deweeding, MDW: Manual deweeding around each cotton plant, CDW: chemical used for deweeding (Pendimetalin + Hit Weed + Targa super)

	June				July				August				September			
	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4
Biodynamic	BDW		BDW		MDW		BDW	MDW					BDW			
Organic	BDW		BDW		MDW		BDW	MDW					BDW			
Conventional	BDW	CDW	BDW		MDW		BDW	MDW					BDW			
Bt-conventional	BDW	CDW	BDW		MDW		BDW	MDW					BDW			

4.2.1.2. Farmer's fields

In 2018, 6 pairs of organic and Bt-conventional cotton systems were selected (details are described in Chapter 3, section 3.3., page 38) within a maximum radius of 35 km of the BioRe field station where the plot trials were located. All selected farms were smaller than 2 hectares. In all cases the cotton crop was sown between May 21st and

June 6th, 2018. In the region, a few farmers partially followed biodynamic farming practices but none of them was Demeter certified (international biodynamic certification scheme). When Bt-cotton became commercialized, conventional farmers who previously used hybrid seeds moved to Bt-cotton crops as the latter were promoted as being productive. The Bt-conventional systems used registered Bt-cotton seeds, the crops in these fields were grown using the same fertilizer and pesticide regime as that used in the plot trial. All the farmers were removing the weed at a different time, apart from 4 farmers, in average farmers were removing the weed three times during the cotton season (Table 4.12).

Table 4.12: Weed removal schedule for each plot-scale system (DW: deweed (the farmer did not indicate the methods used for removal of weed) during the year 2018

	June				July				August				September			
	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4
Organic 1						DW				DW						
Organic 2				DW				DW				DW				
Organic 3				DW				DW				DW				
Organic 4					DW					DW			DW			
Organic 5																
Organic 6																
Bt-conventional 1						DW				DW			DW			
Bt-conventional 2						DW		DW		DW						
Bt-conventional 3																
Bt-conventional 4				DW				DW					DW			
Bt-conventional 5																
Bt-conventional 6																

4.2.2. Sampling design

4.2.2.1. Long term plots (plot-scale trial)

There were four sampling events in 2016 and five in 2017.

In 2016, four arthropod surveys were carried out. The first survey took place before cotton seeds were sown. This survey represented the baseline before cotton growth. The survey was done during the land preparation phase, between the 11th and 19th of May, 2016. Cotton was sown on the 20th of May. The second survey was done during the monsoon break which corresponds to the vegetative stage of the cotton plant. This survey started on the 15th of July 2016 and finished on the 26th of July 2016 (42-49DAS (Date After Sowing)). It would have been difficult to survey the plots during the monsoon due to the intensity of the rain as the rain would affect the survey result. The third survey was done during the flowering and fruiting stage, which began on the 6th of October 2016 and finished on the 19th of October 2016 (126-133DAS). The fourth survey was done after the uprooting of the cotton plants. This survey started on the 9th of December 2016 and finished on the 22nd of December 2016 (Table 4.13,Figure 4.7).

In 2017, five surveys were carried out. Samples were collected once at the vegetative stage, twice during the flowering stage and twice at the fruiting stage of the cotton plant. The cotton was sown on the 23rd of May 2017. The first survey was done on the 4th week (21-25 DAS) after sowing between the 12th of June 2017 to the 16th of June 2017. The second survey was done 8 weeks after sowing (49-54 DAS), between the 10th of July to the 15th of July 2017. The third survey was done 12 weeks after sowing (79-84 DAS), from the 9th of August to the 16th of August 2017. The fourth survey was done 16 weeks after sowing (102-108 DAS), from the 1st of September 2017 to the 6th of September 2017. The fifth survey was done 20 weeks after sowing (134-135 DAS), from the 3rd of October to the 6th of October 2017 (Table 4.14, Figure 4.7).

Table 4.13: 2016 time of the ecological surveys done highlighted in green and date of sowing with pesticides applications (DOS: Date of Sowing, MA: Monoacephate, CD: Comfidor, MN: Monocrotophos, TT: Top Ten, NM: Neem extract, DP: Dipel, LS: Lastraw, BB: Beauveria Bassania, S1: Survey 1, S2: Survey 2, S3: Survey 3, S4: Survey 4).

	May				June				July				August				September				October				November				December			
	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4
Biodynamic			DOS								TT		LS BB				BB															
Organic			DOS								TT		LS BB				BB															
Conventional			DOS											MA CD MN																		
Bt-conventional			DOS											MA CD MN																		
		S1									S2											S3								S4		

Table 4.14: 2017 time of the ecological surveys done highlighted in green and date of sowing with pesticides applications (DOS: Date of Sowing, MA: Monoacephate, CD: Comfidor, MN: Monocrotophos, TZ: Trizophos, TT: Top Ten, NM: Neem extract, DP: Dipel, LS: Lastraw, S1: Survey 1, S2: Survey 2, S3: Survey 3, S4: Survey 4, S5: Survey 5)

	May				June				July				August				September				October			
	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4	w1	w2	w3	w4
Biodynamic			DOS									NM	NM LS											
Organic			DOS									NM	NM LS											
Conventional			DOS								CD	MN MA		MA TZ MN										
Bt-conventional			DOS								CD	MN MA		MA MN										
							S1			S2				S3			S4				S5			

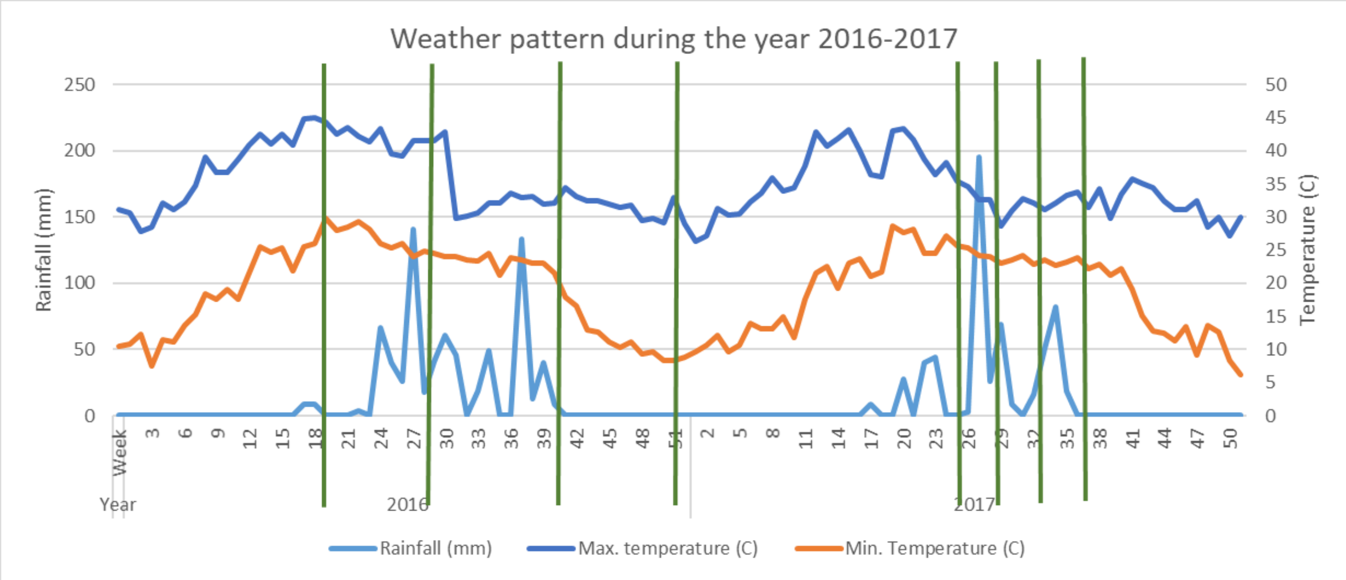


Figure 4.7: Date of ecological survey (green vertical lines) with weather pattern during the year 2016 and 2017 in the district of Khargone (BioRe), with the rainfall (mm), minimum temperature, maximum temperature and the green vertical lines represent the time of the arthropods survey.

4.2.2.2. Farmer's plots (farm-scale systems)

Three surveys were carried out on the farm plots in 2018. Samples were collected twice during the flowering stage and once during the fruiting stage of the cotton plant. The first survey was done between the 13th of August 2018 and the 17th of August 2018. The second survey was carried out between the 12th of September and the 15th of September 2018. The third survey was done between the 10th of October and the 13th of October 2018 (Table 4.15).

Table 4.15: 2018 Date of the ecological surveys done highlighted in green with schedule of farmer's date of sowing and pesticides applications (DOS: Date of Sowing, MA: Monoacephate, CD: Comfidor, MN: Monocrotophos, TT: Top Ten, NM: Neem extract, DP: Dipel, S1: Survey1, S2: Survey2, S3: Survey3)

	May				June				July				August				September				October			
	w1	**w2**	**w3**	**w4**	**w1**	**w2**	**w3**	**w4**	**w1**	**w2**	**w3**	**w4**	**w1**	**w2**	**w3**	**w4**	**w1**	**w2**	**w3**	**w4**	**w1**	**w2**	**w3**	**w4**
Organic 1					DOS							TT	NM		GOC		TT							
Organic 2					DOS									TT	NM	GOC								
Organic 3				DOS										Dipel		TT	NM	NM	DP					
Organic 4					DOS					TT	NM			NM		DP	NM	TT	NM	GOC				
Organic 5				DOS								TT		NM		GOC	TT							
Organic 6																								
Bt-conventional 1					DOS								CD		MA		MA							
Bt-conventional 2					DOS		MA			MA		CD	MA	CD			MA							
Bt-conventional 3																								
Bt-conventional 4						DOS											MA		MA					
Bt-conventional 5				DOS				MN	MN			MN		MA										
Bt-conventional 6					DOS					MA			MA				MA		MA					
														S1				S2				S3		

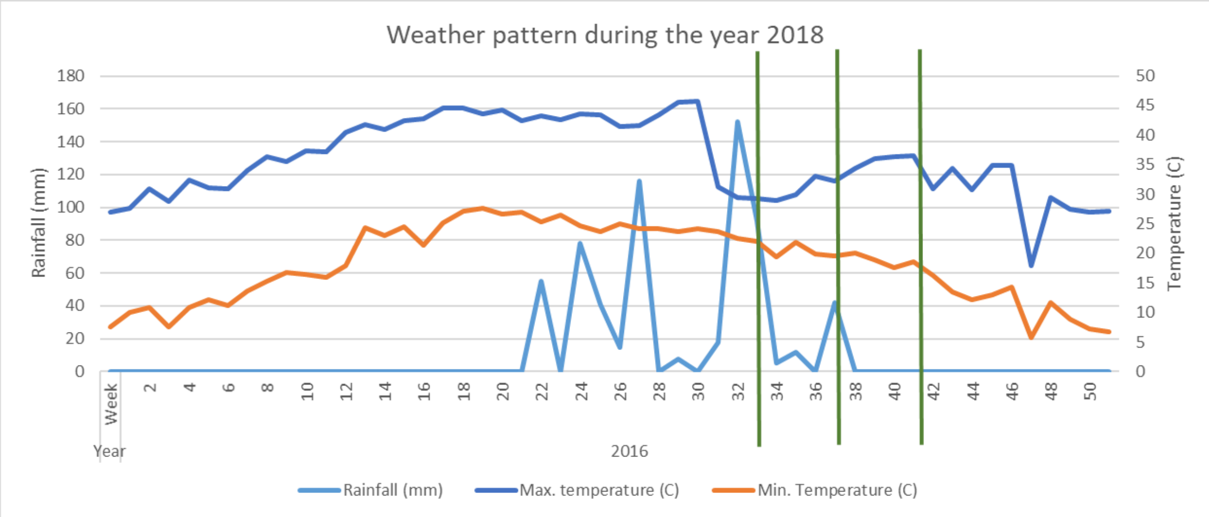


Figure 4.8: Weather pattern during the year 2018 in the district of Khargone (BioRe), with the rainfall (mm), minimum temperature, maximum temperature and the green vertical lines represent the time of the arthropods survey.

In both plot and field trials, arthropods were collected using the following techniques:

4.2.3. Arthropod survey

Arthropod sampling was conducted during the cotton growing season. Arthropods were collected during the key period of the cotton cycles (for details, see Chapter 3: Table 3.10).

4.2.3.1. Pitfall sampling

Ground dwelling arthropods were collected using pitfall traps. 1L plastic cups with a 12 cm diameter were filled with water and 100ml of 40% ethylene glycol (Isaia et al., 2006). Three pitfall traps were placed randomly on each 12x 12m plot. Traps were set in the early morning and left for 36 hours. After 36 hours, they were capped and retained for identification. This method was replicated twice during each survey period. On each plot, the contents of the three samples were averaged for analysis.

4.2.3.1.1. Sample effort: Plot-scale surveys 2016 and 2017

In 2016, 384 samples were collected (4 systems * (3 sub-samples) * 4 blocks * 4 events * 2 Replicates, N=384).

In 2017, 480 samples were collected (4 systems * (3 sub-samples) * 4 blocks * 5 events * 2 Replicates, N=480).

(see Table 4.16)

4.2.3.1.2. Sample effort: Farm-scale surveys 2018

On the farm-plot survey, 108 samples were collected (2 systems * (3 sub-samples) x 6 sites x 3 events, N= 108).
(see table 4.17)

4.2.3.2. Suction sampling

Canopy dwelling arthropods were collected using a suction sampler (inverted leaf blower: STIHL SH86C-E). To collect the arthropods, cotton bags were sewn to fit the blower tube: 40 x 25 cm. Each bag was marked with the survey number, site code, plot number, replicate, date and time. On each plot, three random sub-samples were taken. Each sampling comprised a 30-second suck, moving from the lower part of the canopy to the highest part.

Specimens were stored in the freezer until identification. After identification, they were preserved in 70% alcohol. On each plot, three samples were taken and averaged for analysis.

4.2.3.2.1. Plot-scale surveys 2016 and 2017

Samples were taken both during daylight and at night. Nocturnal surveys were carried out at the end of astronomical twilight. Diurnal surveys were carried out during the early morning between 9 am to 11 am. Each of these surveys was replicated twice, giving a total amount of four surveys total per event.

Table 4.16: Details of the canopy and ground dwelling arthropods surveys for the years 2016 and 2017 on the long-term trials (plot-scale)

		Day/Night	samples	Blocks	Replicates	Events	Systems	Number of samples per system (n)	Total number of samples (N)
2016	Pitfall	1	3	4	2	4	4	96	384
	Vaccum	2	3	4	2	4	4	192	768
2017	Pitfall	1	3	4	2	5	4	120	480
	Vaccum	2	3	4	2	5	4	240	960

4.2.3.2.1. Farm-scale survey 2018

For security reasons, sampling was only carried out during the day on the working farms. Table 4.17 shows the sampling regime.

Table 4.17: Details of the canopy and ground dwelling arthropods surveys for the year 2018 on the farmer's fields (farm-scale)

		Day/Night	Samples	Pair	Events	Systems	Number of samples per system (n)	Total number of samples (N)
2018	Pitfall	1	3	6	3	2	54	108
	Vaccum	1	3	6	3	2	54	108

4.2.3.3. Pollinators survey

Pollinators play an important role in cotton. A tentative study of the long-term effect of CFS on pollinators at the plot scale level was attempted but a large proportion of flower fall meant that insufficient data was collected for analysis. For information only, more details can be found in Appendices A.1.

4.2.4. Laboratory analysis

Arthropods were identified down to Order level principally and family, genus and species when possible. The specimens were then categorised into functional groups. During the identification, I focused Coleoptera, as members of this order have been used previously as bio-indicators of soil health, they are also the most speciose groups of arthropods (Menta and Remelli, 2020; Stork and Eggleton, 1992). I identified Coleoptera to family and assigned them to a functional group (predators; phytophagous; pollinators and decomposers, see section 4.2.5.5.1.). Diptera were identified to Order as few species keys were available.

Insects were identified using a stereoscope at x40 magnification and lit using a white LED light as well as the integrated microscope light. The arthropods caught by the inverted leaf blower were placed in a plastic tray and first separated from the leaves, soil and other debris. Specimens were kept in 70% ethanol until identification. Specimens from the pitfalls were removed, identified and kept preserved in 70% alcohol. To this end, the arthropods were placed in a petri dish below the stereoscope. Data was recorded using a table on paper. Once the analysis was complete, the data were digitized into Microsoft Excel. The Coleoptera specimens were photographed and drawn as well as numbered for further identification.

Identification was carried out using: Handbook of cotton plant health (Kranthi et al., 2013), Complete British Insects (Michael Chinery, 2005), CICR (cicr.org.in, [last accessed 19/10/2020] Spider of India (Sebastian and Peter, 2009) and Araneae (https://araneae.nmbe.ch, [last accessed 10/12/2019]) (Nentwig et al., 2021).
When I was not able to identify the Coleoptera specimens at the family level with the resources available to me, expert assistance was taken from Sholto Holdsworth of the Natural Museum by emailing a picture of the unidentified specimen.

4.2.5. Statistical Analysis

Statistical analysis was done to analyse the data generated by the plot-scale and farm-scale surveys which included the data from the ground-dwelling and canopy-dwelling arthropods' communities. The Order level of the specimens was used for the statistical analysis. Formicidae Order was omitted from the data sets.

4.2.5.1. General representation of the total community

Pie charts were used to visualise the structure of the general invertebrate assemblages. This was done for each farming system and the percentage according to their order and family was plotted using Microsoft Excel. The species or taxonomic groups which represent less than 1% of the total community were clustered together and represented as "others".

4.2.5.2. Analysis of taxonomic groups

4.2.5.2.1. Statistical methods-overview

Diagrams of distribution data were generated in R to establish whether data fitted the normal Gaussian distribution pattern (see example of the distribution in the Appendices B.2, Figure B.3, Figure B.4, Figure B.5 Figure B.6, Figure B.7, Figure B.8, Figure B.9, Figure B.10). Gotelli (Gotelli and Colwell, 2001) asserted that: "normal (bell-shaped) distributions are ubiquitous and turn up frequently in the real world", but researchers are more careful about ecological data and their ability to follow normal distributions. For example, Anderson (2001) stated that normal distribution is "particularly unrealistic for most ecological datasets", this is because the data generally contain lots of zero values. The normality of the data was checked using the visual inspection of density plots generated by the package “ggpubr” in R (Kassambara, 2020). When non-normal distributions were found in the data, General Linear Mixed Model (GLMM), which is tolerant to non-normal data was used. Furthermore, non-parametric tests were used where data were not normally distributed (for example Spearman’s rank correlation instead of Pearson’s correlation coefficient).

4.2.5.2.2. Analysis of plot-scale data

Both the data from the years 2016 and 2017 were analysed separately. There were analysed separately because the design was a rotation design (see Chapter 3: Methodology, section 3.2.2.). Due to the rotational design, repeated measured was inappropriate.

4.2.5.2.2.1. Analysis of the plot-scale data of 2016

In the year 2016, there were 4 sampling events. Instead of transforming the data and using ordinary least squares regression, we applied a GLMM in which “system” is used as the independent variable and the taxonomic group is used as the dependent factor.

For the year 2016, data were analysed data were analysed using a GLMM in R using general linear models using “multcomp” (Hothorn, 2019) and “lme4” (Bates and Maechler, 2019) to determine whether there were significant differences in invertebrate abundance between systems. System (comprising biodynamic, organic, Bt-conventional and conventional farming systems) was included as a fixed factor, block was included as a random factor, the sampling events were average and the response variables (analysed separately) were as follows:

Canopy dwelling invertebrates: Araneae, Coleoptera, Orthoptera, Diptera, Blattodea, Cicadellidae and Others.

Ground dwelling invertebrates: Araneae, Blattodae, Coleoptera, Dermoptera, Diptera, Isopoda, Orthoptera and Others.

4.2.5.2.2.2. Analysis of the plot-scale data of 2017

In the year 2017, there were 5 sampling events. Instead of transforming the data and using ordinary least squares regression, we applied a General Linear Mixed-effects model (GLMM) in which "system" is used as the independent variable and the taxonomic group is used as the dependent factor.

For the year 2017, data were analysed using a GLMM in R using general linear models using "multcomp" (Hothorn, 2019) and "lme4" (Bates and Maechler, 2019) to determine whether there were significant differences in invertebrate abundance between systems. System (comprising biodynamic, organic, Bt-conventional and conventional farming systems) was included as a fixed factor, block was included as a random factor, the sampling events were average and the response variables (analysed separately) were as follows:

Canopy dwelling invertebrates: Araneae, Coleoptera, Orthoptera, Diptera, Hemiptera, Blattodae, Cicadellidae, Miridae, Lepidoptera, Aphidae, Hymenoptera and Others.

Ground dwelling invertebrates: Isopoda, Zygentona, Diptera, Diplopoda, Araneae, Coleoptera, Orthoptera and Others

4.2.5.2.2.3. Analysis of the plot-scale data of 2016 and 2017

To compare the taxonomic groups between the year 2016 and 2017, data were analysed using a General Linear Mixed Effects Model (GLMM) in R using general linear models using "multcomp" (Hothorn, 2019) and "lme4" (Bates and Maechler, 2019). Year was included as a fixed factor; the systems and sampling events were average and the response variables (analysed separately) were as follows:

Canopy dwelling invertebrates: Araneae, Blattodae, Cicadellidae, Coleoptera, Diptera, Hemiptera, MIridae, Orthoptera, Others

Ground dwelling invertebrates: Araneae, Blattodae, Coleoptera, Dermaptera, Diplopoda, Diptera, isopoda, Orthoptera, Zygentoma, Others

4.2.5.2.3. Analysis of farm-scale data of 2018

Data were analysed using General Linear Mixed Models using "multcomp" (Hothorn, 2019) and "lme4" (Bates and Maechler, 2019). Analyses were carried out using a group of arthropod specimens (Order level) as dependent factors in separate analyses for each data set. For the farm-scale data of 2018, Pair was included as a random factor. System (organic and Bt-conventional farming systems) was included as a fixed factor.

Canopy dwelling invertebrates: Aphidae, Araneae, Chrysopidae, Cicadellidae, Coleoptera, Diptera, Miridae, Orthoptera and Others.

Ground dwelling invertebrates: Araneae, Coleoptera, Diplopoda, Diptera, Isoptera, Lepidoptera, Orthoptera, Zygentoma and Others.

4.2.5.3. Functional Biodiversity

4.2.5.3.1. Functional groups

Arthropods were grouped into four functional groups: predators; phytophagous; pollinators and decomposers. The specimens which were not identified were grouped into "Others". Species that feed on other organisms were classified as predators (Sergio et al., 2008).Species that feed on plant tissues, fruits and sap were classified as phytophagous (Trivellone et al., 2017). Species that feed on dead plant or decaying or dead plant as well as animal were classified as decomposers (Veen et al., 2019).

Data from 2017 and 2018 were included. Coleoptera from 2016 were not identified to family level and therefore 2016 data were excluded.

4.2.5.3.2. Testing the relationship between pests and natural enemies.

Non-parametric Spearman's ranked correlations were used to test the relationship between the Cicadellidae (jassids) and the known natural enemies (Araneae (spiders) and Ladybird). The correlation test was conducted in R. In the package "Hmisc" which contains many functions for data analysis, the function "rcorr" was conducted to produce a matrix of correlations between Jassids, which are the main secondary pests and their known natural enemies. "rcorr" "computes a matrix of Spearman's rank correlation coefficient for all possible pairs of columns of a matrix" together with an estimation of significance (CRAN,2019).

4.3. Results

4.3.1. 2016_Plot-scale data set

4.3.1.1. Taxonomic representation of the arthropods' communities

4.3.1.1.1. Canopy dwelling community

From the plot-scale data set of the canopy-dwelling community of 2016, a total of 4836 specimens were collected. The most abundant taxonomic group was Cicadellidae, which is mostly composed of the species *Amrasca biguttula* representing more than 50% of the total number of arthropods. Diptera, Coleoptera and Araneae were the most abundant taxonomic groups after Cicadellidae (Figure 4.9).

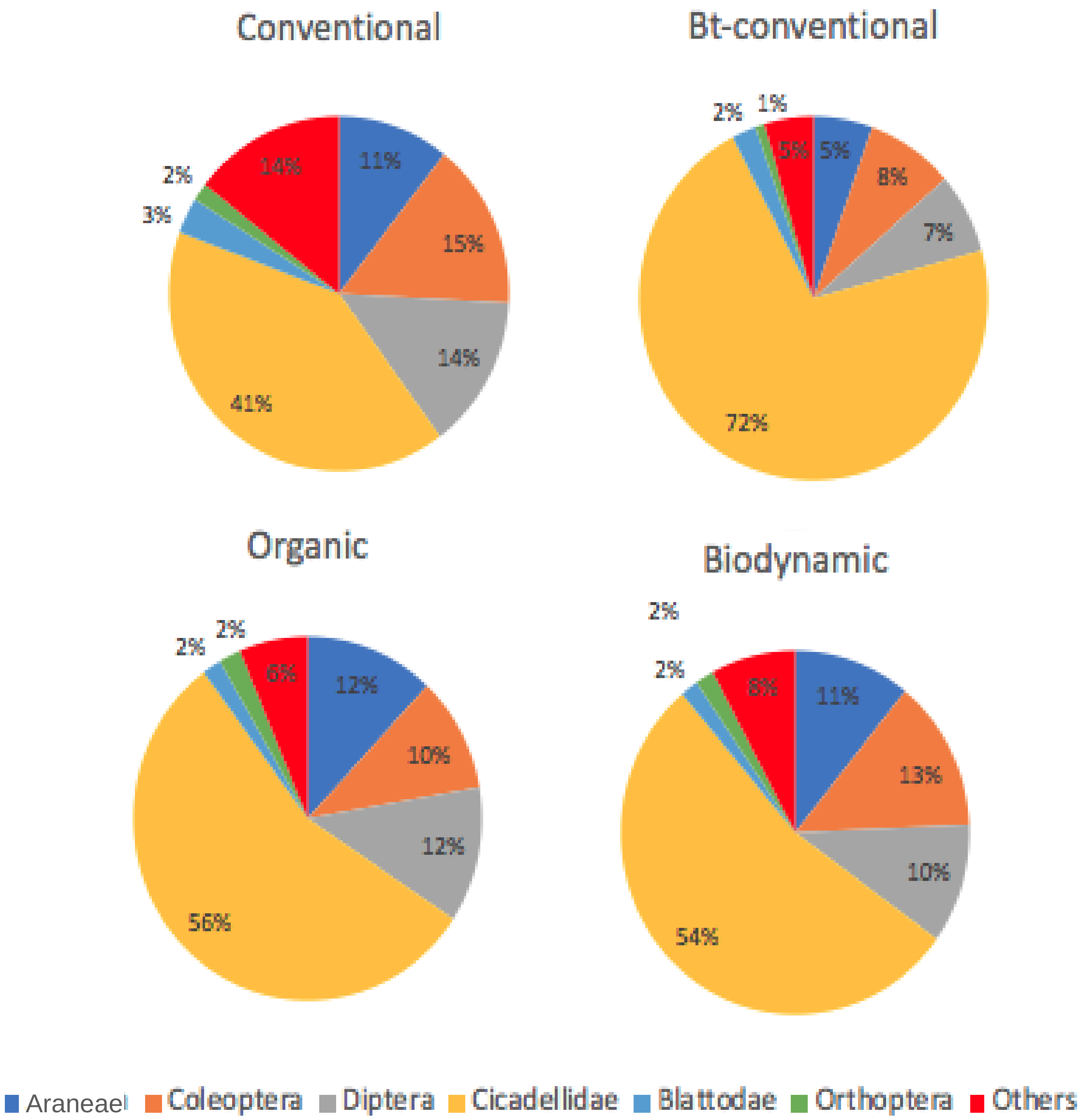


Figure 4.9: Representation in percentage of the number of canopy-dwelling arthropods community in four farming systems (Organic, Biodynamic, conventional, and Bt-conventional during the year 2016

4.3.1.1.2. Ground dwelling community

2141 specimens were collected among the ground-dwelling arthropod community in 2016. The most abundant ground dwelling taxonomic groups were Orthoptera, Araneae and Coleoptera. Clustered together, they represented between 75%, 69%, 78% and 71% of the Bt-conventional, conventional, organic and biodynamic systems respectively (Figure 4.10).

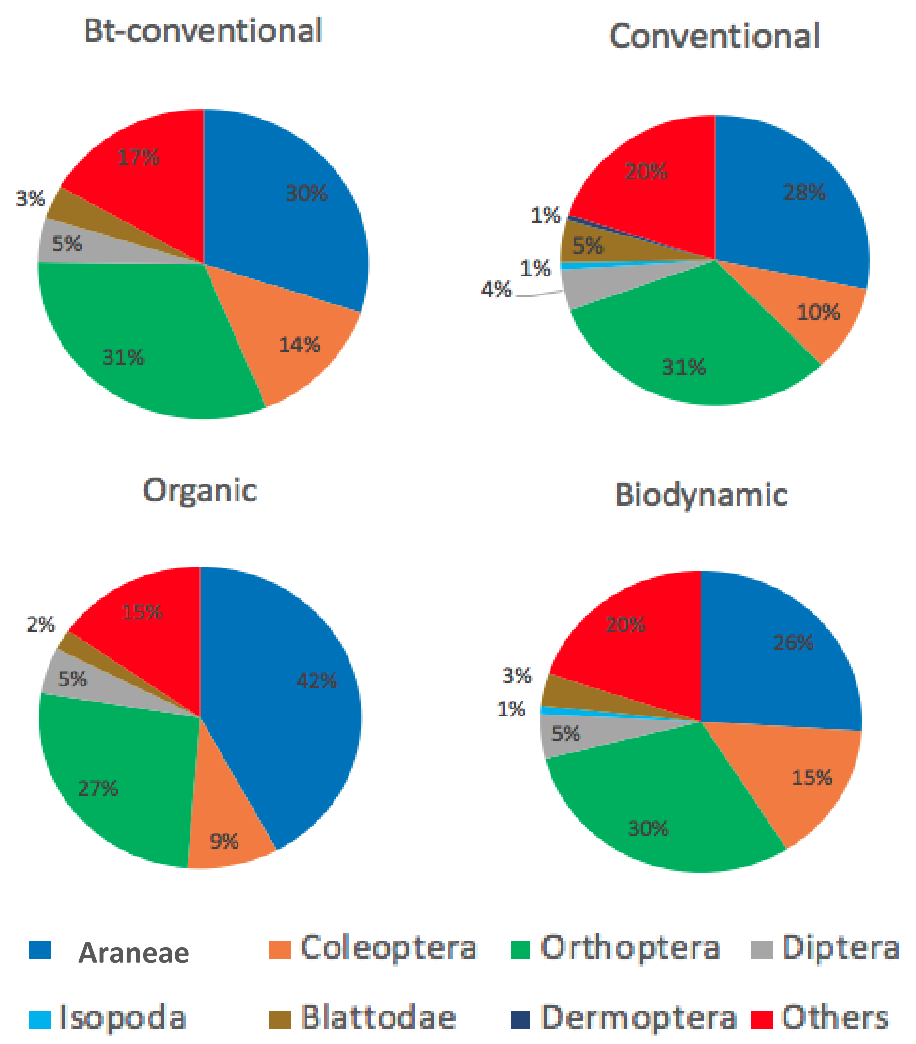


Figure 4.10: Representation in percentage of the number of ground-dwelling arthropods community in four farming systems (Organic, Biodynamic, conventional, and Bt-conventional during the year 2016

4.3.1.2. Analysis of taxonomic groups

4.3.1.2.1. Canopy dwelling community 2016

Araneae were significantly more abundant significantly in organic systems when compared to the Bt-conventional systems (z=3.95, P<0.01) and the conventional systems (z=3.53, P<0.01) and more abundant in the biodynamic systems in comparison to the Bt-conventional systems (z=-2.65, P<0.01) and the conventional systems (z=-2.24, P=0.03). For this taxon, there was no significant difference between the biodynamic and the organic systems and between the Bt-conventional and the conventional systems (Table 4.18).

Cicadellidae were significantly more abundant in the Bt-conventional system in comparison to conventional systems (z=-4.27, P<0.01). Cicadellidae were significantly more abundant in the organic systems in comparison to the conventional systems (z=3.06, P=0.01). Cicadellidae were significantly more abundant in the Bt-conventional systems in comparison to the conventional systems (z=4.27, P<0.01). Coleoptera were significantly more abundant in biodynamic in comparison to Bt-conventional (z=-2.51, p<0.01) and conventional (=-2.09, P=0.05). Diptera were significantly more abundant in the organic systems in comparison to the Bt-conventional systems (z=2.54, P=0.02). The same pattern was observed for Orthoptera (z=2.58, P=0.02), Orthoptera were significantly more abundant in the organic systems in comparison to the conventional systems (z=2.40, P=0.03). Blattodae and Others did not respond to the different systems (Table 4.18, see Appendices B: Table B.2 to Table B.8).

Table 4.18: Summary of results of generalised linear mixed effect model of canopy-dwelling community assemblage in comparison between four cotton farming systems (Organic, biodynamic, conventional and Bt-conventional) during the 2016 survey with mean, Standard deviation (SD) and standard error (SE).

	Systems comparison (p-value)					
	Organic Biodynamic	Organic Bt-conventional	Organic Conventional	Biodynamic Bt-conventional	Biodynamic Conventional	Bt-conventional Conventional
Araneae	0.31	<0.01	<0.01	<0.01	0.03	0.54
Blattodae	0.63	0.55	0.94	0.23	0.55	0.58
Cicadellidae	0.50	0.30	<0.01	0.11	<0.01	<0.01
Coleoptera	0.30	0.14	0.30	<0.01	0.05	0.66
Diptera	0.30	0.02	0.07	0.14	0.36	0.57
Orthoptera	0.41	0.02	0.03	0.10	0.14	0.81
Others	0.69	0.18	0.37	0.07	0.61	0.02

	Organic (n=192)			Biodynamic (n=192)			Bt-conventional (n=192)			Conventional (n=192)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
Araneae	1.02	1.68	0.13	0.84	1.47	0.11	0.45	0.97	0.07	0.52	1.09	0.08
Blattodae	0.16	0.52	0.04	0.13	0.38	0.03	0.19	0.47	0.04	0.16	0.47	0.04
Cicadellidae	4.76	8.21	0.63	4.17	7.76	0.60	5.90	11.45	0.88	2.05	4.18	0.32
Coleoptera	0.86	1.33	0.10	1.02	1.50	0.12	0.65	1.25	0.10	0.71	1.31	0.10
Diptera	1.02	0.82	0.06	0.58	1.33	0.10	0.67	1.33	0.10	0.67	1.43	0.11
Orthoptera	0.18	0.49	0.04	0.14	0.40	0.03	0.08	0.29	0.02	0.08	0.28	0.02
Others	0.54	1.38	0.11	0.60	1.34	0.10	0.36	0.92	0.07	0.68	1.55	0.12

4.3.1.2.2. Ground dwelling community 2016

For the ground dwelling arthropods community, Coleoptera were significantly more abundant in the biodynamic systems in comparison to the organic systems (z=-2.5, P= 0.02) and conventional systems (z=-2.75, P=0.01). Blattodae were significantly more abundant in the biodynamic systems when compared to the conventional systems (z=-2.07, P=0.04). Araneae, Dermoptera, Diptera, Isopoda, Orthoptera and others did not respond to the different systems (Table 4.19, see appendices B: Table B.10 to Table B.16).

Table 4.19: Summary of results of generalised linear mixed effect model of ground dwelling community assemblage comparing four farming systems (Biodynamic, organic, conventional and Bt-conventional) in the survey 2016 with mean, Standard deviation (SD) and standard error (SE).

	Systems comparison (p-value)					
	Organic Biodynamic	Organic Bt-conventional	Organic Conventional	Biodynamic Bt-conventional	Biodynamic Conventional	Bt-conventional Conventional
Araneae	0.26	0.31	0.24	0.75	0.82	0.61
Blattodae	0.06	0.32	0.04	0.15	0.76	0.18
Coleoptera	0.02	0.13	0.93	0.37	0.01	0.12
Dermoptera	1.00	1.00	0.31	1.00	0.31	0.31
Diptera	1.00	0.71	0.63	0.70	0.62	0.89
Isopoda	0.28	0.34	0.10	0.80	0.65	0.45
Orthoptera	0.41	0.58	0.63	0.80	0.76	0.96
Others	0.28	0.89	0.52	0.36	0.72	0.61

	Organic (n=96)			Biodynamic (n=96)			Bt-conventional (n=96)			Conventional (n=96)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
Araneae	2.39	7.15	0.73	1.54	1.46	0.15	1.61	1.72	0.18	1.49	1.69	0.17
Blattodae	0.00	0.00	0.00	0.05	0.26	0.03	0.01	0.10	0.01	0.04	0.20	0.02
Coleoptera	0.52	0.82	0.08	0.90	1.26	0.13	0.74	1.15	0.12	0.51	0.83	0.08
Dermoptera	0.01	0.10	0.01	0.01	0.10	0.01	0.01	0.10	0.01	0.03	0.17	0.02
Diptera	0.28	0.64	0.07	0.28	0.61	0.06	0.25	0.52	0.05	0.24	0.55	0.06
Isopoda	0.13	0.39	0.04	0.21	0.64	0.07	0.19	0.51	0.05	0.25	0.63	0.06
Orthoptera	1.49	2.39	0.24	1.78	2.46	0.25	1.69	2.52	0.26	1.67	2.70	0.28
Others	0.86	1.46	0.15	1.18	2.43	0.25	0.90	1.78	0.18	1.05	2.43	0.25

4.3.2. Plot-scale 2017 data set

4.3.2.1. Taxonomic representation of the arthropods' communities

4.3.2.1.1. Canopy dwelling community

From the plot-scale 2017 data set of the canopy-dwelling community, a total of 9661 specimens were collected. The most abundant taxonomic group was Cicadellidae, which is mostly composed of the species *Amrasca biguttula.* Diptera, Coleoptera and Araneae were the most abundant taxonomic groups after Cicadellidae. Together these four taxonomic groups represented 85% of the biodynamic systems, 86% of the Bt-conventional systems, 86% of the conventional systems and 82% of the organic systems of the total abundance (Figure 4.11).

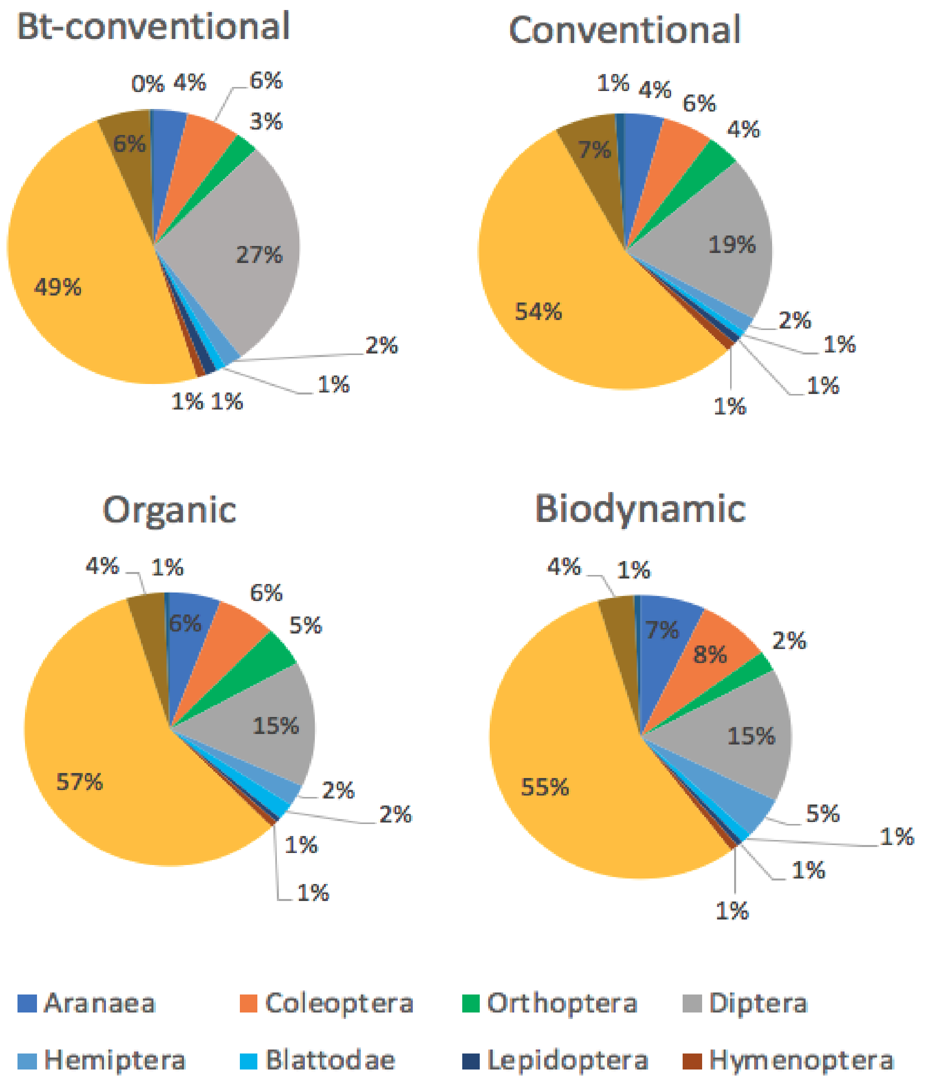


Figure 4.11:Representation in percentage of the number of canopy-dwelling arthropods in four plot-scale cotton farming systems (Bt-conventional, conventional, organic, biodynamic) during the 2017 survey

4.3.2.1.2. Ground dwelling community

2294 specimens were collected during the pitfall survey in 2017. The most abundant species taxonomic group was Orthoptera, representing between 35% to 48% of the total sample (Figure 4.12). The following two most abundant taxonomic groups were Araneae and Coleoptera.

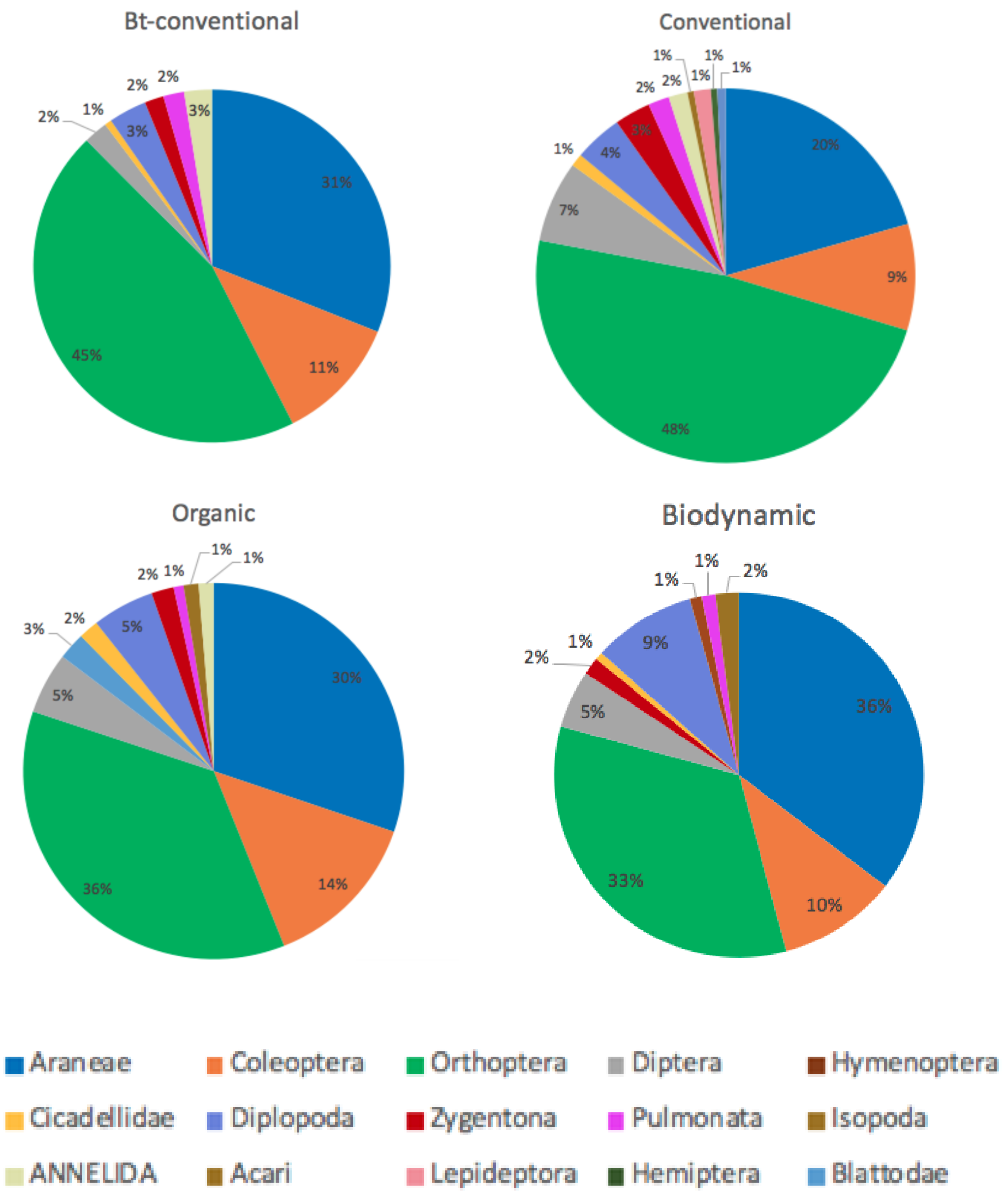


Figure 4.12:Representation in percentage of the number of ground-dwelling arthropods in f four plot-scale cotton farming systems (Bt-conventional, conventional, organic, biodynamic) during the survey 2017.

4.3.2.2. Analysis of taxonomic groups

4.3.2.2.1. Canopy dwelling community 2017

Araneae were significantly more abundant in the biodynamic systems when compared to the Bt-conventional systems (z=1.15, P<0.01), the conventional systems (z=1.67, P<0.01) and the organic systems (z=-2.46, P=0.04). For this taxon, there was no significant difference between the Bt-conventional and conventional systems. Blattodae were more abundant in the organic systems in comparison to the Bt-conventional (z=2.45, P=0.01) and the conventional systems (z=1.11, P<0.01).
Coleoptera were more abundant in the biodynamic system than in the Bt-conventional system (z=-1.08, P=0.01) and in the conventional system (z=-0.51, P<0.01). Diptera were less abundant in the Bt-conventional systems in comparison to the organic systems (z=-0.21, P=0.01) and the biodynamic systems (z=0.10, P=0.04). Cicadellidae were more abundant in the biodynamic systems in comparison to the Bt-conventional systems (z=-0.92, P=0.03). Hemiptera, Miridae, Orthoptera, Others did not respond to the different systems. (Table 4.20, See Appendices B: Table B.18 to Table B.25).

Table 4.20: Summary statistics and significance using t-test of canopy dwelling community assemblage comparing four farming systems (Organic, biodynamic, conventional and Bt-conventional) in the survey 2017 with mean, Standard deviation (SD) and standard error (SE).

	Systems comparison (p-value)					
	Organic Biodynamic	Organic Bt-conventional	Organic Conventional	Biodynamic Bt-conventional	Biodynamic Conventional	Bt-conventional Conventional
Araneae	0.04	<0.01	0.02	<0.01	<0.01	0.38
Blattodae	0.11	0.01	<0.01	0.33	0.07	0.40
Cicadellidae	0.72	0.06	0.30	0.03	0.17	0.39
Coleoptera	0.09	0.19	0.15	0.01	<0.01	0.89
Diptera	0.52	0.01	0.24	0.04	0.59	0.09
Hemiptera	0.22	0.25	0.18	0.11	0.10	0.79
Miridae	0.99	0.34	0.08	0.31	0.06	0.42
Orthoptera	0.23	0.18	0.52	0.75	0.48	0.37
Others	0.42	0.36	0.06	0.96	0.39	0.40

	Organic (n=240)			Biodynamic (n=240)			Bt-conventional (n=240)			Conventional (n=240)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
Araneae	0.88	1.10	0.07	1.18	1.52	0.09	0.52	0.85	0.04	0.61	0.90	0.05
Blattodae	0.30	0.65	0.02	0.19	0.51	0.01	0.14	0.47	0.01	0.10	0.38	0.01
Cicadellidae	8.87	11.70	0.68	9.36	12.51	0.72	6.73	8.16	0.52	7.61	9.89	0.59
Coleoptera	1.01	1.28	0.08	1.31	1.81	0.10	0.83	1.16	0.06	0.81	1.16	0.06
Diptera	2.29	3.76	0.18	2.56	3.61	0.20	3.79	6.51	0.29	2.78	3.68	0.21
Hemiptera	0.39	0.91	0.03	0.79	3.90	0.06	0.28	0.73	0.02	0.26	0.79	0.02
Miridae	0.65	1.54	0.05	0.65	1.29	0.05	0.81	1.54	0.06	0.96	1.54	0.07
Orthoptera	0.73	3.35	0.06	0.40	1.00	0.03	0.36	1.10	0.03	0.53	2.11	0.04
Others	0.30	0.64	0.02	0.38	0.94	0.03	0.38	0.87	0.03	0.46	0.87	0.04

4.3.2.2.2. Ground dwelling community 2017

Orthoptera were significantly more abundant in the Bt-conventional systems in comparison to the organic systems (z=0.58, P=0.04). Isopoda were significantly less abundant in the biodynamic systems in comparison to the Bt-conventional systems (z=1.54, P=0.04). Araneae were significantly more abundant in the biodynamic systems in comparison to the conventional systems (z-0.84, P=0.02). Coleoptera, Diplopoda, Diptera, Zygentoma and Others did not respond to the different systems (see Table 4.21, Appendices B: Table B.27 to Table B.30).

Table 4.21: Summary results of generalised linear mixed effect model comparing the taxonomic group of ground-dwelling community assemblage comparing four plot-scale cotton farming systems (Bt-conventional, conventional, organic, biodynamic) during the 2017 survey with mean, standard deviation (SD) and standard error (SE) for each taxonomic group.

	Systems comparison (p-value)					
	Organic Biodynamic	Organic Bt-conventional	Organic Conventional	Biodynamic Bt-conventional	Biodynamic Conventional	Bt-conventional Conventional
Araneae	0.12	0.46	0.14	0.91	0.02	0.25
Coleoptera	0.38	0.36	0.15	0.27	0.24	0.11
Diplopoda	0.13	0.68	0.79	0.10	0.11	0.89
Diptera	0.82	0.51	0.57	0.33	0.71	0.19
Isopoda	0.31	0.12	0.46	0.04	0.10	0.31
Orthoptera	0.56	0.04	0.10	0.12	0.23	0.79
Zygentoma	0.46	0.73	0.27	0.39	0.12	0.47
Others	0.62	0.57	0.74	0.26	0.93	0.39

	Organic (n=120)			Biodynamic (n=120)			Bt-conventional (n=120)			Conventional (n=120)		
	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE	Mean	SD	SE
Araneae	1.19	1.36	0.12	1.73	3.45	0.31	1.65	6.58	0.60	0.95	1.15	0.10
Coleoptera	0.54	1.05	0.10	0.50	1.00	0.09	0.60	0.81	0.07	0.42	0.81	0.07
Diplopoda	0.21	0.46	0.04	0.44	1.63	0.15	0.18	0.48	0.04	0.19	0.49	0.04
Diptera	0.21	1.45	0.13	0.25	1.42	0.13	0.12	0.43	0.04	0.33	1.68	0.15
Isopoda	0.05	0.22	0.02	0.03	0.16	0.01	0.13	0.55	0.05	0.08	0.29	0.03
Orthoptera	1.43	2.35	0.21	1.63	2.92	0.27	2.39	4.58	0.42	2.23	4.73	0.43
Zygentoma	0.08	0.26	0.02	0.05	0.25	0.02	0.09	0.47	0.04	0.14	0.60	0.05
Others	0.28	0.70	0.06	0.33	0.61	0.06	0.23	0.64	0.06	0.32	0.83	0.08

4.3.2.3. Functional Biodiversity

4.3.2.3.1. Percentage of the total functional biodiversity 2017

For the above ground dwelling arthropods community, around one-third of the biodiversity was categorised as pests. The percentage of pests was slightly higher in both conventional systems in comparison to both organic systems. The percentage of auxiliaries was slightly higher in both organic systems in comparison to both conventional systems (Table 4.22, Table 4.31).

For the canopy dwelling arthropods community around two third of the biodiversity was categorised as pests (Table 4.23, Table 4.31).

Table 4.22:Percentage of the total functional biodiversity of the above ground dwelling arthropods community survey in 2017 with pest (phytophagous and Omnivores), Auxiliary (beneficial: Detrivores, pollinators, predators) and others (not categorised into a functional group)

	Order	Family	Biodynamic	Bt-conventional	Conventional	Organic
	PEST		**35.5%**	**46.7%**	**53.0%**	**37.7%**
Phytophagous	**Coleoptera**	Curculionidea	0.0%	0.0%	0.2%	0.0%
	Orthoptera	Gryllidae	31.5%	42.1%	45.0%	33.4%
	Lepideptora		0.5%	0.2%	1.4%	0.0%
	Hemiptera	Cicadellidae	0.7%	0.6%	1.1%	1.6%
	Hemiptera	Aphidae	0.2%	0.0%	0.0%	0.0%
	Acari		0.5%	0.0%	0.5%	0.0%
	Gastropoda		1.2%	1.8%	1.8%	0.8%
Omnivores	**Orthoptera**	Caelifera	1.0%	2.0%	3.0%	1.9%
	AUXILIARY		47.8%	39.6%	30.6%	42.1%
Detrivores	**Isopoda**		0.5%	2.5%	1.6%	1.2%
	Zygentona		1.0%	1.7%	3.0%	1.9%
	Dermoptera		0.0%	0.2%	0.0%	0.4%
	Blattodea		0.2%	0.2%	0.7%	0.0%
	Isoptera		0.2%	0.3%	0.0%	0.2%
	Haplotaxids		2.0%	0.2%	0.0%	1.2%
Pollinators	**Hymenoptera**	Apoidae	0.3%	0.0%	0.0%	0.6%
	Coleoptera	Melyridae	0.0%	0.2%	0.0%	0.0%
Predators	**Chilopoda**		0.0%	0.6%	0.5%	1.6%
	Diplopoda		8.8%	3.4%	4.1%	5.2%
	Araneae	Opiliones	0.2%	0.2%	0.0%	0.2%
	Araneae	Araneae	34.5%	30.4%	20.4%	29.5%
	Coleoptera	Coccinallidae	0.2%	0.0%	0.2%	0.0%
	OTHER		**16.7%**	**13.7%**	**16.3%**	**20.2%**
Indeterminates	**Coleoptera**		10.0%	11.1%	8.8%	13.4%
	Diptera		5.0%	2.2%	7.0%	5.2%
	Hemiptera		0.5%	0.5%	0.5%	0.0%
	Hymenoptera		1.2%	0.0%	0.0%	1.6%
Total			**100.0%**	**100.0%**	**100.0%**	**100.0%**

Table 4.23: Percentage of the total functional biodiversity of the canopy arthropods community survey in 2017 with pest (phytophagous and Omnivores), Auxiliary (beneficial: Detrivores, pollinators, predators) and others (not categorised into a functional group)

	Order	Family	Biodynamic	Bt-conventional	Conventional	Organic
	PEST		**66.4%**	**58.8%**	**68.0%**	**69.7%**
Phytophagous	**Coleoptera**	Curculionoidea	2.4%	1.5%	2.0%	2.7%
	Hemiptera	Miridae	3.8%	5.8%	6.7%	4.3%
	Hemiptera	Aphidae	0.7%	0.4%	1.1%	0.6%
	Hemiptera	Cicadellidae	54.8%	48.1%	54.1%	58.9%
	Hemiptera	Miridae	2.1%	1.2%	0.9%	2.2%
	Hemiptera	Pentatomidae	0.1%	0.0%	1.5%	0.0%
	Hemiptera	Pseudococcidae	1.7%	0.0%	0.0%	0.0%
	Lepidoptera		0.8%	1.4%	1.0%	0.7%
Omnivores	**Orthoptera**		2.2%	2.6%	3.7%	4.9%
	AUXILIARY		**12.7%**	**10.3%**	**7.4%**	**13.8%**
Detritivores	**Dictyoptera**	Blattodae	1.1%	1.0%	0.7%	2.0%
	Isopoda		0.0%	0.0%	0.0%	0.0%
	Dermaptera		0.1%	0.0%	0.0%	0.0%
	Diptera	Ulidiidae	1.4%	2.7%	2.7%	2.8%
Predators	**Coleoptera**	Coccinallidae	2.1%	1.5%	1.1%	1.9%
	Aranaea		6.9%	3.8%	4.3%	5.8%
	Diptera	Dolochopodidae	0.4%	0.4%	0.5%	0.5%
	Diptera	Syrphidae	0.4%	1.3%	0.5%	0.5%
	Hemiptera	Nabidae	0.0%	0.0%	0.0%	0.0%
	Hemiptera	Lygaeidae	0.3%	0.1%	0.2%	0.1%
	Mantodea		0.0%	0.0%	0.0%	0.0%
	OTHER		**20.9%**	**33.3%**	**25.2%**	**19.7%**
Others	**hymenoptera**	Others	0.8%	1.0%	1.1%	0.8%
	Diptera	Culidae	0.0%	0.1%	0.1%	0.0%
	Diptera	Others	12.4%	22.8%	15.5%	11.5%
	Hemiptera	Others	0.8%	0.5%	0.3%	0.2%
	Coleoptera	Others	3.3%	3.0%	2.6%	2.0%
	Coleoptera	Others	3.3%	3.0%	2.6%	2.0%
	unknown	Others	0.3%	0.3%	0.3%	0.5%
TOTAL			**100.0%**	**100.0%**	**100.0%**	**100.0%**

4.3.2.3.2. Correlation between the main predators and the main secondary pests (jassids)

In 2016, there was no correlation between the main predators and the main secondary pests on the plot-scales systems.

In 2017, on the plot-scale systems, the population of *C. sexmaculata* was negatively correlated to the population of *Amrasca biguttula (*n=219, P=0.01) Araneae showed a positive correlation with *Amrasca biguttula* (n=219, P= 0). (see Table 4.24, Figure 4.13)

Table 4.24: Correlation between the significant natural enemies and the main pest jassids (Hemiptera: Cicadellidae) for the year 2017 on the plot-scale systems.

Year	System	Natural enemies	
		Araneae	*C.sexmaculatus*
2017	Plot scale	0.42	-0.16*

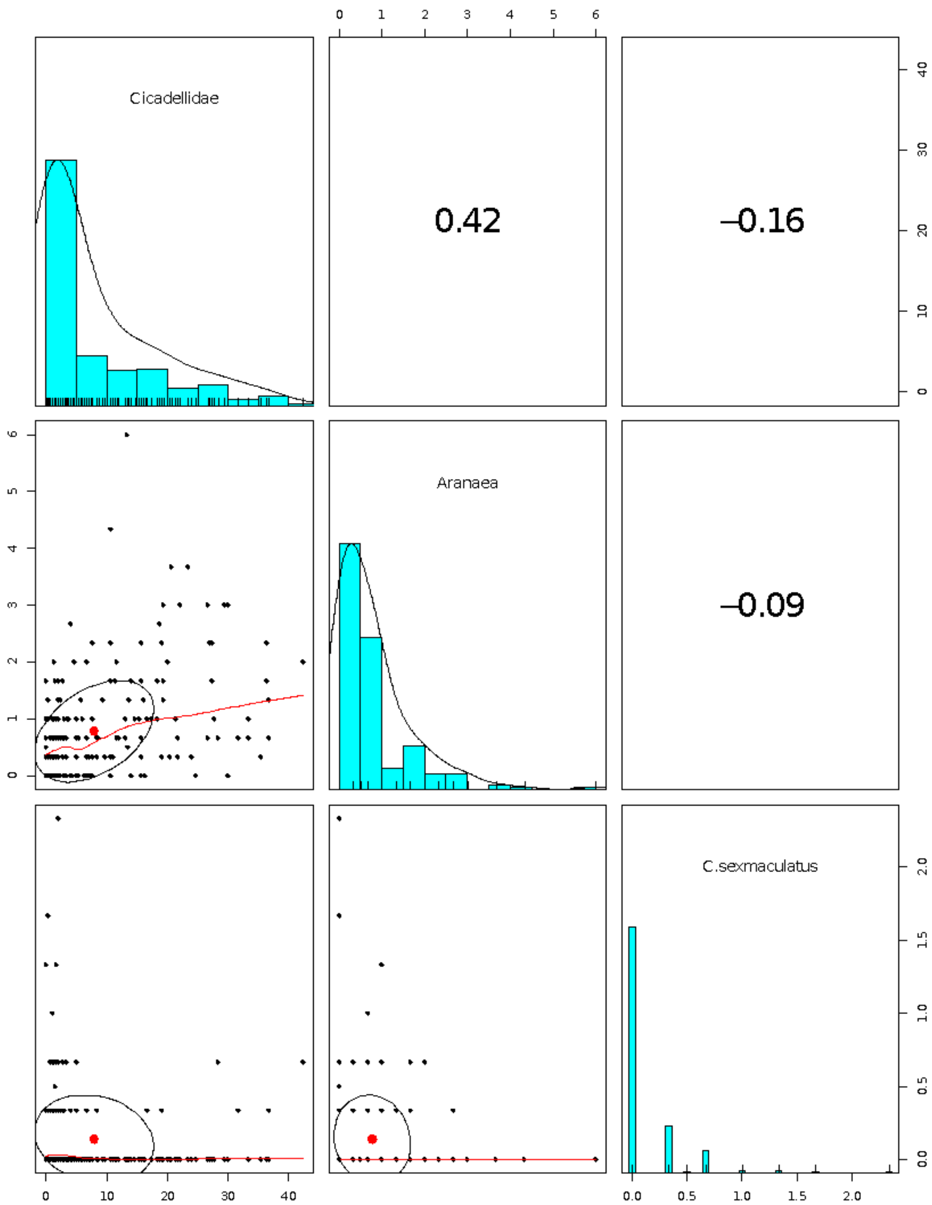


Figure 4.13:Correlation between the main pest, jassids (Hemiptera: Cicadellidae) and their main predators Coccinellidae and Araneae on the plot-scale cotton farming systems during the 2017 survey.

4.3.3. 2016 and 2017 plot-scale data set

In the ground-dwelling arthropods community, in average, there was a significant higher number of Blattodae (z=-1.23, P<0.01), Coleoptera (z=-

2.08, P=0,04), Dermoptera (z=1.26, P=0.01), Isopoda (z=-2.6, P<0.01) and others (z=-2.36, P<0.01) in 2016 in comparison to 2017. In average, there was a significant higher of Diplopoda (z=-8.01, P<0.01) and Zygentoma (z=5.2, P<0.01) in 2017 in comparison to 2016 (see Table 4.25, see Appendices B: Table B.32).

In the canopy-dwelling arthropods community, in average, there was a significant higher number of Others in 2016 in comparison to 2017. There was a significant higher number of Cicadellidae (z=1.03, P<0.01), Coleoptera (z=-1.85, P=0.02), Diptera (z=-3.12, P<0.01), Hemiptera (z=-4.9, P<0.01), Miridae (z=-10.00, P<0.01), Orthoptera (z=-1.56, P<0.01) and Others (z=-2.85, P<0.01) in 2017 in comparison to 2016. (see Table 4.26, see Appendices B: Table B.31)

Table 4.25: Summary of results for the GLMM of arthropods ground-dwelling community assemblage of the survey 2016 in comparison to arthropods community assemblage of the survey 2017.

	2016 (n=384)				**2017 (n=480)**				**p-value**
	Mean	Sum	SD	SE	Mean	Sum	SD	SE	
Araneae	1.76	675	3.86	0.20	1.38	662	3.84	0.20	0.15
Blattodae	0.03	10	0.18	0.01	0.00	0	0.00	0.00	<0.01
Coleoptera	0.67	256	1.05	0.05	0.51	247	1.10	0.06	0.04
Dermoptera	0.02	6	0.12	0.01	0.00	0	0.00	0.00	0.01
Diplopoda	0.00	0	0.00	0.00	0.26	123	0.92	0.05	<0.01
Diptera	0.26	101	0.58	0.03	0.23	108	1.34	0.07	0.6
Isopoda	0.19	74	0.55	0.03	0.07	34	0.34	0.02	<0.01
Orthoptera	1.65	636	2.53	0.13	1.91	921	3.81	0.19	0.23
Zygentoma	0.00	0	0.00	0.00	0.09	43	0.42	0.02	<0.01
Others	0.99	383	2.07	0.11	0.29	139	0.70	0.04	<0.01

Table 4.26: Summary of results for the GLMM of arthropods canopy-dwelling community assemblage of the survey 2016 in comparison to arthropods community assemblage of the survey 2017.

	2016 (n=672)				**2017 (n=642)**				**p-value**
	Mean	**Sum**	**SD**	**SE**	**Mean**	**Sum**	**SD**	**SE**	
Araneae	0.69	466	1.35	0.05	0.79	511	1.15	0.05	0.14
Blattodae	0.15	103	0.45	0.02	0.19	119	0.52	0.02	0.23
Cicadellidae	4.11	2766	8.37	0.32	8.11	5238	10.77	0.43	<0.01
Coleoptera	0.81	546	1.36	0.05	0.98	631	1.39	0.05	0.02
Diptera	0.76	514	1.60	0.06	2.85	1830	4.60	0.18	<0.01
Hemiptera	0.00	0	0.00	0.00	0.42	275	2.08	0.08	<0.01
Miridae	0.00	0	0.00	0.00	0.77	493	1.49	0.06	<0.01
Orthoptera	0.11	76	0.37	0.01	0.50	324	2.12	0.08	<0.01
Other	0.54	365	1.32	0.05	0.38	244	0.84	0.03	<0.01

4.3.4. Farm-scale 2018 data set

4.3.4.1. Taxonomic representation of the arthropods' communities

4.3.4.1.1. Canopy-dwelling arthropods community 2018

From the farm-scale 2018 data set of the canopy-dwelling community, a total of 3488 specimens were collected. The dominant species in the canopy-dwelling arthropods community was the jassids (Hemiptera: Cicadellidae) which represented more than 60% of the total population of arthropods (Figure 4.14).

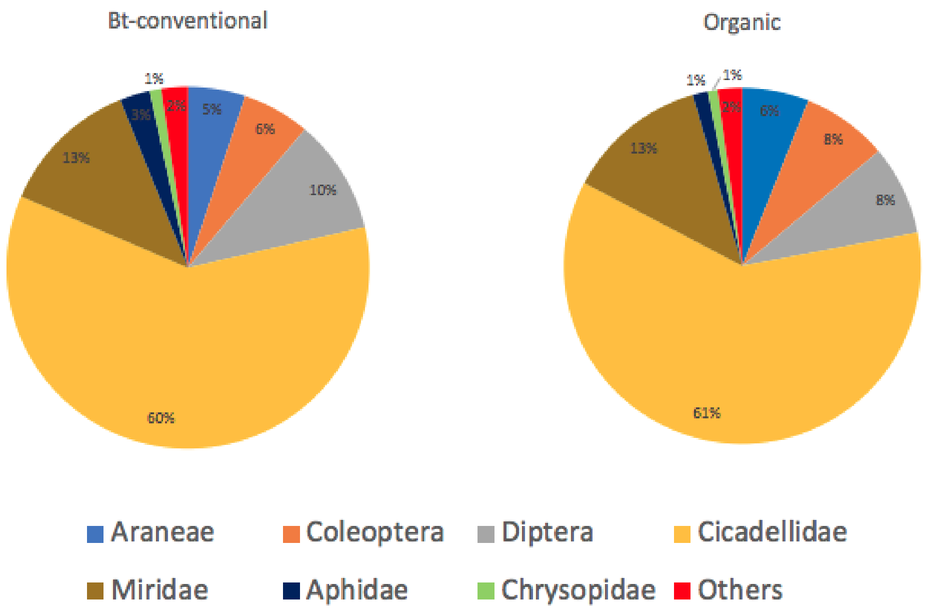


Figure 4.14: Representation in percentage of the number of canopy-dwelling arthropods in two farm-scale cotton farming systems (Bt-conventional, organic) during the 2018 survey

4.3.4.1.2. Ground-dwelling arthropods community 2018

From the farm-scale data set of the ground-dwelling arthropods community, a total of 703 specimens were collected during the survey. The most abundant taxonomic groups were Araneae, followed by Coleoptera and Orthoptera. Clustered together, these three taxa represent 64% and 75% of the total abundance of the invertebrate community in the Bt-conventional and organic system respectively (Figure 4.15).

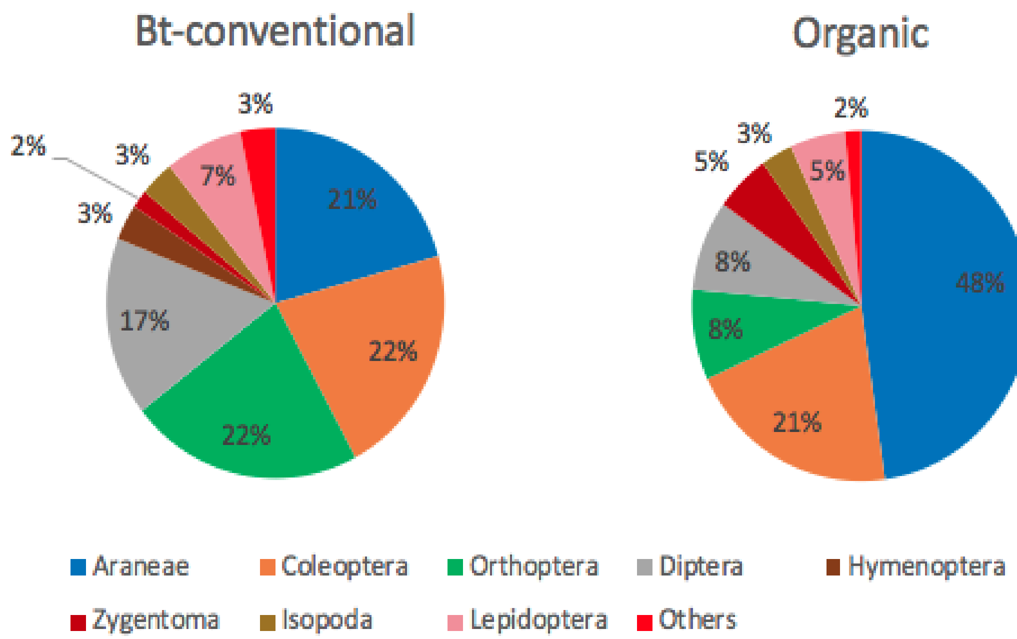


Figure 4.15: Representation in percentage of the number of ground-dwelling arthropods in two farm-scale cotton farming systems (Bt-conventional, organic) during the survey 2018

4.3.4.2. Analysis of taxonomic groups

4.3.4.2.1. Canopy dwelling arthropods community 2018

Araneae were significantly higher in the organic systems in comparison to the Bt-conventional systems (z=-2.34, P=0.05). Cicadellidae were significantly higher in organic systems in comparison to the Bt-conventional systems (z=-1.69, P=0.05). Coleoptera were significantly higher in the organic systems in comparison to the Bt-conventional systems (z=-2.43, P=0.01). (see Table 4.27, for details, see Appendices B: Table B.33 to Table B.40)

Table 4.27: Summary statistics and significance using t-test of canopy dwelling community assemblage in comparison between two farming systems in the survey 2018 (with mean, standard deviation (SD), standard error (SE) and P-value)

	Organic (n=54)			Bt-conventional (n=54)				System comparison (p-value)
	Mean	SD	SE	Mean	SD	SE		Organic Bt-conventional
Aphidae	0.51	1.98	0.07	0.74	2.05	0.10	**Aphidae**	0.28
Araneae	2.24	2.14	0.30	1.40	1.52	0.19	**Araneae**	0.01
Chrysopidae	0.33	0.63	0.04	0.28	0.59	0.04	**Chrysopidae**	0.36
Cicadellidae	22.47	22.21	3.06	16.36	14.38	2.23	**Cicadellidae**	0.05
Coleoptera	2.89	3.11	0.39	1.64	2.10	0.22	**Coleoptera**	0.01
Diptera	3.02	3.39	0.41	2.79	3.25	0.38	**Diptera**	0.36
Miridae	4.75	5.55	0.65	3.40	3.77	0.46	**Miridae**	0.07
Orthoptera	0.09	0.34	0.01	0.06	0.23	0.01	**Orthoptera**	0.27
Others	0.82	1.28	0.11	0.64	1.07	0.09	**Others**	0.22

4.3.4.2.2. Ground dwelling arthropods community 2018

Araneae were significantly higher in the organic systems in comparison to the Bt-conventional systems (z=-1.68, P=0.05). Diptera were significantly higher in Bt-conventional systems in comparison to the organic systems (z=1,65, P=0.05) (see Table 4.28, for details, see Appendices B: Table B.41 to Table B.49).

Table 4.28: Summary statistics and significance using t-test of ground dwelling community assemblage in comparison between two farming systems in the survey 2018 with mean, standard deviation (SD) and standard error (SE).

	Organic (n=54)			Bt-conventional (n=54)				System comparison (p-value)
	Mean	SD	SE	Mean	SD	SE		Organic Bt-conventional
Araneae	2.81	4.30	0.38	1.67	2.33	0.23	**Araneae**	0.05
Coleoptera	1.37	1.64	0.19	1.48	1.94	0.20	**Coleoptera**	0.38
Diplopoda	0.24	0.69	0.03	0.30	1.10	0.04	**Diplopoda**	0.38
Diptera	0.28	0.62	0.04	0.59	1.24	0.08	**Diptera**	0.05
Isoptera	0.13	0.51	0.02	0.30	0.81	0.04	**Isoptera**	0.10
Lepidoptera	0.44	1.30	0.06	0.26	0.55	0.04	**Lepidoptera**	0.17
Orthoptera	1.24	2.00	0.17	1.07	1.69	0.15	**Orthoptera**	0.32
Zygentoma	0.26	0.61	0.04	0.46	1.07	0.06	**Zygentoma**	0.12
Others	0.31	0.63	0.04	0.22	0.57	0.03	**Others**	0.21

4.3.4.3. Functional Biodiversity plot-scale 2018

4.3.4.3.1. Percentage of the total functional biodiversity 2018

For the above ground dwelling arthropods community, around one-fourth of the biodiversity was categorised as pests in both systems. The percentage of auxiliaries was similar in both systems (Table 4.29, Table 4.31).

For the canopy dwelling arthropods community around two third of the biodiversity was categorised as pests (Table 4.30, Table 4.31).

Table 4.29: Percentage of the functional biodiversity of the ground-dwelling arthropods community of the farm scale survey 2018 with pest (phytophagous and Omnivores), Auxiliary (beneficial: Detrivores, pollinators, predators) and others (not categorised into a functional group)

	Order	Family	Bt-conventional	Organic
	PEST		**24.2%**	**26.7%**
Omnivorous	Orthoptera		16.7%	17.0%
Phytophagous	Gastropoda		0.6%	1.3%
	Acari		0.6%	0.0%
	Hemiptera	Miridae	0.6%	0.5%
		Cicadellidae	0.3%	0.0%
	Coleoptera	Curculionidae	1.2%	0.8%
		Elateridae	0.3%	1.0%
	Lepidoptera		4.0%	6.1%
	AUXILIARY		**62.0%**	**62.1%**
Predators	Araneae		25.9%	38.4%
	Opiliones		0.0%	0.3%
	Chilopoda		0.3%	0.3%
	Hemiptera	Mantodea	0.0%	0.5%
	Coleoptera	Coccinallidae	0.3%	0.5%
		Carabidae (scarites)	1.7%	2.5%
Detritivores	Oligochaeta		0.6%	0.5%
	Diplopoda		4.6%	3.3%
	Zygentoma		7.2%	3.6%
	Dermaptera		0.3%	0.3%
	Dictyoptera		0.3%	0.3%
	Isoptera		4.6%	1.8%
	Coleoptera	Scarabaeidae	2.6%	2.8%
		Nitidulidae	6.3%	2.3%
		Tenebrionidae	4.3%	3.8%
	Diptera	Ulidiidae	2.9%	1.0%
	OTHER		**13.8%**	**11.2%**
Indeterminates	Coleoptera		6.3%	6.9%
	Diptera		6.3%	2.8%
	Hymenoptera		1.2%	0.8%
	Others		0.0%	0.8%
	Total		**100.0%**	**100.0%**

Table 4.30:Percentage of the functional biodiversity of the canopy-dwelling arthropods community of the farm scale survey 2018 with pest (phytophagous and Omnivores), Auxiliary (beneficial: Detrivores, pollinators, predators) and others (not categorised into a functional group)

	Order	Family	Bt-conventional	Organic
PEST			**70.3%**	**68.4%**
Phytophagous	**Acari**		0.1%	0.0%
	Coleoptera	Curculionidae	3.3%	2.0%
	Hemiptera	Ciccadellidae	52.7%	53.1%
	Hemiptera	Miridae	9.2%	9.5%
	Hemiptera	Miridae	1.7%	1.7%
	Hemiptera	Pentatomidae	0.1%	0.0%
	Hemiptera	Pseudococcidae	0.1%	0.0%
	Hemiptera	Aphidoidea	2.4%	1.2%
	Hemiptera	Lygaeidae	0.0%	8.6%
	Hemiptera	Others	0.2%	0.3%
	Lepidoptera		0.6%	0.6%
Omnivores	**Orthoptera**		0.2%	0.2%
AUXILIARY			12.8%	9.3%
Predators	**Araneae**		4.5%	5.3%
	Coleoptera	Coccinalidae	0.3%	2.0%
	Diptera	Ulidiidae	0.1%	0.0%
	Mantodea		0.3%	0.5%
	Hemiptera	Nabidae	0.0%	0.0%
	Hemiptera	Lygaeidae	0.0%	0.0%
	Hemiptera	Anthocoridae	0.1%	0.1%
	Neuroptera	Chrysopidea	0.9%	0.8%
Pollinators	**Coleoptera**	Melyridae	0.0%	0.2%
	Hymenoptera		0.6%	0.3%
Detrivores	**Isoptera**		0.0%	0.2%
	Dictyoptera	Blattodae	6.1%	0.0%
	Dermaptera		0.0%	0.0%
OTHER			**11.4%**	**11.1%**
Others	**Others**		0.7%	1.3%
	Diptera	Others	8.9%	7.1%
	Coleoptera	Others	1.7%	2.7%
Total			**100.0%**	**100.0%**

4.3.4.3.2. Correlation between the main predators and the main secondary pests

In 2018, there was no correlation between *Amrasca biguttula, C.sexmaculata* and the Araneae group.

Table 4.31: Coleoptera diversity in the plot scale systems during the survey 2017 and the farm scale systems during the survey 2018

Family	Genus	Species	Stage	Plot-scale		Farm-scale	
				Canopy	Ground	Canopy	Ground
Scarabaeidae	Glycyphana		Adult	▯		▯	▯
Scarabaeidae	Aphodiinae		Adult		▯		
Carabidae	Other		Adult	▯	▯	▯	▯
Carabidae	Scarites		Adult	▯	▯	▯	▯
Carabidae	Scarites		Grub	▯	▯	▯	▯
Elateridae			Adult	▯		▯	▯
Curculionidae	Myllocerus		Adult	▯	▯	▯	▯
Nitidulidae			Adult	▯		▯	▯
Coccinelidae	Menochilus	sexmaculatus	Adult	▯		▯	▯
Coccinelidae	Menochilus	sexmaculatus	Grub	▯		▯	▯
Coccinelidae	Nephus		Adult	▯		▯	▯
Coccinelidae	Other		Adult	▯		▯	
Chrysomelidae			Adult	▯		▯	
Staphilinidae			Adult	▯			
Tenebrionidae			Adult				▯
Aphodiinae			Adult				▯
Coleoptera Morphotype 1			Adult	▯		▯	
Coleoptera Morphotype 2			Adult	▯		▯	
Coleoptera Morphotype 3			Adult	▯	▯		
Coleoptera Morphotype 4			Adult		▯		
Coleoptera Morphotype 5			Adult	▯		▯	

4.4. Discussion

4.4.1. Comparing arthropods present in cotton farming systems

The study has compared the ground dwelling and canopy dwelling arthropods community at the plot-scale in four farming systems and at the farm-scale in two farming systems by quantifying the relative abundance and diversity of the taxonomic groups present. Overall the biodiversity was higher in both organic systems in comparison to both conventional systems. In this study, three taxonomic groups shown significance difference in between the systems (Cicadellidae, Araneae and Coleoptera), showing that these groups were the most impacted by the farming system managements.

4.4.1.1. Plot scale (2016-2017)

4.4.1.1.1. General

Jassids

Jassids have been a major pest in cotton fields (Nangpal, 1948; Saeed et al., 2016). They are among the main reasons for low cotton yields in India (Amin et al., 2016). They have been reported as a serious problem at all stages of the cotton growing season. Jassids and aphids occupy the lower part of the leaf surfaces of the terminal bud while feeding on the leaves and developing bolls (Amin et al., 2016; Prabhakar et al., 2011). They inject toxins into the tissues, causing severe damage and stress to the plant which, in turn, causes the plant to deteriorate leading to a decrease in yield quantity and quality (Amin et al., 2016; Prabhakar et al., 2011).

In this study, over years, Jassids (Hemiptera: Cicadellidae) represented more than 50% of the total number of canopy-dwelling arthropods among all the farming systems. According to the literature available, the abundance of Jassids has been most commonly recorded during the third quarter of the year (Deguine et al., 2000; Márquez-Hernández et al., 2014). A study in India showed that the population size began to increase in the second week of August, reaching its peak in the third week of September (Nagar et al., 2017). In this study, in 2016, the population of

Jassids peaked in October, but in 2017, the population increased from June to July, peaking in August and decreasing afterwards. In 2016, the presence of Jassids was categorised as Grade 4 (Murugesan and Kavitha, 2010) in the four systems and rust-coloured leaves are an indication of high Jassids infestation (see picture 4.1). According to the Centre Institute for Cotton Research, this represented the highest rate of Jassids infestation in cotton fields (CICR, 2018a). Other studies from the same region have found that the peaking of the Jassids' population has been during the first fortnight of October in transgenic Bt cotton (Makwana et al., 2018). In 2017, the incidence of the presence of Jassids were categorised as Grade 2 and 3. In 2016, on the plot-scale systems, the number of Jassids were significantly more abundant in Bt-conventional systems than in organic ones. However, in 2017, Jassids were more abundant in the biodynamic systems in comparison to the Bt-conventional systems. The differences between the years are most likely due to the yearly weather fluctuations and the micro-climate in this specific region (Soni and Dhakad, 2016). The population of Jassids has been correlated with weather patterns (Shahid et al., 2009; Soni and Dhakad, 2016) and these studies have shown that under humid and hot conditions the Jassids' population thrives (Khan & Ullah,1994). Many studies based in India have shown a correlation between the population of Jassids and high temperatures (Nemade,2007). This could be the reason for the mixed results in my study and could explain the fluctuations in the sucking pest population in 2016 and 2017.

Photo 4.1: Picture of damage caused by the infestation of Cicadellidae (2016)

Araneae

Between the canopy and ground-dwelling arthropods community, Araneae represented the most abundant group of natural enemies. Araneae are recognized as valuable biological pest control agents in cotton (Dippenaar-Schoeman et al., 1999; Mellet and Schoeman, 2006) and other crops (Chatterjee et al., 2009). Araneae are among the first predators to inhabit the young cotton plants; their population increases as availability of available prey (Marc and Canard, 1997).

Araneae abundance was more abundant in the organic systems when compared to the Bt-conventional systems for both canopy and ground-dwelling communities. Araneae are polyphagous and have a higher abundance of Araneae in a system could have the potential to enhance pest control (Duguma et al., 2019).

Coleoptera

Between the canopy-dwelling community, the Coleoptera taxon was found to be significantly more abundant in the biodynamic systems than in the Bt-conventional and conventional systems on the plot-scale systems. Coleoptera is the taxa that is the most affected by insecticides, with Neoticotinoids being the most harmful (Gunstone et al., 2021). These insecticides are used in both conventional systems and could potentially be responsible for the lower abundance of Coleoptera in these systems.

Coleoptera is a diverse functional group which includes decomposers, predators, pests and pollinators (Susilo, 2009) and is possibly the most speciose group among animals (Mckenna et al., 2019). To understand the community assemblage and the role of the different Coleoptera in the cotton agrosystem, specimens were identified down to family level, the three main family present in the cotton systems were Curculionidae, Nitidulidae and Coccinellidae:

Curculionidae: Myllocerus spp.

The Grey weevil (Curculionidae: Coleoptera) *Myllocerus sp*. was already considered a minor pest in 1948 (Nangpal, 1948). They feed on leaves by nibbling at the edges (Anonymous, 2000) and can feed on a variety of host plants. However, there is little literature on Grey weevils in cotton crops in India. In

Pakistan, they have been identified as major pests in cotton crops (Ashfaq et al., 2011) and reported as a major pest in India since 2002 (Dhillon et al., 2013).

Nitidulidae

Nitidulidae are sap beetles that could be potential pests. They have been recorded as a major pest in different crops such as passion fruit flowers (Potin et al., 2016) but have been reported only in low numbers in cotton flowers (Ewing and Cline, 2005). They do not seem to create visible damage in cotton (Toshiyuki, 1957). There is very little information on their presence in cotton flowers. They have even been called pollen beetles, but no existing data is showing their ability to transfer pollen (Rhodes, 2002). There is a need for more research on this family of Coleoptera, found in high numbers in the different CFS.

Cheilomenes sexmaculata (Coleoptera: Coccinellidae)

Among these three driving community specimens (Myllocerus spp, Nitidulidae and C.sexmaculata), *Cheilomenes sexmaculata* abundance was overall different in between systems, but no difference was found when each system was compared to the other on the plot-scale.

The results from this study have shown that there was a significant negative correlation between *C.sexmaculata* and *Amrasca biguttula*, meaning a significant positive effect on the suppression of Jassids. Studies have shown that they consume Jassids in the larval stages as well as during their adult life; females have been observed to be more voracious and have greater longevity than males (Abro et al., 2004; Amin et al., 2016). Coccinellidae have been used as biocontrol agents

- adults have been observed to consume 22.4+/- 2.51 and larvae to consume

33+/- 5.21 sucking pest per day (Rana and Abbas, 2011). The species *M. sexmaculatus* has been recognized as an efficient predator of the main pest *A.b.biguttula* (Bukero et al., 2014; Xiao et al., 2016). It is well-known that Coccinellidae are natural enemies of many pest species (Weber and Lundgren, 2009). They are highly polyphagous and are aggressive predators (Mellet and Schoeman, 2007). *C.sexmaculata* (Coccinellidae: Coleoptera) is an important predator against sucking pests as well as bollworms (Bukero et al., 2014).

4.4.1.1.2. Biodynamic vs Organic systems

Overall, there were no significant differences between the arthropods' community for the canopy- and ground-dwelling varieties. The pest management practices of biodynamic systems and organic systems were identical (see methodology chapter, section 3.2.2.2) which explains why there is no difference between the arthropods' community in above-ground ecosystem. The only difference between these systems was the use of biodynamic preparations in the biodynamic systems for fertility management. Further studies are needed to deduct any differences between biodiversity taxonomic groups at the below-ground ecosystem level.

4.4.1.1.3. Data between years of survey (2016-2017)

There was an expected difference between the results 2016 and 2017.In the canopy-dwelling arthropods community, apart from Araneae, Blattodae, all the taxonomic groups (Cicadellidae, Coleoptera, Diptera, Hemiptera, Miridae, Orthoptera, Others) were significantly higher in 2017 than in 2016 surveys. This was expected as in 2016, the first survey was done before sowing (no foliage) and after the last cotton was harvested (foliage was almost non-existent) (see Table 4.26). Weather has also an important influence on arthropods diversity and could possibly explain the significant difference between the years as well (Sharma and Dhillon, 2018). Rainfall can affect community composition and arthropods density. Detritivores arthropods have been observed to respond strongly to seasonal rain and could be used as indicators of droughts in future research (Fischer et al., 2022).

4.4.1.2. Farm-scale organic vs Bt-conventional systems (2018)

Jassids

Jassids' abundance was not significantly different between organic and Bt-conventional systems for the canopy-dwelling community. In India, a previous study found a higher abundance of Jassids in Bt-conventional systems compared to organic systems at a farm-scale level (CSA, 2006). A study in the laboratory has shown that the number of Jassids' eggs laid was significantly higher in Bt-cotton varieties in comparison to desi (Indian) hybrid cotton varieties (Kumar et al., 2020). Previous authors have suggested that natural enemies do not control pest damage effectively in cotton fields, and, therefore, recommend pesticides for pest control (Saeed et al., 2015). However, these results and previous studies question the efficacy of chemical pesticide application to reduce the sucking pest population. An 11-year-long study in Maharashtra has shown, using a non-Bt *G. hirsutum* hybrid, higher yields and lower pest damage in organic cotton in comparison to conventional systems (Blaise et al., 2006). This study's results demonstrate that with good organic pest management practices, it is possible to reduce the sucking pest population and increase the yield of organic cotton systems.

Coleoptera

Coleoptera abundance was significantly higher in organic systems in comparison to Bt-conventional ones. These results were similar to the plot-scale results. These results have supported by other studies which have found Coleoptera abundance higher in organic systems (Krauss et al., 2011; Scalercio et al., 2009). In this study, I identified Coleoptera to the family level and found that ladybugs was greater in the organic systems. However, ladybugs abundance in the field was possibly too low to obtain a significant difference between systems.

At the farm-scale level, the composition has shown that among the Coleoptera order, Nitidulidae family, *Myllocerus sp*., and *Cheilomenes sexmaculata* were significantly responsible for the difference between systems. The number of *C. sexmaculata* may have been too small to detect any significant differences. However, it has been documented that insecticides have a fatal toxic effect on Coccinellidae as they are highly sensitive to chemicals (Obrycki and Kring, 1998; Saner et al., 2014; Weber and Lundgren, 2009). Imidacloprid, which is a systemic pesticide, is harmful to Coccinellidae (Saminathan et al., 2003). When exposed to Imidacloprid, their fecundity decreases (Xiao et al., 2016). This chemical is used in Bt-conventional and non-conventional systems which could explain the lower abundance of Coccinellidae in these systems.

Araneae

On the plot-scale systems, a significant positive correlation was identified between the abundance of Jassids and Araneae, indicating that the Jassids exerted a bottom-up effect on spiders in cotton crops. Other studies have shown both bottom-up (Tsutsui et al., 2016) as well as top-down effects that help lower pest densities and stabilize their population (Maloney et al., 2003). Araneae are considered to play a positive role in the reduction of sucking pests which, in turn, results in a positive effect on yields (Nangpal, 1948).

This is in agreement with earlier studies which have shown that Araneae are more abundant in organic and biodynamic systems than in conventional systems (Klaus Birkhofer et al., 2008; Isaia et al., 2006). Research has shown that the use of pesticides has a negative effect on the Araneae abundance (Gluck and Ingrisch, 1990; Pekár, 1998; Picchi et al., 2016) including in cotton systems. Interestingly, some studies of the ground-dwelling arthropods community revealed no difference in the ground-dwelling natural enemy community. These studies from other Bt crops (potato and corn) claimed that the ground-dwelling community is not expected to be negatively impacted by the pesticides applied to the cotton canopy which target foliar pests (Lozzia 1999, Al- Deeb and Wilde 2003, Candolp et al. 2004, French et al. 2004) and Bt potato (Riddick et al. 2000, Reed et al. 2001, Duan et al. 2004). My results do not agree with those studies. My results could be explained by the fact that spiders often share canopy and ground habitats, which exposed them to insecticides applied to the cotton canopy. However to confirm this, research looking specifically on the spider community and their multi-trophic interaction with cotton ecosystems is needed.

4.2.1. Long-term impact of Bt-conventional system on the arthropods community

To be able to investigate if Bt-cotton has a long-term impact on the arthropods community, in this part, I discuss the Bt-conventional systems and conventional systems from the plot-scale 2016 and 2017 data set. These two systems were following the same pest management practices. The only difference in the fertilizer management practices is that Bt-conventional systems were applying 18 kg of urea per acre more than conventional systems (see methodology chapter table 3.5 and 3.7).

Jassids-main sucking pests

In 2016, the population of Jassids was significantly higher in Bt-conventional in comparison to conventional systems. With the introduction of Bt-conventional, a surge of secondary pests has been observed in cotton systems (Kranthi and Stone, 2020; Zhao et al., 2011). I have visually observed that Bt-conventional cotton plants were taller and had a darker shade of green in comparison to conventional cotton plants. Both of these systems received the same amount of pesticides; however, Bt-conventional systems received a higher amount of fertilizers. Studies have shown that increasing the rate of nitrogenous fertilizer increases the Jassids' population (Anusha et al., 2017; Belbase et al., 2019) and, therefore, reduces the yield in the long run. Nitrogen fertiliser increases leaf development rates and sucking pests tend to prefer young leaves with high nutritional quality (Anusha et al., 2017). This could explain the higher number of Jassids in the Bt-conventional system in comparison to the three other systems in 2016.

Predators

At the plot level, in 2016 and 2017, there were no significant differences in *C.sexmaculata* (Coleoptera: Coccinellidae) and Araneae abundance between the conventional and Bt-conventional systems, suggesting that Bt toxins do not indirectly affect the population of natural enemies for the canopy- and ground-dwelling arthropods community in the long-term. This correlates with previous research which has shown no effect on Coccinellidae feeding in Bt-cotton fields (Obrycki and Kring, 1998).

The effect of transgenic cotton on non-target insects has been a concern since the commercialisation of Bt seeds and has been a well-documented research topic (National Research Council, 2002). Transgenic pesticidal farming systems have been a challenge to study as they are similar to conventional crops. This study has not found lacewings' presence in the plot-scale systems. However, an interesting study done in the laboratory has shown an increase in lacewing larvae mortality when they directly consume Bt toxin and are indirectly consumed by preying on caterpillars that have themselves eaten Bt toxins (Hilbeck et al. 1998a,1998b, Orr and Landis 1997). However other studies have not observed a negative effect on non-targeted natural enemies (National Research Council, 2002). Even if natural enemies are negatively impacted by both conventional systems, natural enemies still play a very important role in suppressing sucking pests in Bt systems (Ali et al., 2016). Natural enemy communities are probably more linked to changes in insecticide applications than the presence of Bt-toxins in plants (Luttrell et al., 1994). Studies have shown a change in the natural enemy community in cotton correlated to insecticide use patterns (Naranjo and Ellsworth, 2009). There is a need to be careful while interpreting the obtained results between Bt and non-Bt cotton systems which rely on pesticides to reduce the pest population not targeted by Bt plants (National Research Council, 2002).

4.2.2. Functional Biodiversity-Pest management

Functional biodiversity is the major determinant for the functioning of ecosystems; with an increase in functional biodiversity, an ecosystem is more stable and its productivity increases (Tilman et al., 2014). One of the challenges of modern agriculture is to transit towards higher yields while conserving biodiversity to achieve greater sustainability (Mall et al., 2018). One alternative approach is integrated pest management which reduces the use of chemical pesticides and promotes ecological sustainability by conserving biodiversity and conserving natural enemies(Krishna et al., 2003). With the support of scientific knowledge, ecological solutions can be provided to farmers to improve their productivity while conserving biodiversity and the ESs they provide.

Studies have shown that monoculture (Gurr et al., 2003) and pesticide application have a damaging effect on the population of natural enemies such as ladybirds (Youn et al., 2003) and spiders (Chatterjee et al., 2009). With a significantly higher number of spiders in the organic systems, but no difference in sucking pest abundance between organic and conventional systems, the results from this study questioned the efficacy of pesticides and suggested that natural enemies could be as effective and efficient as the application of pesticides.

My study has shown that the overall number of natural enemies per pest was higher in organic systems in comparison to conventional systems. Other studies still show that in Bt cotton systems as well as organic cotton systems, Coccinellidae and Araneae are the most abundant natural enemies and this corresponds to my results (Ali et al., 2016; Biradar and Vennila, 2008). The loss of functional biodiversity of important natural enemies such as Araneae has a negative effect on ecosystem functioning which reduces the primary productivity of ecosystems (Tilman et al., 2012). If no significant difference in pest abundance has been found between the conventional and organic systems, there is a possibility that pesticide resistance has taken place in conventional systems as using pesticides invariably results in the development of resistance to insecticides (Sagar and Balikai, 2014).If there is pesticide resistance among Jassids, further research using assays will need to be done (Sagar and Balikai, 2014). If this is the case, alternative solutions need to be discussed with the farmers to create sustainable pest management (Holland, 2020).

Literature and media have been focusing on the negative effects of bollworms and pink bollworms on the yield of Indian cotton. However, sucking pests have been mainly responsible for the decrease in cotton productivity (Shahid et al., 2009). A study has shown a decrease of 3% damage in yield in unprotected crops in comparison to 10% in effectively protected systems due to sucking pests (Makwana et al., 2018). There is a need for further studies to focus on understanding their pattern correlated to weather fluctuation to prevent attacks from sucking pests like Jassids. This study has shown a higher diversity and population in organic systems. These results are in accordance with other studies which confirmed that intensive agriculture has negative environmental impacts such as a decrease in biodiversity (Mkenda et al., 2019). This confirms that intensive agriculture is related to negative environmental impacts, including a decrease in functional biodiversity, which can lead to an increase in pest damage. With the climate crisis and weather pattern fluctuations, there is a need to find a solution which can control pest outbreaks to reduce their frequency. For a farming system to thrive, the biodiversity in it must be diverse and adaptable. This is particularly true for natural enemies and beneficial arthropods which can help prevent pest outbreaks(Hamilton, 2008). Pest invasions are often linked to abnormal climatic conditions which are more and more common due to the climate crisis (C2ES, 2022). Thus, a stable ecosystem with suitable functional biodiversity will also increase sustainability in the face of the adverse effects of the climate crisis (Hamilton, 2008).

To increase biodiversity and decrease pest attacks, farmers need to reduce pesticide use. Economic studies commonly assumed that pests are better controlled when enough pesticide is used (Gutierrez et al., 2015). The study of Li (Li and Yang, 2015) has shown that pesticide application is crucial for the control of the pest population. Regular application of pesticides has been observed to increase the population of pests and reduce the population of beneficial arthropods, creating the risk of a pest outbreak which can negatively impact the productivity of the crop (Hamilton, 2008). This correlates with the theory of hormesis which say that a continuous application of a small amount of pesticides enhances pest populations, whereas a single large dose of pesticide application reduces pest populations (Blaise et al., 2006; Luckey et al.,1968). It has been demonstrated that the best method to apply pesticides is not on a regular frequency, but when the pest population is relatively high (Li and Yang, 2015).

Composition of functional biodiversity

By looking at the composition of the functional biodiversity in the canopy and ground dwelling arthropods, results have shown that around two third of the total biodiversity in the foliage of the cotton are pests for both the farm-scale and plot scale systems. In both conventional systems in the plot-scale systems, the ground dwelling arthropods have a higher population of pests in comparison to beneficial arthropods. However, in both the organic systems in the plot-scale systems and both organic and Bt-conventional systems in the farm scale systems have a higher population of beneficial arthropods in comparison to the pest population. The plot-scale systems are more managed than the farm-scale systems (frequency of wedding is higher than both farm-scale systems) which could explain the difference in the composition of the community between the plot-scale systems and farm scale systems.

Weed management and its potential effect on arthropods community

According to the literature, it has been estimated that weeds in India reduce yields by one third in cotton fields (Jabran, 2016; Sushilkumar and Mishra, 2018). The presence of weeds three weeks after sowing affect significant reduction in growth as well as lint yields as cotton is very sensitive to weed competition in the first 60 days of crop growth (Papamichail et al, 2002). On the other hand, weeds play a host role for beneficial and pest arthropods. Weed species are an alternative host for phytophagous arthropods, these arthropods are source of food for natural enemies. Therefore indirectly weed can increase the amount of beneficial arthropods in the field (Norris and Kogan, 2005). On the plot-scale systems, removal of weeds happened 7 times during the season between June to September (see Table 4.11). During the same period, on the farm-scale systems, in average removal of weeds happened 3 times (see Table 4.12). In the plot-scale systems, the percentage of pest varied between one third of the arthropods community for the organic systems to half of the ground dwelling community for the conventional systems. In the farm-plot systems, the percentage of pests for the ground dwelling arthropods community represent only one fifth of the total community for both the systems. The data suggests that over removal of weeds could lead to an increase in the number of pests present at the ground level arthropods community. If weeds are used as food or shelter by arthropods, then weed control, regardless of the methods used, has the possibility to change the composition of arthropods community present in the crop field (Norris and Kogan, 2005). Management of weeds is an important aspect and difficult one to deal with. Too much weeds reduces the yield, yet over weeding reduces the wild life. Focusing on unselective weed removal can create a low diversity of competitive and resistant species that can be problematic for biodiversity and crop production. There is a need to reassess weed management and look towards new methods that can sustain cotton yield while maintaining biodiversity and natural ecosystems (MacLaren et al., 2020). There is little literature on ecological weed management and weed ecology can be complex, therefore, I suggest that a more in-depth study should be to conduct to look at the correlation existing between, weed removal, biodiversity community and yield.

Insecticide application and arthropods community

The composition of the beneficial ground-dwelling arthropods are mainly predators and decomposers. These results are in agreement with the study done in Brazil in cotton field in a similar climate (Potin et al., 2023). The same study has shown that ground dwelling arthropods were not affected by the broad-spectrum insecticides applied on the foliage (Potin et al., 2023). The explanation could be that the pesticide doesn't reach the ground due to the protection given by the foliage of the plant. The denser is the plant, the less chance insecticides have to reach the ground level. The preservation of natural enemies is directly linked to the reduction of phytophagous arthropods in crop ecosystems (Letourneau et al., 2009)

Biodiversity is elusive because it encompasses many dimensions including the diversity of species, their abundances and the way they interact in between each other and react to crop management. It has been observed by many studies that organic systems are favourable to biodiversity in comparison to conventional systems. There has been a gradual improvement in understanding the non-target effects of transgenic crops, but there is still controversy over every published study. One of the biggest research gaps is in the ability to standardize the assessment of biodiversity and being able to evaluate non-target effects of Bt-conventional systems in comparison to non-Bt conventional systems (National Research Council, 2002).

4.2.3. Limitations of this study

The Diptera and Hymenoptera group were only identified at the order level. These two groups include natural enemies such as syrphid or parasitoid wasps which play an important role in controlling insect pests in cotton crops (Dhaka and Pareek, 2007). This group includes pests as well as natural enemies such as parasitoids which have been found in studies to have an effective and efficient role in biological control in cotton fields (Ghahari et al., 2008). Parasitoids such as Trichogramma have been a potential solution against bollworms (Naik et al., 2019). During the survey, no data were collected from the border crops. However, predatory wasps normally nest largely in field borders, and, therefore, these natural enemies are connected mainly with the bordering landscape, making it difficult to separate the direct effect of cotton farming systems from the adjacent landscape (Torres and Ruberson, 2005). Hence, only natural enemy communities most connected to the cotton ecosystem and exposed to farmer practices were selected for this study.

A further study should be made on the relationship of specific pest-predator interactions rather than examining the overall biodiversity. Araneae have shown significant differences between systems and have been observed to be a good indicator to compare farming system practices (Isaia et al., 2006; Maelfait and Hendrickx, 1998). They play an important role in reducing pests in cotton fields and specifically in reducing the population of *Helicoverpa sp.* by feeding on their eggs. A study in the laboratory has been done (sahra Ghavani, 2008). Further studies should explore the effect the Araneae community has on *Helicoverpa sp.* as well as the sucking pest population in the field.

In 2016, the variety of cotton used in the systems was different from the variety used in 2017. This could explain the difference between the years specifically for the Jassids' outbreak.

Other limitations of the studied design should be considered, for example, the lack of Bt and non-Bt cotton farming systems without insecticides' application. Having access to unsprayed Bt and non-Bt farming systems would have helped separate pesticide effects from those attributable to plant types. The long-term trials are based on local use practices. For this reason, it is not realistic to compare Bt cotton and non-Bt cotton system with no pesticide application in the region which was studied.

4.2.4. Conclusion and recommendations

Through diversity indices, this study confirmed the hypothesis that organic farming management is more beneficial for ground and canopy-dwelling agrobiodiversity in comparison to conventional farming management in cotton farming systems.

It has been observed that there is no adverse effect of Bt transgenic crops on the arthropods community when compared to non-Bt systems getting the same type of management.

Ladybirds and spiders have proved to be good bio-indicators in evaluating the ESs of pest control biodiversity. My results, supported by other studies, suggest that pesticides negatively impact the arthropods community and that the natural enemies are the most affected due to their sensitivities to harmful chemicals (Torres and Ruberson, 2005). My recommendation is to encourage Bt-conventional farmers to use pesticides only when the pest population is above the economic threshold; this will in an overall reduction in the amount of pesticides applied (Naranjo and Ellsworth, 2009; Sandhu et al., 2010). We also recommend that organic farmers should practice integrated best management. The future challenge is to encourage local cotton farmers to use ecological solutions which increase productivity while conserving functional biodiversity (Mall et al., 2018; Scherr and McNeely, 2008).

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4.3. Highlights

Results

- This study has indicated that the long-term planting of **transgenic cotton does not** significantly **affect** the most common taxa of **soil invertebrates**.
- **Jassids** (Hemiptera: Cicadellidae), which are the main sucking pests **represented more than 50%** of the total number **of canopy-dwelling arthropods** in all the farming systems.
- Among the ground dwelling arthropods, **Coleoptera were** found to be significantly **more abundant in the biodynamic systems** than in both **conventional systems** at the plot-scale systems.
- Among the ground dwelling arthropods, **Coleoptera abundance** was significantly **higher in organic systems** in comparison to Bt-conventional systems at farm scale systems. However, it is possible coleoptera could be pests rather than natural enemies.
- Among the canopy and ground-dwelling arthropods community, **Araneae represented the most abundant group of natural enemies.**
- A significant **positive correlation** was identified **between** the abundance of **jassids and Araneae**, indicating that the jassids exerted a bottom-up effect on spiders in cotton crops.
- There was a **significant negative correlation between *C.sexmaculata* and *Amrasca biguttula (Jassids)*,** suggesting that *C.sexmaculata have* a significant positive effect on the suppression of Jassids.
- On both the plot-scale and farm-scale systems, **Araneae** abundance was **higher in the organic systems** when compared to the Bt-conventional systems for both canopy and ground-dwelling communities

Interpretations

- Araneae abundance has been negatively impacted by conventional Cotton farming system in comparison to organic systems.
- Jassids could have developed a resistance to pesticides

- The results from this study questioned the efficacy of pesticides in cotton fields and suggested natural enemies could be as effective and efficient as the application of pesticides in cotton fields.
- Araneae have confirmed to be a good bio-indicators to compare the ecological sustainability of farming systems

Recommendations

- Study of Jassids community to confirm the hypothesis that they have developed resistance to pesticide applications.
- More research on the impact of the Coleoptera family pest such as Nitidulidae or Curculionidae on cotton productivity should be explored
- Araneae and Coccinellidae are useful indicators that should be used to assess the ecological sustainability of farming systems.
- Farmers should explore integrated pest management to reduce pest resistance and encourage the natural enemies' population.

Chapter 5 Ecological sustainability: Belowground biodiversity

Abstract

Sustainable agriculture is directly linked to soil fertility, which provides ecosystem services that enhance productivity without harming the environment. After plant protection, soil fertility has been another factor for the low productivity in Indian CFS. The following study has looked at the belowground biodiversity with a focus on the functional biodiversity that provides supporting services such as nutrient cycling, primary production, and soil formation. The study has surveyed macroorganisms (earthworms) and micro-organisms (fungi) in long-term trials and farmer's fields of different CFS. To assess ecological sustainability, the study has looked at the abundance and biomass of earthworms as well as the general assemblage community of fungi. The first part of the study has shown that earthworm abundance and biomass were significantly higher in organic systems on long-term trials as well as farmer's fields. The second part of this study has shown that fungi species richness was higher in both organic systems in comparison to both conventional systems. *Trichoderma,* an antagonist fungal agent presence was significantly higher in both organic systems indicating that these systems are better prepared to fight soil-borne pathogens.

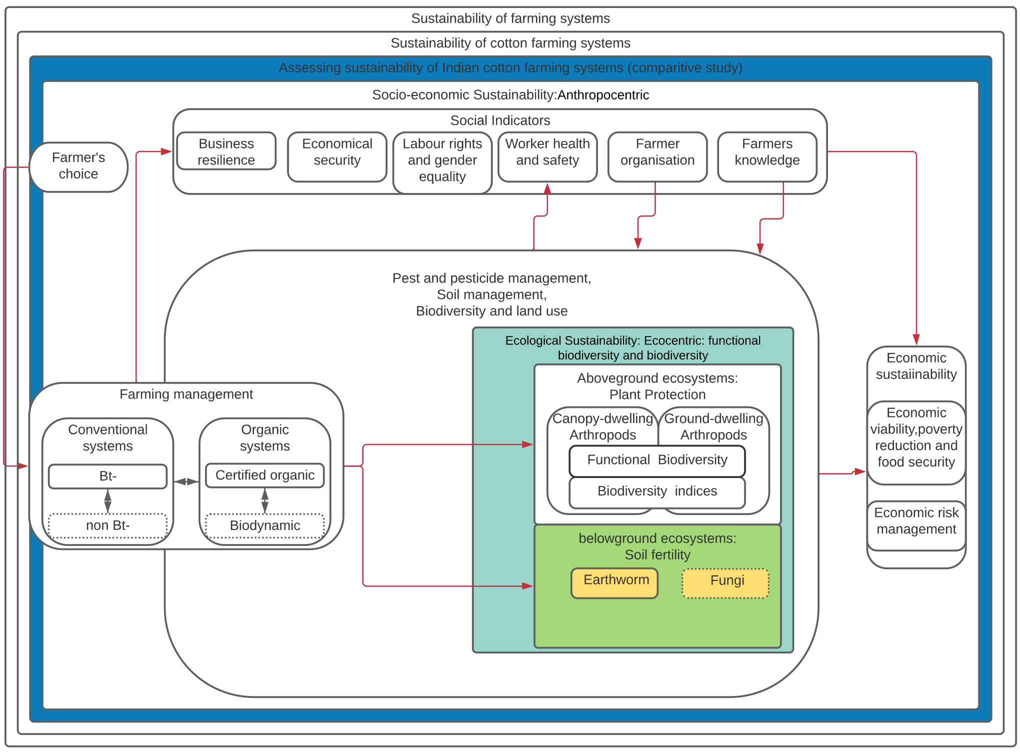


Figure 5.16: Scheme representing the chapter within the thesis

5.1. Introduction of this chapter

The 21st century has seen an alarming rate of soil depletion across the world, leading to a decrease in productivity (Lal, 2006). Soil depletion and soil degradation is a modern problem that cannot be ignored. Sustainable agriculture is directly linked to soil fertility, which provides ESs that enhance productivity without harming the environment (K. Birkhofer et al., 2008; Paoletti et al., 1991). Soil is the earth's most complex and diverse ecosystem (Gunstone et al., 2021). It consists of a vast community of living organisms, all highly diverse, including fungi, bacteria, protozoa, nematodes, and vertebrate and invertebrate organisms such as earthworms (Brussaard et al., 2007). These groups are major actors in soil functions; soil formation, recycling of nutrients, modifying soil structure (Edwards, 2004) as well as playing an integral role in sustaining the soil fertility and plant productivity through the ESs they provide (Henneron et al., 2014; Johansson et al., 2004).

"Soil invertebrates perform a variety of different ecosystem services essential for agricultural sustainability"(Gunstone et al., 2021).

Agroecosystems are considered highly controlled and easily influenced by human activity such as fertilisation, soil management, and pest control practices. These activities have a direct effect on soil biodiversity (Pfiffner and Mader, 1997). The overuse of chemicals has been identified to be the critical damaging factor responsible for the loss of soil biodiversity in the last decade. Pesticide and fertiliser use in agricultural practices has intensified rapidly over the past decade and has been observed to be one of the major driving factors for the loss of entomofauna and other biodiversity (Sánchez-Bayo and Wyckhuys, 2019). Turning the attention to Indian CFS, Monocrotophos and Imidacloprid are the primary choice of pesticides to fight sucking pests (Chowdappa and Balikai, 2013). Amongst these pesticides, Imidacloprid has recently been observed to be a threat to soil invertebrates (Gunstone et al., 2021), and could prove an additional threat to the stability of ESs provided by soil biodiversity.

Bt-cotton represents more than 95% of the total grown cotton in India (James, 2014). Present farming management practices are known to have negative effects on the soil ecosystem. Transgenic crops could have further additional impacts on soil biodiversity (Mishra, 2017). There is little knowledge of the detrimental long-term effects of Bt toxins on the soil ecosystem (Blackwood and Buyer, 2004; Donegan et al., 1995) and very few studies have looked at this potential hazard (Mishra, 2017). Long-term studies to assess these potentially adverse effects are essential (Zeilinger et al., 2010) and have been called by numerous scientists and academics (ASHA and Kranthi, 2020; FAO, 2001).

In this study, I have looked at the effects of biodynamic, organic, conventional, and Bt-conventional cotton systems management on the functional biodiversity of two different taxonomic groups: earthworms and fungi.

The fungi study was only carried out on the plot-scale systems as a first-of-its-kind experiment while the earthworm study was carried out on the plot-scale systems as well as the farm-scale systems.

PART I: Earthworms as Bio-indicators to evaluate soil fertility

5.2. Introduction

Earthworms are essential components of soil biodiversity and are key antagonists for pedogenesis (Edwards, 2004). Beyond soil formation, they play a fundamental part in soil fertility and soil health (Kale and Karmegam, 2010). By feeding on the soil, earthworms accelerate the mineralisation of nitrogen (Hernández-garcia et al., 2018; Sankar and Patnaik, 2018), modify soil proprieties (Chaoui et al., 2003), improve soil fertility, and alter plant nutritional quality and physiology, leading to an increase in plant productivity and an indirect increase in pest resistance (Xiao et al., 2019).

Earthworms are easy to breed and have a short generation time (OECD, 1984), they are easy to monitor and cost-effective (Bart, 2017), making them valuable monitoring tools. Climate variables and landscapes have been found to shape earthworm communities more than soil properties (Phillips et al., 2019), therefore importance to study them in both temperate as well as tropical climates. However, there is still a research gap in earthworm studies under tropical conditions (Daam et al., 2020). Due to their sensitivity to their environment (Pfiffner and Mader, 1997), earthworms serve as one of the best indicators to assess soil health in agricultural systems (Bai et al., 2018). Earthworm abundance and biomass vary greatly according to farming practices employed such as the type of soil management (Smith et al., 2008) or use of pesticides and fertilisers (van Eekeren et al., 2009). They have been used extensively for eco-toxicological testing and to evaluate the effect of pesticides on soil (Spurgeon et al., 2003). One of the main problems for Indian cotton farmers is pest management (Ramasundaram, 2001). To fight against pests, conventional farmers rely on chemicals and pesticides. In Indian cotton conventional farming systems, hazardous pesticides like Imidacloprid and Monocrotophos are regularly used against sucking pests. Studies have shown that pesticides have easily found their way into the soil and there is a general concern regarding the damage they could have on the soil biota (Henneron et al., 2014; Pimentel, 2005).

Cotton accounts for 6% of total fertilizer consumption in India (FAO, 2005) and its consumption has increased since the introduction of Bt-cotton (Kranthi, 2014). Excessive application of nitrogen has been linked to nitrate leaching in conventional farming systems (Wang et al., 2018) which increases soil salinity and soil acidity (Han et al 2014), and therefore plays a role in soil degradation. Soil management practices influence external aspects such as abiotic factors, soil texture (Pelosi et al., 2009), and moisture-holding capacity (Edwards, 2004; Kale and Karmegam, 2010) which in (re)turn affects earthworm activity. In laboratory experiments, earthworms have proven to be valuable tools in evaluating the impact of external factors on soil health as well as understanding the impact they have on their respective environment (Fründ et al., 2010). Studies in the laboratory(Angst et al., 2017) as well as at the field level (Condron et al., 2000; Mathews et al., 2001) have shown that earthworm populations have been strongly affected by the percentage of the organic carbon content of soil (Condron et al., 2000; Mathews et al., 2001), by the salinity of soil (Guzyte et al., 2011) and other physicochemical parameters(Sankar and Patnaik, 2018).

Plants genetically modified with *Bacillus thuringiensis* genes are referred to with the prefix Bt, such as Bt-corn or Bt-cotton. The 'Cry' gene, extracted from the bacterium *Bacillus thuringiensis*, has been incorporated into Bt-plants to resist Lepidopteran pests (Mishra, 2017). Globally, the two main commercial Bt crops are maize and cotton (Koch et al., 2015). Bt-toxins are released by genetically modified plants through the rhizosphere and detritus from the plants, binding to the minerals and organo-minerals present in the soil (Crecchio and Stotzky, 2001; Zeilinger et al., 2010). Before the commercialization of Bt-crops, concerns existed around the effects on non-target organisms present in the soil, and earthworms were widely viewed as "a reliable tool for monitoring the possible effects of GMOs" (Paoletti, 1999a). The consequences of Bt crops on soil-borne communities are still a concern and merit further exploration (Icoz and Stotzky, 2008). A large majority of studies have been done in-laboratory and are short-term experiments generally relying on Bt-maize (Emmerling et al., 2011; Saxena and Stotzky, 2001; Schrader et al., 2008; Shu et al., 2017; Zwahlen et al., 2003). Under field conditions, studies have detected Bt toxins in the gut of earthworms(Saxena and Stotzky, 2001) but no studies on the long-term effects of Bt-cotton on soil health using earthworms as a bio-indicator have been published (Vercesi et al., 2006).

The majority of comparative studies which have used earthworms as bio-indicators have been carried out in temperate climates with no existing data for the effect of Bt crops (Henneron et al., 2014; Pelosi et al., 2009; Pfiffner and Mader, 1997;

Zeilinger et al., 2010). In India, studies of earthworms have been generally focused on vermiculture (Kale and Karmegam, 2010; Sinha et al., 2010; Suthar, 2007). However, one study was conducted in a northern semi-arid region of India (Suthar, 2009) comparing long-term farming systems which suggested that earthworms were more abundant in integrated and organic systems when compared to conventional systems. More detailed studies are needed in India to better understand the effect of agroecosystems on earthworm communities and the soil ecosystem using earthworms as bio-indicators (Zeilinger et al., 2010), particularly in India. To my knowledge, no previous study has been carried out on earthworms in cotton crops in India.

This chapter aimed to compare the effect of biodynamic, organic, conventional, and Bt-conventional CFS on soil health using earthworms as a monitoring tool.

The objectives of this study were:

1) To compare the effect of farming systems on earthworms at plot-scaled in four farming systems (biodynamic, organic, conventional, and Bt-conventional) and farm-scale in two farming systems (organic and Bt-conventional).

2) To investigate the impact of other abiotic factors (bulk density, NPK, EC (electrical conductivity), and pH) on the earthworm community.

3) To evaluate if Bt-transgenic cotton crops have a long-term impact on soil health looking at earthworm abundance and biomass.

5.3. Materials and methods

Earthworm surveys were carried out on both the plot-scale trial (Long Term Experiment) and the farm-scale trial (farmers' fields). A similar methodology was used in both types of systems.

5.3.1. Experimental site and design

5.3.1.1. Plot-scale

For details refer to chapter 3: Methodology, section 3.2., page 29

5.3.1.2. Farm scale

For details refer to chapter 3: Methodology, section 3.3, page 38.

5.3.2. Earthworm survey

Earthworm surveys were conducted early mornings when earthworms were nearer to the surface. In 2016, two methods of earthworm survey were tested. The first method was a mustard extraction technique which involved applying a mixture of 15g of mustard powder diluted in 1.5 litres of water (Valckx et al., 2011) to a 0.25x 0.25 m quadrat and surrounded by a 0.35x 0.35m wood quadrate to contain the liquid going. The mustard extraction was unsuccessful, drawing no earthworms to the surface, and was discontinued in the following years. The second method was the traditional hand-sorting collection; a soil pit (25 cm x 25 cm x 20cm) was dug out and hand sorted. The soil samples were manually unearthed to a depth of 10 cm using a spade and a sampling frame that had sidewalls of 10 cm depth to avoid the earthworms from escaping while being unearthed. They were then hand sorted and placed safely in closed boxes until analysis. In the following hour, in the laboratory, the individual earthworms were counted and each individual was rinsed in water and was patted dry with a cotton cloth to remove the moisture on the surface and weighed to the nearest $0.1.10^{-8}$g using a weighing scale- WENSAR^{TM} (ISO 9001: 2000 certified). In 2016 and 2017, live earthworms were counted in the field and then released. In 2018, earthworms were retained, they were first kept for 24 hours in formalin and then transferred to 80% ethanol for preservation.

5.3.2.1. Plot-scale

In 2017, after 10 years of the trials' establishment, earthworms were sampled in each farming management system (biodynamic, organic, conventional, Bt-conventional) of the plot-scale systems. Sample collection was carried out during the cotton growing season on each farming management system in the following weeks after sowing (WAS): 13th WAS (14/08/17); 15th WAS (31/08/17); 17th WAS (18/09/17) and 21st WAS (14/10/17). The samples were collected to compare the biomass and the population density of earthworms in the different farming systems.

5.3.2.2. Farm scale

In 2018, the farm-scale systems (Organic and Bt-conventional) were surveyed following the same protocol as the plot-scale systems on the 13th WAS (21/08/18), 15th WAS (04/09/18), and 17th WAS (18/09/18). The samples were collected to compare the biomass and the population density of earthworms in the different farming systems. Two sampling points were selected randomly (see methodology chapter).

5.3.3. Soil survey on the plot-scale

For each earthworm survey, 500 g of soil was collected using a soil core from 0 to 10 cm in each surveyed plot. Soil samples were sampled on the 13th, 15th and 17th WAS.

5.3.4. Laboratory analysis

5.3.4.1. Plot scale

Earthworm analysis

In the following hour, after earthworms were unearthed, the individual earthworms were brought to the laboratory were counted. Each individual was rinsed in water and patted dry with a cotton cloth to remove the moisture on the surface and weighed to the nearest $0.1.10^{-8}$g using a weighing scale- WENSAR^{TM} (ISO 9001: 2000 certified).

In 2017, the specimens were released after weighing. In 2018, earthworm specimens were kept for 24 hours in Formalyde and then transferred to an 80% ethanol solution to preserve them (Photo 5.2).

Soil analysis

The preliminary soil analysis included electric conductivity, soil pH, and bulk density. This was done on the same day as sampling. The remaining material was air-dried and kept in the freezer for further analysis. Subsequently, organic carbon was measured using the Walkley-Black method (Bornemisza et al., 1978), and total Nitrogen was carried out using the Kjeldahl digestion method (Kirk, 1899). Nitrate and Ammonium were analysed using KCl extraction (Nelson, 1983).

5.3.4.2. Farm scale

Earthworm analysis

In the following hour, after earthworms were unearthed, the individual earthworms were brought to the laboratory were counted. Each individual was rinsed in water and patted dry with a cotton cloth to remove the moisture on the surface and weighed to the nearest $0.1.10^{-8}$g using a weighing scale- WENSAR^{TM} (ISO 9001: 2000 certified).

In 2018, earthworm specimens were kept for 24 hours in Formalyde and then transferred to an 80% ethanol solution to preserve them (Photo 5.2)

Photo 5.2: (a)frame 25cm x25 cm used to sample the earthworms (b) hand sorted of the earthworms (c)transfer of the sampling in a marked container (e)earthworms are kept aside till the analysis (d) materials used to wash the earthworm before weighting them (e) (f)example of earthworms sampled

5.3.5. Statistical analysis

5.3.5.1. Plot-scale trial

5.3.5.1.1. System comparison

In the years 2017 and 2018, there were 3 sampling events for each year. Instead of transforming the data and using ordinary least squares regression, I applied a GLMM.

The data for the year 2017 and 2018 were analysed separately. Data were analysed using a General Linear Mixed Effects (GLMM) in R using “multcomp” (Hothorn, 2019) and “lme4” (Bates and Maechler, 2019) to determine whether there were significant differences in biomass and density between systems. System (Biodynamic, organic, Bt-conventional and conventional farming systems) was included as a fixed factor, block was included as a random factor, the sampling events were average and the response variables were Biomass (g per m^2) and Density (per m^2). The response variables were analysed separately. All standard errors, means, minimum and maximum were calculated in R with the package dplyr (Wickham, 2020).

5.3.5.1.2. Abiotic factors

In 2018, there were 3 sampling events. Data were analysed in R using “multcomp” (Hothorn, 2019) and “lme4” (Bates and Maechler, 2019) to determine whether there were significant differences in the abiotic factors between systems. System (Organic, biodynamic, conventional and Bt-conventional systems) was included as a fixed factor, block was included as a random factor, the sampling events were average and the response variables were:

Nitrate (NO_3^-), Ammonium (NH_4^+), Organic carbon (OC), electric conductivity (EC) and pH. The response variables were analysed separately.

All standard errors, means, minimum and maximum were calculated in R with the package dplyr (Wickham, 2020).

Non-parametric Spearman's ranked correlations were used to test the relationship between nitrate, ammonium, pH, organic carbon and electric conductivity with the earthworm biomass and density (analysed separately). The correlation test was conducted in R. In the package "Hmisc" (Harell, 2019) which contains many functions for data analysis, the function "rcorr" was conducted to produce a matrix of correlations between the different abiotic factors and the earthworm biomass and earthworm density. "rcorr" "computes a matrix of Spearman's rank correlation coefficient for all possible pairs of columns of a matrix" together with an estimation of significance (CRAN,2019).

5.3.5.2. Farm-scale trial

5.3.5.2.1. Systems comparison

In 2018, there were 3 sampling events. Instead of transforming the data and using ordinary least squares regression, I applied a GLMM. Data were analysed in R using "multcomp" (Hothorn, 2019) and "lme4" (Bates and Maechler, 2019) to determine whether there were significant differences in earthworm biomass and earthworm density between systems. System (Organic and Bt-conventional systems) was included as a fixed factor, pair was included as a random factor, the sampling events were average and the response variables were Biomass (g per m^2) and Density (per m^2). The response variables were analysed separately. Standard errors and means were calculated in R with the package dplyr (Wickham, 2020).

5.3.5.2.2. Abiotic factors

In 2018, there were 3 sampling events. Data were analysed in R using "multcomp" (Hothorn, 2019) and "lme4" (Bates and Maechler, 2019) to determine whether there were significant differences in the abiotic factors between systems. System (Organic and Bt-conventional systems) was included as a fixed factor, pair was included as a random factor, the sampling events were average and the response variables were:

Nitrate (NO3-), Ammonium (NH4+), Organic carbon (OC), electric conductivity (EC) and pH. The response variables were analysed separately.
Standard errors and means were calculated in R with the package “dplyr” (Wickham, 2020).

Non-parametric Spearman’s ranked correlations were used to test the relationship between nitrate, ammonium, pH, organic carbon and electric conductivity with the earthworm biomass and density (analysed separately). The correlation test was conducted in R. In the package “Hmisc” (Harell, 2019) which contains many functions for data analysis, the function “rcorr” was conducted to produce a matrix of correlations between the different abiotic factors and the earthworm biomass and earthworm density. “rcorr” “computes a matrix of Spearman’s rank correlation coefficient for all possible pairs of columns of a matrix” together with an estimation of significance (CRAN,2019).

5.4. Results

5.4.1. Plot-scale trial

5.4.1.1. Systems Comparison

On the plot-scale experiment, for the year 2017, the organic systems had significantly higher earthworm density in comparison to the conventional systems ($z=3.14$, $P<0.01$) and the Bt-conventional systems ($z=3.03$, $P<0.01$). With the same pattern, the biodynamic systems had significantly higher earthworm density in comparison to the conventional systems ($z=-3.30$, $P<0.01$) and the Bt-conventional systems ($z=3,20$, $P<0.01$). Earthworm biomass was significantly higher in the organic systems in comparison to the conventional systems ($z=2.13$, $P<0.01$), and the Bt-conventional systems ($z=2.05$, $P<0.01$) With the same pattern, the biodynamic systems had significantly higher earthworm biomass in comparison to the conventional systems ($z=-2.53$, $P<0.01$) and the Bt-conventional systems ($z=2.45$, $P<0.01$) (Figure 5.17, Table 5.32, Table 5.33)..

For the year 2018, the organic systems had significantly higher earthworm density in comparison to the conventional systems ($z=4.02$, $P<0.01$) and the Bt-conventional systems ($z=4.33$, $P<0.01$). With the same pattern, the biodynamic systems had significantly higher earthworm density in comparison to the conventional systems ($z=-3.45$, $P<0.01$) and the Bt-conventional systems ($z=-3.85$, $P<0.01$). Earthworm biomass was significantly higher in the organic systems in comparison to the conventional systems ($z=2.29$, $P<0.01$), and the Bt-conventional systems ($z=2.16$, $P<0.01$). With the same pattern, the biodynamic systems had significantly higher earthworm biomass in comparison to the conventional systems ($z=-2.53$, $P<0.01$) and the Bt-conventional systems ($z=2.45$, $P<0.01$). For earthworm density and biomass, there were no significant difference between the organic and biodynamic systems and the conventional and Bt-conventional systems (Figure 5.17, Figure 5.18. Table 5.32. Table 5.33, for more details, see appendices C: Table C.51 to Table C.53).

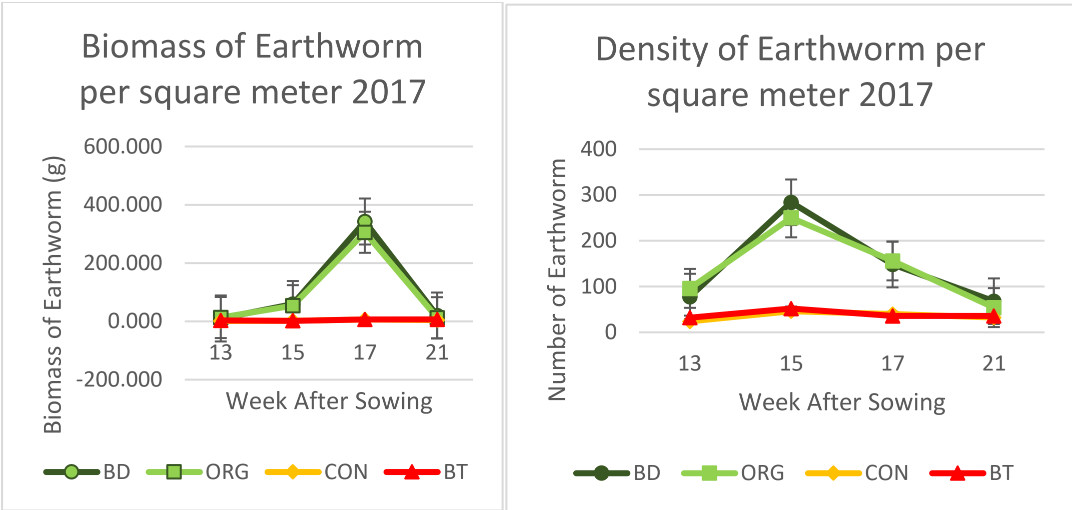


Figure 5.17: Long-term effect on the average Biomass per Earthworm and average Density per square meter of the earthworm samples on the 13th, 15th, 17th and 21st WAS for the survey done in 2017

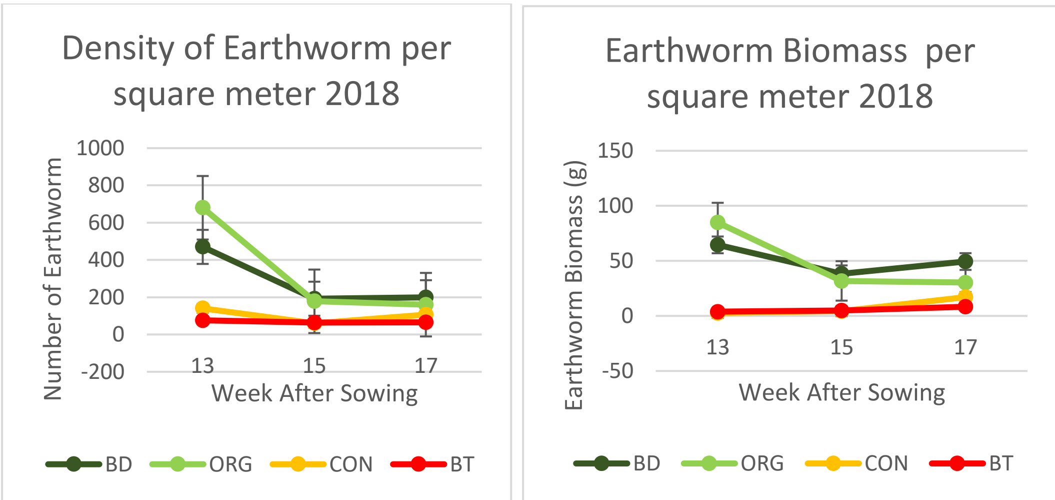


Figure 5.18: Long-term effect on the average earthworm biomass per earthworm per square meter collected by hand sorting core (25 x 25 cm^2) in four different farming on vertisol for the survey 2018

Table 5.32: Summary of the descriptive statistic of the density and biomass of earthworms per square meter on the plot scale systems (Biodynamic, organic, conventional, Bt-conventional) during the surveys 2017 and 2018

	2017					
Systems	**Biomass (g per m2)**			**Density (per m2)**		
	Mean	**SD**	**SE**	**Mean**	**SD**	**SE**
Biodynamic (n=192)	11.78	17.97	1.30	144.5	131.44	9.49
Organic (n=192)	10.18	13.45	0.97	139	134.88	9.73
Bt-conventional (n=192)	2.01	1.9	0.14	39	27.85	2.01
Conventional (n=192)	1.69	1.23	0.09	35.5	131.44	9.49
	2018					
	Biomass (g per m2)			**Density (per m2)**		
	Mean	**SD**	**SE**	**Mean**	**SD**	**SE**
Biodynamic (n=144)	2.96	1.14	0.10	287.33	178.97	14.91
Organic (n=144)	2.62	0.86	0.07	339.33	302.7	25.23
Bt-conventional (n=144)	1.49	0.8	0.07	68.67	26.08	2.17
Conventional (n=144)	1.21	0.95	0.08	102	178.97	14.91

Table 5.33: Summary of Results of general linear mixed effect models comparing earthworm biomass and density in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2018

	p-value			
	2017		**2018**	
	Biomass	**Density**	**Biomass**	**Density**
Organic Biodynamic	0.77	0.9	0.41	0.61
Organic Bt-conventional	0.02	<0.01	<0.01	<0.01
Organic Conventional	0.02	<0.01	<0.01	0.01
Biodynamic Bt-conventional	0.04	<0.01	<0.01	<0.01
Biodynamic Conventional	0.04	<0.01	<0.01	<0.01
Bt-conventional Conventional	0.58	0.68	0.45	0.12

5.4.1.2. Abiotic factors comparison between systems (2018)

5.4.1.2.1. Nitrate and ammonium

On the plot scale trial, there were no significant differences between the systems in the amount of ammonium and nitrate present in the soil. We observed that from week 13 to week 17 after sowing, the amount of nitrate in both conventional systems had decreased while it increased in both organic systems (Table 5.34,Table 5.35).

5.4.1.2.2. Organic Carbon

On the plot-scale experiment, there was a significant difference in the amount of organic carbon between the organic systems and the conventional systems ($z=2.79$, $P=0.03$) as well as between the biodynamic systems and the conventional systems ($z=-3.57$, $P<0.01$) (Table 5.34, Table 5.35, for details see appendices C: Table C. 57).

5.4.1.2.3. Electric conductivity and pH

The electric conductivity was significantly higher in the Bt-conventional systems in comparison to the organic systems ($z=-3.02$, $P=0.01$), biodynamic systems ($z=3.41$, $p<0.01$), and conventional systems ($z=3.59$, $P<0.01$). There was no significant difference in the pH on the plot-scale experiment (Table 5.34, Table 5.35, for details see appendices C: Table C.56).

Table 5.34: Soil abiotic factors from the 2018 earthworm surveys on the long-term plots (BD: Biodynamic; ORG: Organic; CON: Conventional; BT: Bt-conventional) and on the field-scale experiment (ORG: Organic, BT: Bt-conventional) with means ± standard error.

Location	WAS	Treatment	NH4+ (kg/ha)	NO-3 (kg/ha)	OC (kg/ha)	pH	EC (uS/cm)
Long Term plot	Week 13	BD	204.06 ± 34.24	80.40 ± 23.93	8192.268 ± 1452.86	8.11 ± 0.14	173 ± 35
		ORG	187.97 ± 37.15	78.31 ± 14.62	7794.864 ± 2250	8.06 ± 0.18	181 ± 18
		CON	193.22 ± 15.87	134.09 ± 23.22	5496.62 ± 1876.9	8.15 ± 0.08	170 ± 22
		BT	193.81 ± 15.06	118.46 ± 13.13	8043.84 ± 1856	8..09 ± 0.09	244 ± 54
	Week 15	BD	140.62 ± 15.31	98.99 ± 8.34	9580.79 ± 2213.26	7.58 ± 0.37	138 ± 17
		ORG	182.07 ± 23.34	104.05 ± 9.04	8857.8 ± 1655.56	7.86 ± 0.39	129 ± 4
		CON	176.26 ± 27.93	124.47 ±26.64	6613.82 ± 2357.90	7.87 ± 0.48	123 ± 6
		BT	160.65 ± 25.81	98.45 ± 12.50	9161.04 ± 2692.68	7.57 ± 1.02	196 ± 149
	Week 17	BD	196.90 ±27.83	108.86 ± 24.30	10413.90 ± 995.55	8.40 ± 0.23	169 ± 48
		ORG	206.16 ± 12.72	97.90 ± 15.39	9787.87 ± 442.89	8.21 ± 0.53	164 ± 24
		CON	189.90 ± 36.24	87.32 ± 20.10	8088.53 ± 972.24	8.12 ± 0.37	177 ± 89
		BT	133.59 ± 38.75	87.30 ± 19.19	7820.40 ± 608.37	8.18 ± 0.45	152 ± 76

Table 5.35:Summary of the results of general linear mixed effect model comparing Organic Carbon (OC) in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2018

Systems	NH4+ (kg/ha)	NO3- (kg/ha)	OC (kg/ha)	EC	pH
Bt-conventional Biodynamic	0.46	0.99	0.49	<0.01	0.96
Conventional Biodynamic	0.89	0.43	<0.01	0.99	0.77
Organic Biodynamic	0.98	0.95	0.86	0.98	0.57
Conventional Bt-conventional	0.87	0.36	0.14	<0.01	0.47
Organic Bt-conventional	0.25	0.98	0.92	0.01	0.86
Organic Conventional	0.7	0.18	0.03	0.94	0.11

5.4.1.3. Correlation between abiotic factors and earthworm biomass and density

5.4.1.3.1. Organic Carbon

There was no significant correlation between the amount of organic carbon present in the different farming systems and the earthworm biomass and density (Table 5.36)

There was no significant correlation between the amount of organic carbon present in the different farming systems and the earthworm biomass and density (Table 5.36).

5.4.1.3.2. Electric conductivity and pH

In the biodynamic systems, the electric conductivity showed a positive correlation between the earthworm biomass ($r=0.77$, $P=0.02$) and earthworm density ($r=0.91$, $P<0.01$).

In the conventional systems, the electric conductivity showed a positive correlation between the earthworm biomass ($r=0.73$, $P=0.04$) and earthworm density ($r=0.85$, $P<0.01$).

In the Bt-conventional systems, only the biomass was significantly positively correlated with the electrical conductivity factor ($r=0.75$, $P=0.03$) (Table 5.36).

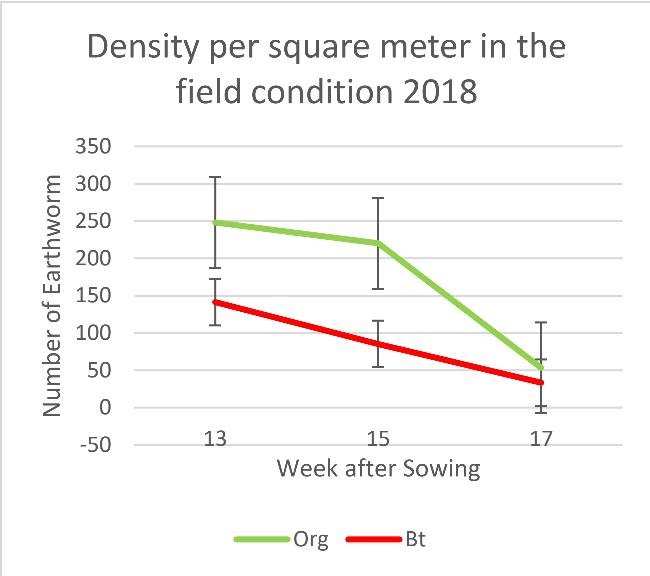
Table 5.36: Correlation between the abiotic factors (OC, EC and pH) and earthworm biomass and density in the four farming systems (Biodynamic, organic, conventional and Bt-conventional) during the survey 2018.

Systems	Biomass					
	OC (kg/ha)		EC		pH	
	Pearson correlation	p-value	Pearson correlation	p-value	Pearson correlation	p-value
Biodynamic	0.3	0.34	0.77	0.02	-0.13	0.7
Organic	0.14	0.66	0.51	0.19	-0.19	0.55
Conventional	0.24	0.46	0.73	0.04	-0.13	0.68
Bt-conventional	0.27	0.4	0.75	0.03	0.11	0.75
	Density					
	OC (kg/ha)		EC		pH	
	Pearson correlation	p-value	Pearson correlation	p-value	Pearson correlation	p-value
Biodynamic	-0.1	0.76	0.91	<0.01	0.02	0.95
Organic	-0.16	0.62	0.67	0.07	-0.15	0.64
Conventional	-0.41	0.19	0.85	<0.01	0.09	0.79
Bt-conventional	0.04	0.89	0.5	0.2	0.1	0.76

5.4.2. Farm-scale cotton farming systems (2018)

5.4.2.1. Systems Comparison

On the farm-scale systems, results have shown a significant difference for the earthworm biomass (z=2.37, P=0.02) and earthworm density (z=2.49, P=0.02) between organic systems and Bt-conventional systems (Figure 5.19, Table 5.37, see appendices C: Table C.52 , Table C.53).



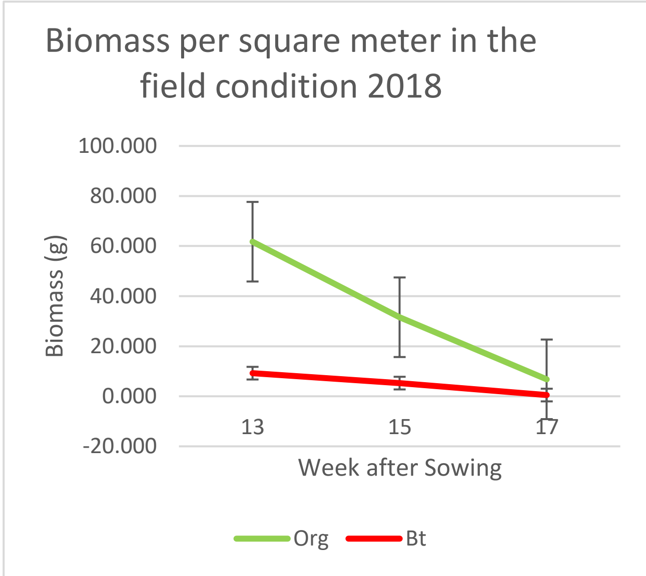


Figure 5.19: Effect of farming systems on the Biomass (g per m²) and Density (per m²) of Earthworm on the farm-scale systems during the survey 2018

Table 5.37: Summary of the results of general linear mixed effect model comparing the biomass and density of earthworms on the farm-scale systems (Bt-conventional and organic) during the survey 2018 with Mean, SD: Standard Deviation and SE: Standard Error.

	Biomass (g per m2)			p-value
	Mean	**SD**	**SE**	
Bt-conventional (n=36)	6.86	14.87	2.47833	0.02
Organic (n=36)	19.7	28.95	4.825	
	Density (per m2)			**p-value**
	Mean	**SD**	**SE**	
Bt-conventional (n=36)	86.67	118.96	19.8267	0.02
Organic (n=36)	173.78	174.19	29.0317	

5.4.2.2. Abiotic factors in between farming systems

5.4.2.2.1. Nitrate and ammonium

In the farm-scale experiment, there were no significant differences between the systems in the amount of ammonium and nitrate present in the soil. We observed that from week 13 to week 17 after sowing, the amount of nitrate in both conventional systems had decreased while it increased in both organic systems (Table 5.38, Table 5.39).

5.4.2.2.2. Organic Carbon

On the farm-scale experiment, there was no significant difference between the organic and Bt-conventional was also observed on the field-scale experiment (Table 5.38, Table 5.39).

5.4.2.2.3. Electric conductivity, pH, and salinity

In the farm-scale experiments, the electric conductivity was significantly higher ($z=8.23$, $P<0.01$) in the Bt-conventional systems in comparison to the organic systems. The pH was significantly higher ($z=7.85$, $P<0.01$) in the organic systems in comparison to the Bt-conventional systems (Table 5.38, Table 5.39, see Appendices C: Table C.58, Table C.59).

Table 5.38: Soil abiotic factors (Ammonium (NH4+),Nitrate (NO3-), OC (Organic Carbon), Electric conductivity (EC) and pH0 from the 2018 earthworm surveys on the long-term plots (BD: Biodynamic; ORG: Organic; CON: Conventional; BT: Bt-conventional) and on the field-scale experiment (ORG: Organic, BT: Bt-conventional) with means ±standard error

Location	WAS	Treatment	NH4+ (kg/ha)	NO-3 (kg/ha)	OC (kg/ha)	pH	EC (uS/cm)
Farmer's plot	week 13	ORG	203.29 ± 45.24	140.57± 12.35	13087.2± 2471.99	7.98± 0.11	161± 42
		BT	203.56± 67.40	222.51± 115.59	8645± 1590.94	7.364± 0.58	259± 115
	week 15	ORG	203.24 ± 52.21	183.13 ± 114.74	9256.8 ± 2835.32	7.57 ± 0.20	182 ± 69
		BT	156.38 ± 72.71	109.09 ± 20.61	8990.8 ± 2152.33	7.42 ± 0.41	404 ± 317
	week 17	ORG	234.36 ± 24.85	156.24 ± 46.52	11143.61 ± 2780.90	8.12 ± 0.34	202 ± 34
		BT	278.46 ± 65.60	218.96 ± 109.75	10232.83 ± 1796.72	7.79 ± 0.31	344 ± 205

Table 5.39: Significance (p-value) of the soil abiotic factors (Ammonium (NH4+), Nitrate (NO3-), OC (Organic Carbon), Electric conductivity (EC) and pH) from the earthworm survey from the surveys 2018

Systems	NH4+ (kg/ha)	NO3- (kg/ha)	OC (kg/ha)	EC	pH
Organic Bt-conventional	0.93	0.48	0.08	<0.01	<0.01

5.4.2.3. Correlation between abiotic factors and earthworm biomass and density

5.4.2.3.1. Organic Carbon

There was no significant correlation between the amount of organic carbon present in the different farming systems and the earthworm biomass and density (Table 5.40)

5.4.2.3.2. Electric conductivity and pH

There was no significant correlation between the amount of organic carbon present in the different farming systems and the earthworm biomass and density (see Table 5.40)

Table 5.40: Correlation between earthworm density and biomass with significant abiotic factors from 2018 on the farm-scale survey

Systems	Biomass					
	OC (kg/ha)		EC		pH	
	Pearson correlation	p-value	Pearson correlation	p-value	Pearson correlation	p-value
Organic	-0.39	0.71	0.16	0.56	-0.37	0.73
Bt-conventional	-0.01	0.82	-0.13	0.78	0	0.53
	Density					
	OC (kg/ha)		EC		pH	
	Pearson correlation	p-value	Pearson correlation	p-value	Pearson correlation	p-value
Organic	-0.36	0.86	-0.05	0.65	-0.33	0.34
Bt-conventional	-0.02	0.74	-0.02	0.45	-0.05	0.68

5.5. Discussion

5.5.1. Comparing Farming Systems

We observed that the earthworm density and biomass were higher in both organic systems than in both conventional ones. Other studies done in temperate climates comparing organic and conventional systems have shown similar results (Condron et al., 2000; Paoletti, 1999b; Paoletti et al., 1991; Pelosi et al., 2009; Pfiffner and Mader, 1997). A study with four different farming systems (similar to the plot-scale experiment design) was carried out in a temperate climate from 1990 to 1992. Similar to my study, the study has concluded that the biomass and the density were not significantly different between the organic and biodynamic farming systems but significantly different between the two conventional systems (conventional and mineral) and the two organic systems (biodynamic and organic) (Pfiffner and Mader, 1997).

Earthworms are very sensitive to chemical compounds due to their permeable cuticle which exposes them directly to soluble pesticides and fertilisers present in the soil (Fründ et al., 2010; Svobodová et al., 2018), this makes them an excellent tool for eco-toxicological tests. Laboratory studies have recognized the negative impact of pesticides and fertilisers and active ingredients such as Monocrotophos (Booth and O'Halloran, 2001; Zhou et al., 2007) and Imidacloprid (Dittbrenner et al., 2011; Faheem and Khan, 2014) on earthworm populations. Studies have shown the negative effects of Imidacloprid on earthworm biomass and population (Dittbrenner et al., 2011; Lima e Silva et al., 2017) in temperate and tropical climates (Faheem and Khan, 2014; Roger et al., 2013). The negative effects of Monocrotophos have been recognized by many countries and despite research from India showing the harmful effect of these chemicals on soil bio-indicators such as earthworms, this pesticide is still used legally in the country (Abbiramy et al., 2018; Bharathi and Subba Rao, 1986).

Organic vs Conventional (plot-scale and farm-scale systems)

This significant difference between organic and Bt conventional systems was on both plot scale as well as farm scale in earthworm biomass and density.

Locally, there were inconsistencies among farmers who were applying biodynamic principles and there were no biodynamic certified farming systems, therefore amongst both organic systems (biodynamic and organic), only certified organic systems were surveyed at the farm scale. In countries where transgenic cotton crops were approved, conventional farmers used transgenic seeds. In India, 97% of cotton farmers are growing Bt-cotton crops conventionally (ISAAA, 2017). As there was no significant difference between the conventional systems (conventional and Bt-conventional) in the plot-scale systems, only conventional farms using Bt-cotton seeds of *Gossypium hirsutum* were surveyed. Supported by other similar studies done in temperate climates (Carpenter-Boggs et al., 2000; Mader, 2002; Pelosi et al., 2014), my study which was carried out in a tropical system, has confirmed that organic practices significantly benefit earthworm density and earthworm abundance when compared to both conventional systems.

5.5.2. Long-term impact of Bt-conventional

This is the first study outside of the laboratory to evaluate the effect of Bt-cotton on earthworms in India. At the plot scale, results showed that transgenic cotton and more specifically the Bt-protein has no significant effect on the earthworm population in comparison to non-Bt cotton. Laboratory studies that compared the effect of Bt-toxin in corn in conventional systems (Saxena and Stotzky, 2001) showed that after 40 days and 50 days of exposure, there was no statistically significant difference in the biomass and density of the earthworm community between the conventional and non-Bt conventional system (Saxena and Stotzky, 2001; Shahid et al., 2016). In a short-term (84 days) laboratory study, Liu et al., (2009) demonstrated that biomass and numbers of a specific species of earthworm (*E.fetida*), was greater in the non-Bt-fed-earthworm community than that in the one fed on Bt-cotton leaves.

Zwahlen (Zwahlen et al., 2003) observed in the laboratory that the relative weight of earthworms decreased in the Bt-corn litter-fed earthworms after 200 days. In this experiment, the laboratory results differ from the ones in the field. In the laboratory studies, directly feeding earthworms on the leaves of Bt plants resulted in a negative effect on the biomass or the population of earthworms. Whereas in my study conducted under field conditions, this effect was diluted or buffered by other factors such as the addition of organic matter to the soil in the form of FYM.

5.5.3. Abiotic factors and correlation with earthworm biomass and density

Nitrate

The presence of earthworms in higher numbers favours the mineralisation of nitrate present in soil (Helling and Larink, 1998). Efforts in conventional agriculture have mostly been focused on the use of efficient fertilizers for increasing yield (Linquist et al., 2013). However, with the leaching of nitrate being a major hazardous risk for the environment it is also important that research focuses on a more sustainable resource of available nitrogen and the prevention of nitrate leaching. This study did not observe a relationship between earthworms and the mineralisation of nitrogen, however, studies have shown that earthworms play an important role in the mineralisation of nitrogen (Helling and Larink, 1998). Research and effort to conserve and maintain the earthworm population through sustainable farming management could prevent the runoff of nitrogen and increase available nitrogen to the plant (Bityutskii et al., 2002).

Carbon

At the plot scale, during the cotton season, less farmyard manure was applied in the conventional systems than in the organic systems. At the farm scale, organic farmers were applying farmyard manure and compost while the conventional farmers were only applying farmyard manure before sowing but were not adding compost. Studies have shown and confirmed that greater access to organic matter results in a higher earthworm density and biomass in the organic systems in comparison to conventional systems (Kale and Karmegam, 2010; Salehi et al., 2013; Scullion and Malik, 2000). Through their casts, earthworm activity promotes the carbon cycle and organic matter stabilization (Scullion and Malik, 2000), enhancing soil fertility grandly (Singh et al., 2017). Even though this study did not allow to establish a clear conclusion on the effect of organic carbon on earthworm populations, the positive effect of organic matter on earthworm biomass and density has been found in other studies in temperate climates (Mathews et al., 2001; Pelosi et al., 2009; Pfiffner and Mader, 1997; Turinek et al., 2009), and this study has shown a higher density of earthworms in the organic system.

Salinity

Previous studies have shown that the application of chemical fertilisers that occur in conventional farming can lead to an increase in soil salinity (Ikemura and Shukla, 2009). In line with the literature, this study has shown a higher salinity level in Conventional systems in comparison to both organic systems. Globally 23% of cultivated land has become saline due to the application of chemical fertilizers. Due to the excessive nitrogen application, the dissolved salts from fertilization accumulate in the soil (J. Han et al., 2015). Salinity hurts growth and reproduction as well as increases mortality of the earthworm population (Guzyte et al., 2011; Sharif et al., 2015) and has been observed to be responsible for low yield in cotton systems (Zörb et al., 2019). Reducing the use of chemical fertilisers and increasing the humic acid content of the soil, helps overcome soil salinity issues (Sharif et al., 2015; Zhang et al., 2015).

5.5.4. Limitation of the study

In my study, as more than 90% of the samples collected were juveniles, it was not possible to analyse the earthworm diversity. Kim et al., (2017) used DNA analysis to identify the earthworm diversity however, due to the complexity of this process, it was not possible to conduct it at the remote location of the field laboratory which was used. Studies have shown that to compare the difference in farming systems, sorting earthworms in a taxonomic order does not add valuable information to comparative studies (Paoletti, 1999a).

PART II: Fungal community as soil Bio-indicators to evaluate soil health

5.6. Introduction

5.6.1. What are fungi

Fungi are eukaryotic microorganisms. They are a complex group, that includes club mushrooms, bread moulds, chytrids, mycorrhizas, and sac fungi. The knowledge of fungi is still limited (Barnett and Hunter, 1998; Folli-Pereira et al., 2020). To date, 148 000 Fungi have been described (Cheek et al., 2020) but a recent estimation suggests that around 2.2 and 3.8 million fungal species are existing (Hyde et al., 2020).

5.6.2. Fungi Guild and their role in sustainable agriculture

Fungi can be categorised into three trophic modes: **decomposers, mutualists and pathogens**. They facilitate ESs that are important for agriculture such as primary production, carbon sequestration, nutrient recycling, plant protection and plant productivity (Averill et al., 2019). (Zhang and Qiu, 2020)(Zhang and Qiu, 2020)(Zhang and Qiu, 2020)(Zhang and Qiu, 2020)(Zhang and Qiu, 2020)(Zhang and Qiu, 2020). Most fungi are saprotrophic fungi, in other words, they are **decomposers**, and they can break down all kinds of organic matter from animals to plants. **Mutualist** fungi, also known as symbiotrophs, include both mycorrhizal fungi and non-mycorrhizal fungal as well as certain rhizobacteria, they exchange nutrients with the plant in exchange for energy through the roots (Rasmann et al., 2017). Endophyte symbiosis fungi live inside plants and generally have a mutualistic relationship with their hosts (Clay et al., 2014). Endophytic fungi increase growth and enhance the defence mechanism of plants (Dini-andreote, 2020). Some fungi are **pathogenic** which means that they feed on living organisms. For example, Phytopathogenic fungi are pathogenic to plants and are responsible for considerable losses to productivity in crops (Abawi and Widmer, 2000). The severity of plant disease is driven by the interaction between the host (crop), the pathogen fungi (causal agent) and the favoured environmental condition, this interaction is called the plant disease triangle (Zhang and Qiu, 2020). Farming practices that modify one of the three factors will influence the soilborne pathogen fungi development (Krupinsky et al., 2002) and can affect the productivity of the crop. Fungi that suppress and/or kill phytopathogenic fungi are called antagonists and have a positive impact on the growth and productivity of crops (Rezvani et al., 2020). They have the aptitude to improve crop yield, through a mix of complex synergy, mycoparasitism, competition, and antibiosis (Kamal et al., 2018; Verma et al., 2007). Antagonist fungi can help to suppress soilborne plant diseases and therefore the health of a system can be quantified by the fungi's ability to suppress them (Elsas et al., 2002). Other pathotroph fungi can attack animals or even other fungi and some species are used in biological pest control (Rasmann et al., 2017). In this study, Soil fungi will be identified and categorised into their guild.

5.6.3. Farming organic vs conventional

Crop protection is one of the major concerns in Indian CFS (Vennila et al., 2000). Chemical fungicides and pesticides negatively affect soil-borne pathogens but their effects on beneficial soil microflora and fauna are understudied (Abawi and Widmer, 2000; Lo, 2017).

Seeds which are treated with fungicides and pesticides have been designed to protect plants at an early stage to alleviate seed-borne pathogens (Shahbaz et al., 2018). However, they are not species-specific (Nettles et al., 2016). Indeed, there is little information on the effect of these treated seeds on the non-targeted fungal community (Mahal, 2014), including the beneficial fungi which help plant growth. Both conventional systems in this study have been using pesticides Imidacloprid coated seeds, which are not used as fungicides, since the beginning of the trial (refer to the method chapter). One of the objectives of this study has been to assess the effect of applied pesticides and pesticide-coated seeds on the fungal communities.

One of the major problems plaguing today's agricultural practices is the degradation of soil health and the application of chemical fertilizers to maintain yields (Abawi and Widmer, 2000). Like pesticides, the fungal community respond differently to chemical fertilizers (Marschner et al., 2003). Inorganic fertilizers directly affect the growth and activity of fungi, but their effect is highly species-specific (Donnison et al., 2000). One of the aims of this study has been to investigate the effect of fertilizers on the fungal community in CFS.

5.6.4. Bt crops

Bt crops produce insecticidal recombinant Cry1Ac protein, which is found in the leaves, stems and root tissue (Valldor et al., 2015). There is a possibility that this protein enters the rhizosphere and becomes an additional nutrient for the soil's microorganism community (Li et al., 2018). One of the major environmental risks is the possible effect that this protein could have on non-target organisms(Blackwood and Buyer, 2004). Bt-maize is being cultivated on 58.9 million hectares and Bt-cotton on 24.9 million hectares in the world (ISAAA, 2018). This makes the Cry protein the most "abundant recombinant protein released into agricultural soils worldwide" (Valldor et al., 2015). Non-target organisms are exposed to the Cry protein which could have a direct or indirect effect on them (Padmaja et al., 2008). By comparing the Bt-conventional managed systems with conventionally and organically managed non-Bt systems, this study attempts to understand if the systems which produce Cry protein affect fungi communities.

The majority of studies which focus on fungal communities and functionality in agricultural soil have been done in temperate climates (Averill et al., 2019). Therefore the importance to study more systems in tropical climates (Abawi and Widmer, 2000; Elsas et al., 2002). To my knowledge, there is no study done on the fungal community in a long-term trial in India.

The objectives of this study were as follows:

(1) To study the effect of long-term cotton of different farming systems on the soil fungal biodiversity and fungi guild in an Indian context.

(2) To compare the fungi communities between Bt conventional and none- Bt conventional systems.

(3) To identify key species that could be used as a bio-indicator to evaluate the health of the ecosystem.

5.7. Methodology

5.7.1. Sampling

The study was conducted at the BioRe association research centre, Madhya Pradesh, India in the long-term experiment (*See Chapter 3: Methodology*). Soil samples were taken using a soil core. 500 grams of soil were taken randomly in the 12x12m middle of each plot at a depth of 0 to 20 cm from the soil surface. On each plot, around 10 sample cores were taken. These soil cores were mixed together, dried, and sieved to 1mm and then put into labelled plastic bags. The bags were labelled according to the plot number, system and date of the sampling and kept till analysis in the freezer (-8 degree Celsius).

5.7.2. Laboratory analysis

The obtained soil samples were tested in a laboratory. 10 grams of the soil samples were mixed with 90 ml of distilled water. Afterwards, the dilution was made from 10^{-1} to 10^{-5} suspense. For each dilution, 1 ml of each dilution was poured on a separate sterile PDA (Potato dextrose agar) media then spread evenly and incubated for 7 days at room temperature. Fungi were identified with the help of Dr Regina Sharmila -who specialized in Mycology, Fungal/Molecular genetics and Mycotoxicology, Myconanotechnology, and Food and Agricultural Microbiology- from Pondicherry University (Figure 5.20).

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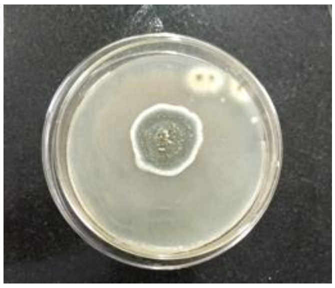

Figure 5.20: from left to right, picture 1: Dilution of a soil sample and pouring of each dilution on a PDA petri dish in a Laminar Air Flow, Picture 2: example of a soil sample 7 days after incubation of, picture 3: isolation of Trichoderma sp.

5.7.3. Statistical Analysis

To look at the functional biodiversity of the fungal community, the presence (1) and absence (0) of the fungi species were used for the analysis.

5.7.3.1. Community Assemblage

5.7.3.1.1. Primer

Non-metric dimensional scaling (NDMS) in PRIMER-E (version 7) was used to determine if there was a variation in fungi community, using a similarity matrix based on Euclidean distance. Ordination plots were inspected and where the plots suggested a pattern, ANOSIM routine (which is analogous to univariate ANOVA) was used to test for significant difference in community assemblage between the faming systems.

5.7.3.2. Biodiversity index: Species richness

Species richness was used as a measure of fungal biodiversity. Data were analysed using “plyr” package (Wickham, 2016) and “vegan” package (Oksanen et al., 2019).
“plyr” package (Wickham, 2016) allows manipulation of the data by splitting the data, manipulating them and putting them together.
“vegan” package (Oksanen et al., 2019) was created for the ecologists’ community, it contains a series of multivariate analyses commonly used to analyse ecological communities as well as other helpful functions. I used “ vegan” in R to obtain to obtain Richness’ index I used the function RICHNESS.
Species richness is a measure of the number of taxa present at a site. Sites with more taxa are considered richer- they are likely to be more complex.

5.7.4. Fungi Guild

Fungi were classified according to their guild and trophic mode using the FunGuild website. Each fungus was researched using Scopus to look at the literature and information concerning the particular fungi. Among the identified fungi, few species have been considered as indicators of soil health. Some fungi were categorised as beneficial fungi and considered as an indicator of healthy soil and others fungi were labelled as deleterious fungi and were considered indicators of poor soil (Frac et al., 2018).

5.8. Results

5.8.1. Community Assemblage

Analysis of survey data has shown that the biodynamic and organic fungal communities were closer in similarities. The same pattern occurred with the conventional and Bt-conventional community.

5.8.1.1. Primer

ANOSIM analyses revealed significant difference in species composition between the organic systems and the Bt-conventional systems (R=0.15, P<0.01), between the organic systems and conventional systems (R=0.19, P<0.01), between the biodynamic and Bt-conventional systems (R=0.32, P<0.01), between the biodynamic and conventional systems (R=0.34, P<0.01) and between the biodynamic and organic systems (R=0.03, P=0.03). The Primer analysis graph and R statistic showed a similarity between the organic and biodynamic fungal community as well as between the conventional and Bt-conventional systems (Figure 5.21, see Appendices C, Table C.60).

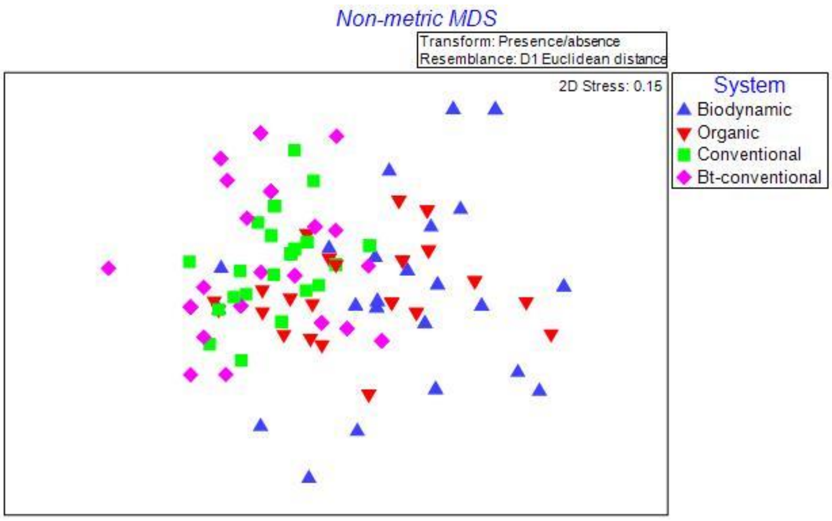

Figure 5.21: Primer analysis of the community assemblage of fungal community in four different farming systems (biodynamic, organic, conventional and Bt-conventional) on the plot-scale trial for the survey 2016 and 2017

5.8.2. Species richness

On average, biodynamic had the highest species richness of fungi diversity, followed by organic, Bt-conventional and finally conventional systems. These results have shown a significantly higher species richness in biodynamic systems in comparison to conventional systems (z=3.23, P<0.001) (Table 5.41, for details, see Appendices C: Table C.61).

Table 5.41: Descriptive statistic and summary of the results of genera linear mixed effect model comparing fungi species richness in four different farming systems (Biodynamic, organic, conventional and Bt-conventional in the plot-scale trial)

Species Richness				
Descriptive statistics			**Systems comparison**	
			Systems	**p-value**
Organic (n=34)	**Mean**	5.53	**Organic Biodynamic**	0.85
	SD	4.74		
	SE	0.81	**Organic Bt-conventional**	0.99
Biodynamic (n=35)	**Mean**	6.11		
	SD	2.40	**Organic Conventional**	0.07
	SE	0.41		
Bt-conventional (n=33)	**Mean**	5.36	**Biodynamic Bt-conventional**	0.75
	SD	1.90		
	SE	0.33	**Biodynamic Conventional**	<0.01
Conventional (n=32)	**Mean**	3.78		
	SD	1.96	**Bt-conventional Conventional**	0.12
	SE	0.35		

5.8.3. Fungi Guild in different farming systems

Symbiotroph fungi were found in the biodynamic and organic systems and none were detected in the Bt-conventional and conventional systems. The majority of the fungi found in the four different systems were pathotroph- animal pathogens (Table 5.42, **Error! Reference source not found.** 5.23).

Table 5.42: List of fungi species which have been found in the four different systems (Biodynamic, organic, conventional, Bt-conventional) and their guild (pathotroph, saprotroph, symbiotroph) during the survey done in 2018

	Guild			System			
	Pathotroph	**Saprotroph**	**Symbiotroph**	**Biodynamic**	**Bt-conventional**	**Conventional**	**Organic**
Aspergillus species	▯						
Aspergillus brasiliensis	▯			▯	▯	▯	▯
Aspergillus candidus	▯			▯			▯
Aspergillus flavus	▯			▯	▯	▯	
Aspergillus flavus columnaris	▯						
Aspergillus fumigatus	▯			▯	▯	▯	▯
Aspergillus nidulans		▯					▯
Aspergillus ochaceous	▯			▯	▯	▯	▯
Aspergillus oryzae	▯			▯		▯	
Aspergillus parasiticus	▯			▯	▯	▯	▯
Aspergillus terreus	▯			▯	▯	▯	▯
Aspergillus versicolor	▯			▯	▯		▯
Aspergillus violaceo	▯				▯		▯
Aspergillus wenti	▯			▯	▯		
Chaetomium species		▯		▯			▯
Chaetomium globosum	▯			▯			▯
Chaetomium indicum		▯		▯			▯
Cladosporium species	▯			▯	▯		▯
Cladosporium cladosperioides	▯				▯		
Cladosporium herbarum	▯				▯		
Curvularia species	▯				▯		
Curvularia lunata	▯			▯	▯		
Fusarium species	▯			▯	▯		▯
Fusarium verticillioides	▯				▯		
Helminthosporium oryzae	▯			▯	▯	▯	▯
Mucor spp		▯			▯	▯	▯
Mycelia spp				▯	▯	▯	▯
Mycelia sterilia				▯	▯	▯	▯
Paecilomyces species			▯	▯			▯
Paecilomyces lilacinus			▯	▯			
Penicillium species	▯			▯			
Penicillium chrysogenum	▯			▯			
Rhizopus species	▯			▯	▯	▯	
Trichoderma species	▯			▯	▯		▯
Trichoderma harzianum	▯			▯			▯
Trichoderma koningii	▯						▯
Trichoderma viride	▯						▯
Wild yeast				▯	▯		
Yeast				▯	▯	▯	▯

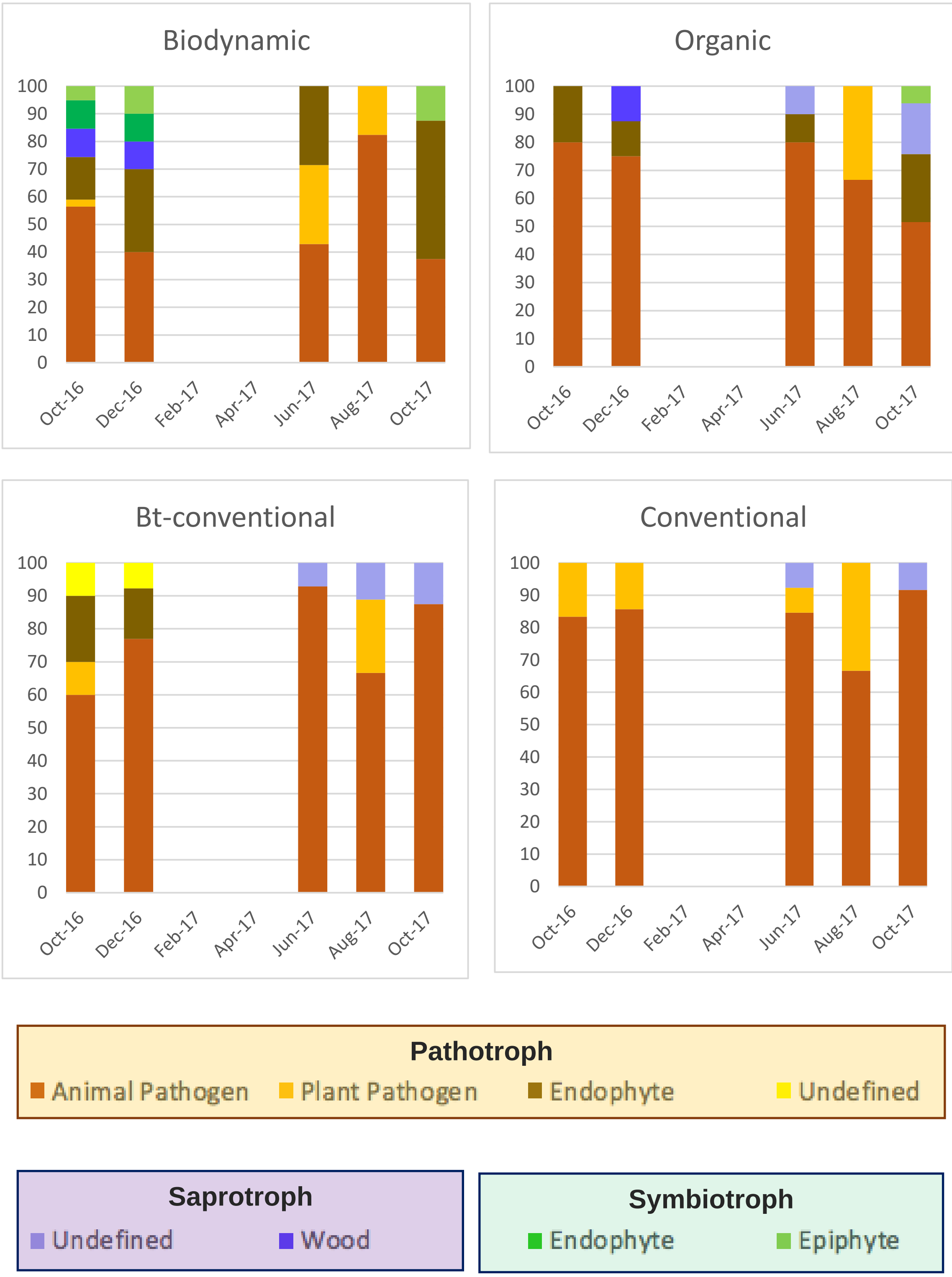

Figure 5.22: Fungi guilds and tropics modes of the fungal community in biodynamic, organic, conventional and Bt-conventional cotton farming systems on the plot-scale trial in 2016 and 2017

5.8.4. Pathotroph_*Trichoderma*

There was a significantly higher presence of *Trichoderma spp.* in the biodynamic systems in comparison to the Bt-conventional systems (z=4,24, P<0.001) and the conventional systems (z=4.51, P<0.001). There was a significantly higher presence of *Trichoderma spp.* In the organic systems in comparison to the Bt-conventional systems (z=4.53, P<0.001) and the conventional systems (z=4.80, P<0.001) systems. There was a significant higher presence of *Trichoderma spp.* In the Bt-conventional systems in comparison to the conventional systems (z=4.51, P<0.01) (**Error! Reference source not found.** 5.24, Table 5.43, for more details s ee Appendices C: Table C.62)

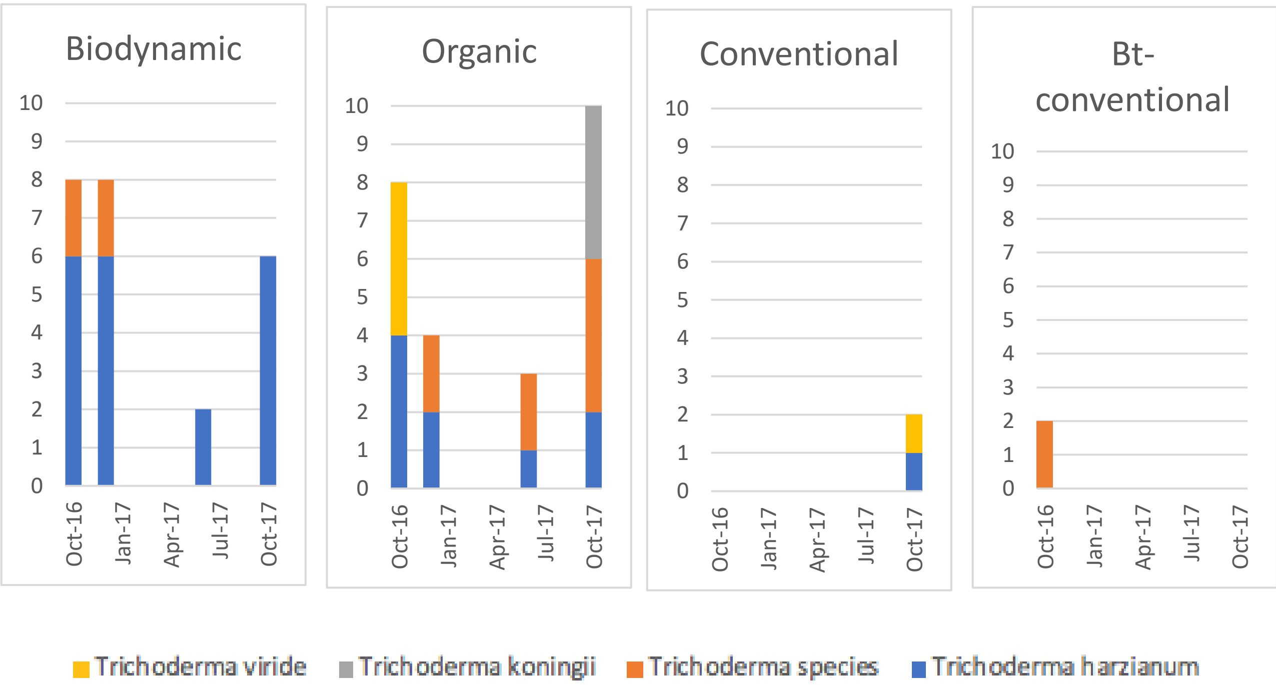

Figure 5.23: Presence of Trichoderma colonies in soil samples from the long-term management of four cotton farming systems (biodynamic, organic, conventional and Bt-conventional) during the year 2016 and 2017

Table 5.43: Descriptive statistic and summary of the results of generalised linear mixed effect model comparing the presence and absence of Trichoderma spp. (T.harzarium, T.viride, T. koningii and T.spp.)in four different farming systems (Biodynamic, organic, conventional and Bt-conventional) in the plot-scale trial during the year 2016 and 2017

Trichoderma

Descriptive statistics			Systems comparison	
			Systems	**p-value**
Organic (n=34)	**Mean**	0.74	**Organic Biodynamic**	0.99
	SD	1.02		
	SE	0.17	**Organic Bt-conventional**	<0.01
Biodynamic (n=35)	**Mean**	0.69		
	SD	0.67	**Organic Conventional**	<0.01
	SE	0.11		
Bt-conventional (n=33)	**Mean**	0.06	**Biodynamic Bt-conventional**	<0.01
	SD	0.24		
	SE	0.04	**Biodynamic Conventional**	<0.01
Conventional (n=32)	**Mean**	0.00		
	SD	0.00	**Bt-conventional Conventional**	<0.01
	SE	0.00		

5.9. Discussion

To my knowledge, this was the first study of fungi biodiversity and fungi guild done on a long-term cotton farming system trials in India.

5.9.1. Long-term effect on the soil fungal biodiversity and fungi guild

These results have shown a higher number of fungi species in both organic systems in comparison to both conventional systems. More important than biodiversity, the functional diversity was also higher in both organic systems. Symbiotroph species were found in both organic systems while none were found in both conventional one. From this study, it was not possible to determine which of the chemicals used in both conventional systems were responsible for the negative effect on the fungal community. In the discussion, I will look at studies done on the pesticides and fertilisers which were applied in the conventional to understand the effects they have on the fungi found in my study.

Imidacloprid was applied to both conventional systems against jassids and aphids. There are shreds of evidence of the negative effect of a short-term period of the applied pesticide Imidacloprid on the taxonomic structure and activity of the fungal community (Astaykina et al., 2020). However, it seems that the fungal communities can recover after some time (Devashree et al., 2014; Shu et al., 2015). In both conventional systems, seeds were treated with Imidacloprid. Seed treatment with Imidacloprid reduces the losses in yield by reducing the disease incidence (Shahbaz et al., 2018) by influencing the fungal community of the rhizosphere (Nettles et al., 2016). A study has shown that pesticide-treated seeds increase germination and agronomic yield in a short-term study (Mahal, 2014) while on the other side, a mid-term study (3 years) has not shown clear benefits on growth and yield (Nettles et al., 2016). However, this finding was not entirely clear in my study due to the other inputs that were applied in the different farming systems. Therefore, more research should be done on this specific aspect to confirm this hypothesis.

A study has shown that the systematic nature of pesticides (such as Imidacloprid) affects the endophyte fungal community (Nettles et al., 2016). This study has shown no presence of endophyte fungi in both conventional systems when it was present in both organic systems. Endophyte fungi play an important role in protecting plants from biotic and abiotic stresses (Schmidt et al., 2019). Even if the mechanism is not known, there are pieces of evidence of the role of fungal endophytes to help plants to be drought tolerant (Clay et al., 2014; Rodriguez, 2004). Cotton crops require a lot of water and their yield depends on the amount of rainfall it receives every season (Chapagain et al., 2005). Due to climate change, it is well known that the frequency of extreme weather patterns is going to increase (Mirza, 2003). By having a higher number of endophyte fungi present in the soil, organic systems are more adapted to face environmental stresses, making these systems more sustainable in a long term.

Chemical fertilisers as well as compost were applied to the conventional systems while only compost was applied to the organic systems (see methodology chapter). It is known that inorganic fertiliser reduces the growth of mycelium while organic fertiliser increases it (Gryndler et al., 2006). Organic fertilisers provide energy for the growth and reproduction of the fungal community (Vries et al., 2015). Adding compost to the crop helps the proliferation of antagonist fungi by providing an ideal substrate (Raviv et al., 1998). Wilt diseases such as verticillium have been reported to be a major problem in cotton crops (Lang et al., 2012) and therefore compost could indirectly help reduced significantly wilt disease symptoms in soil (Lang et al., 2012). The organic amendment has been proposed as a strategy to manage soil-born pathogens (Bonanomi et al., 2010) as it seems that a higher number of manure amendments decreased the relative abundance of Fusarium (Ding et al., 2017).

In contrast, inorganic fertilisers reduce fungal activities in agricultural soils (Ding et al., 2017; Gryndler et al., 2006; Schmidt et al., 2019). This corresponded to the results of this study. The less impacted fungi seem to be the saprotrophic fungi (almost unaffected) (Gryndler et al., 2006). This study confirmed the importance of the organic matter in the soil (Magdoff and Van Es, 1992) in helping increase the biological diversity such as fungal communities (Abawi and Widmer, 2000) and indirectly contributing to the lessening of soil-borne pathogens.
From the earthworm’s study, I observed that the salinity was significantly higher in both conventional systems in comparison to both organic systems. The application of fertilisers increases soil salinity (J. Han et al., 2015). Salinity can decrease microorganism activity by inhibiting enzymes which are catalysts of the soil microorganisms’ activity (Luo et al., 2017), creating a more stressful environment for

the soil microorganisms (Yuan et al., 2007), which results in a negative effect on plant growth and microbial community (Sardinha et al., 2003; Yuan et al., 2007). This could be another one of the factors which explain the lower fungal biodiversity in both conventional CFS.

5.9.2. Long-term effect of Bt-conventional on the fungal community

There was no significant difference between the Bt-conventional and conventional cotton systems, which means that the fungal community did not respond to the presence of *Bacillus thuringiensis* protein in the soil which is in agreement with previous research (Li et al., 2018). The rhizosphere during the growing stage releases a very small quantity of Cry protein and very little enters the soil (Saxena et al., 2002). It could be that there is not enough protein released in the soil to affect the fungal community (Valldor et al., 2015). The majority of sources of Bt toxin come from the dead plant biomass, such as leaves that fall during plant growth as well as the crop residue left in the field after harvest (Padmaja et al., 2008). In the systems studied (as well as the local cotton fields), the practice is to uproot the entire plant and remove it from the field, leaving behind very few sources for Bt toxin to enter the soil. However, the Bt toxin can remain in the soil and especially in more clayey soil, where they bind directly to clay particles (Crecchio and Stotzky, 2001), they do not get degraded and their insecticidal activity remains (Tapp and Stotzky, 1998). Enzymes present in the soil can degrade the Cry1Ab and utilize it like any other protein (as a carbon source). The protein is then degraded and used as a source of carbon like any natural protein (Valldor et al., 2015). The Cry protein is highly unstable in soil water and quickly degraded in the soil aqueous phase, therefore, Cry protein is hardly detected in the soil even after many years of cultivating Bt-crops (Baumgarte and Tebbe, 2005). The studied area received a high flow of rainwater and often the fields get flooded during monsoons. The weather pattern, the type of soil and the chemical proprieties of the Cry protein could explain the non-responses of the fungal communities in Bt-conventional cotton systems in comparison to the non-Bt conventional systems in this study.

5.9.3. Using key species as a bio-indicators

By looking at the diverse functional groups of fungi which are dominantly present in different farming systems, it is possible to assess the soil and plant health (Elsas et

al., 2002; Frac et al., 2018). Microorganism communities are affected by farming management and cropping history (Schmidt et al., 2019), therefore the importance of assessing the consequences of long-term farming practices is paramount.
This study has shown that species richness was higher in both organic systems in comparison to conventional systems. Fungi species composition and species richness play an important role in plant productivity (van der Heijden et al., 1998) as it is known that a more diverse community contributes to the maintenance of ecosystem functioning (Zhang et al., 2007). However, to evaluate the health of the soil, assessing fungal biodiversity cannot be restricted to the determination of biodiversity indexes (Frac et al., 2018). Functional biodiversity has been considered a more sensitive indicator of agricultural sustainability than the generic biodiversity of edaphic communities (Heemsbergen et al., 2004).

Trichoderma which is one of the most studied genera of fungi in agriculture has been categorized as an antagonist fungal agent (Calistru et al., 1997). *Trichoderma* had a significantly higher presence in biodynamic and organic systems in comparison to Bt-conventional and conventional systems which is in agreement with previous studies (Ding et al., 2017). A significantly higher presence of *Trichoderma* in both organic systems means that these systems are better prepared to fight soil-borne pathogens associated with cotton seeds such as *Fusarium oxysporum f. sp. vasinfectum, Colletotrichum gossypii, C. g. var. cephalosporioides, Rhizoctonia solani, Alternaria spp., Aspergillus spp.* and *Penicillium spp.* (Ferreira de Lima Cruz et al., 2020). In 2011, *T.viride* was applied once in the organic and biodynamic systems and could have helped increase the population of existing *Trichoderma sp*. in the soil. The presence of *Trichoderma sp.* incited cotton plants to be more resistant to plant pathogens (Gajera et al., 2020). *Trichoderma* inhibits the growth of pathogenic fungi through parallel appressed growth with the pathogen’s hyphae as well as coiled around them (Mortuza and Ilag, 1999). As they are highly competitive and can fight and eliminate plant pathogens, *Trichoderma* is used as a biocontrol against fungal disease and has been used as an indicator of healthy soil (Frac et al., 2018). For example, *T.koningi* and *T.viride* have been observed to exhibit the growth of the cotton seed rotting pathogen *Rhizotonia solani* while *T.harzianum* has been observed to form inhibition zones (Gajera et al., 2020). Recently, the microbiolization of seeds with *Trichoderma* has been proven to be more efficient than the chemical treatment at the early stage of seedling growth in cotton culture (Ferreira de Lima Cruz et al., 2020). For a more sustainable way of controlling disease, using microbiolization of seeds with *Trichoderma* as an alternative to pesticide and fungicide-coated seeds should be explored.

5.10. Conclusion of this chapter

5.10.1. Assessing the long-term effect of farming systems on soil biota

This study has shown that both soil biota from two different taxonomic groups has been negatively impacted by conventional system management in comparison to organic system management. In the first part of the study, earthworms are a good indicator of soil fertility and more broadly of the health of a farming system (Andriuzzi et al., 2016; Suthar, 2009) by showing significantly a higher abundance and biomass in both organic systems in comparison to both conventional systems. Similarly, in the second part of the study, the fungal communities have shown to be significantly different between both conventional and organic systems. This study clearly has shown a lower diversity and abundance in both conventional systems in comparison to both organic systems.

It is still unclear if these results are due to the applied fertilisers or applied pesticides. Previous studies suggested that pesticide-coated seeds and a reduced amount of applied compost could be the main cause of a lower diversity in conventional farming systems (Gunstone et al., 2021). These results conclude that conventional systems managements are a clear threat to soil organisms. Loss of soil biodiversity due to agricultural intensification can reduce by around 60% soil ESs (Veresoglou et al., 2015) and as consequence reduce the sustainability of farming systems.

5.10.2. Comparing the long-term effect of soil biota between Bt conventional and none- Bt conventional systems

As laboratory studies have shown different results in comparison to on-field studies (Helling and Larink, 1998; Zwahlen et al., 2003), more farm-scale research is needed to understand the long-term effects of Bt-crops on soil biodiversity in farm conditions. To quantify the effect of Bt-toxin under field conditions, it was important to differentiate between the effect of biomass inputs on soil and the effect of Bt toxin. From both studied taxonomic groups, the results have shown that there is no significant difference in the long-term systems between standard conventional and Bt-conventional cotton systems. One hypothesis could be that the quantity/concentration of *Bacillus thuringiensis* protein present in the soil was not enough to show/have an effect on the soil biota. Indeed, the local practice of uprooting the cotton plants after harvested leaves no/very little crop residues behind, reducing the chance for the Bt protein to infiltrate the soil. This study has not measured the quantity of Bt protein present in the soil. The quantity of Bt-protein present in the soil should be measured to confirm that in the field study, Bt-conventional systems do not significantly affect the soil biota in comparison to non-Bt-conventional systems.

In this study, earthworm biomass and density have shown to be easy to monitor and cost-effective when it comes to assessing using comparative study if one system is "better" than another one. Earthworm biomass and density will be used as ecological indicators in the assessment of sustainability. The presence and absence of *Trichoderma* have shown to be a good indicator of the health of the soil. Indeed, *Trichoderma* which has been one of the most studied and used commercially as a bioagent has been revealed to be a bio-indicator for the soil health of the different farming systems showing a significant difference between organic and conventional systems. Now that this study has confirmed the presence of Trichoderma in the soil ecosystem of the area at the plot-scale systems, a study focusing on identifying Trichoderma as an indicator of soil health should be explored on field-scale systems.

There are many soil organism's species and their ecology is still not fully understood. A different approach to evaluate the effect of genetically modified organisms would be to look at targeted soil functions instead of looking at biodiversity itself. Differences or changes between these soil functions would indicate that non-targeted species were affected by the transgenic crops (National Research Council, 2002).

5.10.3. Soil biota for ecological sustainability

Many studies when it comes to assessing biodiversity focus on the above organism, and therefore ecological understanding of the soil biota is still limited (Veresoglou et al., 2015). This study has attempted to increase the knowledge of the effect of CFS in tropical climates on soil biota. More studies are needed to investigate the adverse effects of agricultural management on fungi in the tropics. It is also imperative for research to focus on restoring soil habitat and on conserving soil biota to secure free

ESs (Lal, 2015). As a functional group, earthworms play a major role in the decomposition of biomass, the formation of soil and soil fertility (Kale and Karmegam, 2010). Their ability to reduce salinity-induced plant stress, their role in the mineralisation of nitrogen (Helling and Larink, 1998) and their ability to decrease carbon content in the soil (Suthar, 2007), make them valuable resources and an alternative to improve soil fertility. They modify the activity of soil microbial communities and influence the above-ground primary producers (Chaoui et al., 2003). Promoting the proliferation of species such as *Trichoderma* which is already naturally present in the soil could be a cheap and viable strategy that farmers could take on if they were made aware of it. Encouraging farmers to follow more sustainable practices could mitigate detrimental effects due to environmental stresses.

5.11. Highlights

Results

- This study **Earthworm density** and **biomass** were **higher** in both organic systems than in both conventional ones in the plot-scale systems and the farm-scale systems.
- **No** significant **difference between Bt-conventional** and **none-Bt-conventional** on the long-term trials (plot-scale systems) for **earthworm** and **fungal communities**.
- **Higher salinity** level **in** both **conventional systems** in comparison to both organic systems.
- This was the **first study of fungi biodiversity** and **fungi guild** done on a long-term cotton farming system trials in India.
- **Higher number of fungi species** in **both organic systems** in comparison to both conventional systems.
- **Symbiotroph species** were found in **both organic systems** while none were found in both conventional one.
- **Fungi species richness** was **higher** in both **organic systems** in comparison to conventional systems.
- ***Trichoderma*** had a significantly **higher** presence in **biodynamic and organic systems** in comparison to Bt-conventional and conventional systems.

Interpretation

- This study has attempted to increase the knowledge of the effect of CFS in tropical climates on soil biota.
- Studies have shown the negative effects of Imidacloprid and Monocrotophos on earthworm's biomass and fungal community. These two pesticides applied in conventional systems could be responsible for fungi's higher species richness in organic systems, the absence of symbiotroph species in both conventional systems and the higher number of Trichoderma in organic systems.

- Studies have shown that fertilisers increase the salinity in the soil, and that salinity can decrease microorganism activity.
- These results conclude that conventional systems managements are a clear threat to soil invertebrates.
- The weather pattern, the type of soil and the chemical proprieties of the Cry protein could explain the non-responses of the fungal communities in Bt-conventional cotton systems in comparison to the non-Bt conventional systems in this study.
- Due to the higher presence of soil macro- and micro-organisms, organic systems are more adapted to face environmental stresses, making these systems more sustainable in a long-term
- Earthworm biomass and density have shown to be a good ecological indicators in the assessment of soil health in CFS.
- Imperative for research to focus on restoring soil habitat and on conserving soil biota to secure the free ESs

Recommendation

- More farm-scale research is needed to understand the long-term effects of Bt-crops on soil biodiversity in farm conditions.
- Reducing the use of chemical fertilisers and increasing the humic acid content of the soil would help overcome soil salinity issues.
- Study focusing on identifying Trichoderma as an indicator of soil health should be explored on field-scale systems.
- For a more sustainable way of controlling disease, using microbiolization of seeds with *Trichoderma* as an alternative to pesticide and fungicide-coated seeds should be explored.

Chapter 6: Sustainability of cotton farming systems_ case study

Abstract

This chapter compares the socio-ecological sustainability of agriculture of 6 pairs of organic and Bt-conventional local Indian cotton systems at the farm-level. To assess the socio-ecological sustainability of these cotton farms, the FAO "measuring sustainability of cotton farming systems, a guidance framework" has been used (Soldi et al., 2019) and additionally, ecological indicators have been integrated. Overall, the results showed that organic systems achieved a higher 'sustainable performance' score than Bt-conventional systems.

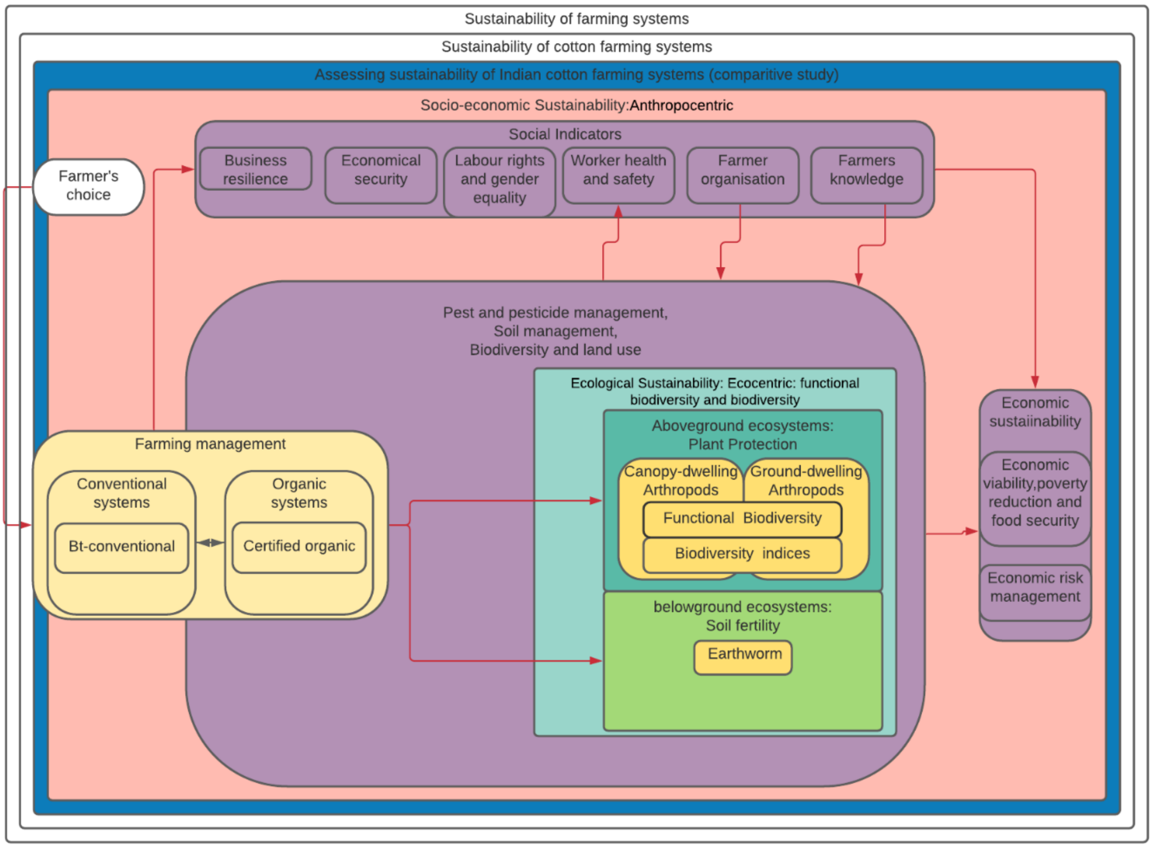

Figure 6.24:Diagram summarising the thesis

6.1. Introduction

Agriculture exists at the intersection of human and ecological systems. The complex issue of agricultural sustainability is poorly addressed by single-discipline approaches (Lescourret et al., 2015). Assessing sustainability requires an integrated framework that incorporates social, ecological and economic approaches (De Olde et al., 2016). In the introductory chapter, I defined sustainable agriculture using literature reviews and discussed the existing frameworks assessing sustainability at the farm-level. Many interdisciplinary frameworks already exist, differing in “their goal, their disciplinary background, their applicability, the temporal, social and spatial scales addressed and their conceptualization of the social and ecological systems as well as their interaction” (Binder et al., 2013). It is important to assess these systems to provide a benchmark on their sustainability. Sustainable assessments provide guidance for decision makers in understanding the effects of farming management (Ssebunya et al., 2019).

In previous chapters, the ecological dimension of cotton farming was evaluated by assessing aboveground and belowground biodiversity. Although focusing on the impact of agricultural management on biodiversity is essential to ensure a productivity that is not damaging ecosystem services it provide, there are also other essential factors which affect sustainability at the farm-level (Wittman et al., 2016). Looking at socio-economic variables that play an interconnected role in managing cotton systems is essential to assessing this sustainability as they have a major impact on activities of agricultural productivity.

Worldwide, there have been a series of initiatives and frameworks promoting and evaluating the sustainability of farming systems. Some of these have been specifically focused on nudging cotton farmers to embrace a more sustainable system.

“The Better Cotton Initiative” (BCI), is an example that currently operates in eight different countries, including India. It trains farmers to grow cotton according to its own standard of farming practices management such as use of IPM, no child labour, no discrimination, etc (De Hoop, 2018). Farmers are encouraged to assess their methods, report upon their performance, and adopt sustainable practices (BCI, 2013).

Similar to the BCI, but specific to the African continent, “Cotton made in Africa” (CmiA) is an initiative that enables farmers to produce cotton according to a sustainability standard practice of good farming management. To be able to participate in this initiative, farmers need to follow the sustainable criteria based on indicators selected by CmiA. They are directly linked to retail partners, giving them easier access to the market (CmiA, 2014, 2013).

To evaluate the sustainability of farming cotton systems frameworks such as RISE, COSA, and SAFA have been used. Response-Inducing Sustainability Evaluation (RISE) evaluates sustainability through a 508-question-interview with farmers, combined with a software-supported methodology. By 2015, RISE had monitored 220 farms in 47 different countries (HAFL, 2017). The Committee On Sustainability Assessment (COSA) was created as a business-oriented framework balanced with scientific methods. It assesses the economic, social and environmental dimensions, and was developed to measure the sustainability of the coffee sector. It is similar to the 2015 FAO guidance framework, and has a comprehensive list of quantitative and quantitative sustainability indicators (COSA, 2013).

The SAFA (Sustainability Assessment of Food and Agriculture) was developed by the FAO in 2013 to assess the sustainability of a range of farming systems. Examining methods as a comprehensive whole (FAO, 2013b) is harmonising sustainability assessments by making them more transparent and comparable (FAO, 2013b). Recent studies have used the SAFA framework to compare different systems all over the world. A comparative study has been done in Mexico (Pérez-Lombardini et al., 2021), looking at three different silvopastoral systems. It was found that native and intensified silvopastoralism achieved better sustainability performances than monocultural silvopastoralism. Conventional and certified coffee production systems in Ethiopia and Brazil have been compared using the SAFA framework (Winter et al., 2020). The study proves that an identical management system in two different countries is subject to different environmental, economic and social factors. It also emphasizes the importance of evaluating sustainability for the same crop and management system in different countries (Winter et al., 2020). SAFA was used to evaluate three Ugandan farmer groups of organic and fair trade, fair trade only, conventional/non-certified Arabica and Robusta coffee (Ssebunya et al., 2019). The data has shown that all farms performed well in the environmental and social dimension but had low scores in the governance and economic dimensions. However, certified coffee farms had a significantly higher sustainability score than non-certified farms (Ssebunya et al., 2019). Another study using the SAFA framework has compared three different banana agrosystems in Ecuador. Organic and fair-trade farms have shown to perform better in sustainability in the environmental, governance and economic dimensions while conventional farms display better outcomes in social dimension due to the size of the farms being larger than the two other systems (Bonisoli et al., 2019). To date, there is no publication using the SAFA framework to assess the sustainability of CFS.

A guidance framework, 'Measuring The Sustainability Of Cotton Farming Systems', was developed by the FAO (FAO and ICAC, 2015) using five cotton-specific programmes ("Better Cotton Initiative, Cotton made in Africa, Fairtrade cotton, Organic cotton and Australian Best Management Practices programme" (FAO and ICAC, 2015) and four broader frameworks of sustainable agriculture (SAFA, RISE, Committee on Sustainability Assessment Initiative, The Alliance for Sustainable Agriculture) (FAO and ICAC, 2015). The FAO guidance framework includes a multidimensional assessment of the social, economic and environmental themes and multi-functional perspective for sustainable agriculture (Binder et al., 2010). Similar to SAFA, the FAO guidance framework can be adapted to specific contexts, and presents and recommends "a core set of indicators" divided into eleven themes to benchmark the performance of sustainability in CFS. These indicators have been reviewed and validated by cotton systems experts. The themes are part of the three dimensions of sustainability: "pest and pesticide management, water management, soil management, biodiversity and land use, climate change, economic viability, poverty reduction and food security, economic risk management, labour rights and standards, occupational health and safety (OHS), equity and gender, and farmer organization" (FAO and ICAC, 2015). For my study, the FAO guidance framework was the most suitable model to develop and design this context-based assessment tool. To my knowledge, no publications using the FAO guidance framework to assess the sustainability of farming systems have been used at the farm-level.

ESs provided by biodiversity play an important role in ecological sustainability. Previous studies have used bio-indicators to evaluate the ecological sustainability of farming systems. In a recent literature review, Chopin et al. (2021) have identified the lack of indicators and the importance for precise indicators to evaluate the sustainable performance of farming systems. In this study I aimed to integrate indicators based on biodiversity survey into an existing assessment tool and assess the value of including them.

Objectives of this chapter

1. To develop and integrate additional biological indicators for an assessment tool based on the FAO guidance framework using a case study of Indian farms based in Madhya Pradesh.

2. To apply the tool to evaluate and compare the sustainability of two cotton farming systems in Madhya Pradesh, central India.

6.2. Methodology

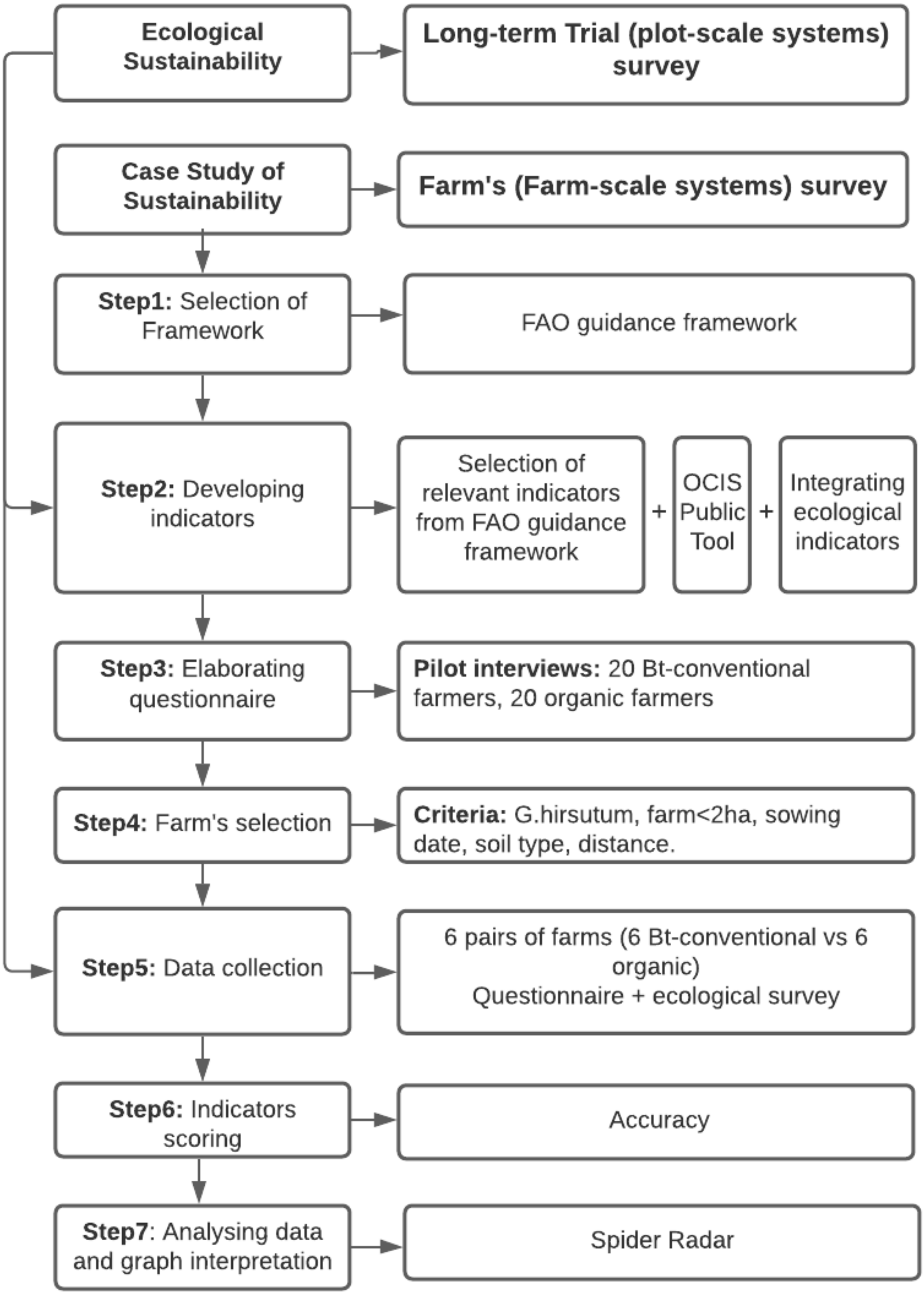

Figure 6.25: Timeline representing the procedure of assessing the sustainability with its step by step methodology

6.2.1. Conceptualizing the Application

6.2.1.1. Step 1: Selection of framework

In this study, I have used the guidance framework developed by the FAO (FAO and ICAC, 2015) model to develop and design a context-based assessment tool and compare the sustainable performance of 6 pairs of Bt-conventional and organic cotton farms. A complete explanation can be found in the FAO guidance framework(FAO and ICAC, 2015).

Previously, Local Indian cotton farms have been monitored and assessed using the FAO conceptual framework at the farm-level (Soldi et al., 2019). A monitoring tool has been designed and a list of indicators have been developed to assess the sustainability of CFS at the farm-level.

I have selected a series of frameworks using the literature available. A general research was the first step was to do a general research. I have searched the following terms: “sustainab* AND assess* AND tools”, “agricultur*” AND sustainab* AND framework”. Using the Scopus database, I have identified a set of multidisciplinary frameworks which evaluate sustainable agriculture at the farm-level. After analysis each sustainability framework, the framework developed by FAO called “measuring sustainability in cotton farming system (FAO and ICAC, 2015) was considered the most suitable model to use to develop this monitoring tool

To evaluate sustainability, the core indicators have been classified into three priority themes: Environmental, Economic and Social (FAO and ICAC, 2015).

6.2.1.2. Step2: Developing indicators

The challenge was to build an integrated assessment tool which evaluate the environment, social and economic dimensions while introducing ecological indicators to the framework. The data collected for the framework were primary data.

The FAO guidance framework comprised a total of 189 indicators. These indicators were selected through a scoring process by experts using 5 assessment criteria: “comparability, significance, conceptual logic, accessibility and accuracy” as well as 3 additional criteria (relevance, usefulness and feasibility). This list can be found in the appendices of the FAO guidance framework (FAO and ICAC, 2015). From the FAO guidance framework (FAO and ICAC, 2015), I have aggregated 44 of these indicators based on their feasibility, relevance, and applicability to these case studies. To select these 44 indicators, the first criterion was that the indicators should be relevant to the specific context of Indian cotton farmers in central India. The second criterion was that the data should be measurable at the farm-level.

In addition to this list of indicators proposed by the FAO guidance framework, I have created and added 5 extra indicators. 3 indicators were ecological indicators which can be found in the Environment and Social themes (see next section). The ecological indicators were created using the ecological surveys that were undertakenon the plot scale cotton systems. Including the ecological indicators into the framework was an important aspect to have an integrated evaluation of CFS. Most sustainability assessment tools have not involved ecological approaches (Lescourret et al., 2015). The two other added indicators which have been selected were from the OCIS public tools. They were added to the social theme of the framework (Gerrard et al., 2011).

The list of indicators was an important starting point to assess the different farming systems. The list of aggregated indicators can be found below. I have mentioned the context and the principles for each sub-theme.

6.2.1.2.1. Environment

A list of environment indicators was selected and used to evaluate the sustainability of the CFS. The indicators were divided into sub-themes: “Pest and pesticides management”, “Soil management” and “Biodiversity and land use”.

Under the sub-theme “Soil management”, I have created and added an ecological indicator to assess the soil health using earthworms as bio-indicators. In the sub-theme “Biodiversity and land use”, I have integrated an indicator based on the ecological survey of the above ground arthropod community on each farm. use arthropods as a bio-indicator to assess the ecosystem service of the biocontrol.

For the details list of questions see Appendices C: Table C.63, Table C.66 to Table C.85)

6.2.1.2.1.1. Pest and pesticide management

Context: Inadequate plant protection is the main factor responsible for the low production of cotton yield in India (Ramasundaram, 2001). Pest damage is estimated to be responsible for the loss of one-fourth of the production (Gangan, 2020). The overuse or misuse of certain pesticides have raised serious concern for human and environment health. With India being one of the biggest consumers of pesticides in the world (Bhardwaj and Sharma, 2013), plant protection plays an important role in the sustainability of farming systems.

Principles: The questions from the questionnaire were designed to quantitatively monitor the amount of pesticide and active ingredients used in the field. During the interview, farmers were asked about the name, frequency, and quantity of pesticide applied on their cotton crops. (Table 6.44)

Table 6.44: List of indicators for "Pest and Pesticide management" sub-theme, list of questions for this sub theme can be found in the appendix

1.1.Pest and Pesticide management	1.1.1. Pesticide application	Quantity of active ingredients of pesticde used (kg/ha)
		Quantity of active ingredients of highly hazardous pesticides used (kg/ha) pesticde used (kg/ha)
		Number of pesticide applications per season
	1.1.2. Action to minimise pesticide	Existence of a time-bound IPM plan
	1.1.3. Register Pesticide	The farm uses only pesticides which are nationally registered to use on cotton
		The farmer uses pesticides which are labelled according to national standards, in at least one national language
	1.1.4. Pesticide safety	The farmer uses proper disposal methods for pesticide containers and contaminated materials including discarded pesticide application equipment
		The farmer is following the national recommended practices for pesticide mixing and application and cleaning of application equipment
		The farmer has dedicated storage facilities that keep pesticides safely and out of reach of children
	1.1.5. Pesticide and health	Total percentage of cotton area involving vulnerable persons applying pesticides
		(Percentage) of workers applying pesticides that have received training in handling and use
		The Farmer has access to and uses adequate /provides to the workers/ protective equipment (by type)
		Knowledge on effect on pesticide on human

6.2.1.2.1.2. Soil management

Context: Soil depletion and degradation of soil fertility has been one of the major problems in CFS. It has been estimated that soil is being lost at 24bn tonnes a year due to agricultural land (Watts, 2017). The way farmers manage their land determinates the sustainability of soil conservation.
In 1998, a conference was held in the US to create awareness about the importance of soil organisms as bio-indicators of soil health (Doran and Zeiss, 2000). In the original framework, soil fertility and soil analysis were the two main indicators for assessing the soil health of the ecosystem. The innovative part of this sub-theme is the integration of a soil biodiversity indicator: earthworms were used as a bio-indicator to assess soil health and soil fertility.

Principles: In terms of monitoring, assessing the damage done to the soil due to land management is generally achieved by measuring the quality of soil through abiotic and biotic soil analysis. The indicators in this sub-theme used two types of methods. One part of the indicators was based on the questionnaire (applied fertilisers on the farming system). The other part of the indicators was based on the soil biotic and abiotic factors (Table 6.45).

Table 6.45: List of indicators for "Soil management" sub-theme, list of questions for this sub theme can be found in the appendix

1.2.Soil Management	1.2.1. Soil Analysis	Soil characteristics: organic matter content,
		Soil characteristics: pH
		Use of soil sampling for N, P, K
	1.2.2. Soil Fertility	Fertilizer used by type (kg/ha) - Quantity and type of fertilizer applied can provide an indication of integrated soil fertility
		Soil management
	1.2.3. Soil Biodiversity	Soil Biodiversity (earthworm survey)

6.2.1.2.1.3. Biodiversity and Land use

Context: Biodiversity plays a crucial role in maintaining the productivity of a crop farming system (FAO and ICAC, 2015). ESs play an important role in controlling pests and diseases (De Groot et al., 2002). By assessing biodiversity, it is possible to assess the ESs they provide. ES was not considered as an indicator in the original framework
Principles: This sub-theme assessed the farm in regards to crop varieties and ESs provided by the unplanned biodiversity. It included the productivity of the crop for the last three years which is linked to health of the ecosystem, as well as the crop diversity. In the previous chapter, I have surveyed biodiversity above ground including the major predators and pests of the cotton crop. In this framework, I have converted my results from the previous chapter (above ground biodiversity) to integrate it to this assessment tool. Above ground biodiversity surveys were done in Bt-conventional and organic farming systems to assess the biodiversity. After identification and statistical analysis, the main secondary recorded pests were jassids (Hemiptera:Cicadellidae: *Amrasca biguttula*) and the main predators were *C.sexmaculata* (ladybug) and Araneae taxonomic group (spider) (see chapter 4). These two natural enemies were added together. To calculate the ratio “pest: natural enemy”, the number of jassids was divided by the number of these two natural enemies. (Table 6.46)

Table 6.46: List of indicators for "Biodiversity and land use" sub-theme, list of questions for this sub theme can be found in the appendix

1.3.Biodiversity and Land use	1.3.1. Production	Average yield (tonne of cotton lint/ha)
	1.3.2. Crop diversity	Total area (ha) and % of natural vegetation converted for cotton production (ha)
		Border crops
		crops per 3-year period -crop rotation
	1.3.3. Ecosystem services	Scoring of the Ecosystem services provided by the system (above ground ratio pest:predator)

6.2.1.2.2. Economy

For the details list of questions, see appendices D: Table D.86 to Table D.91

A list of economy indicators was selected. The indicators were divided in 2 categories: "Economic viability, poverty reduction and food security" and "Economic risk management".

6.2.1.2.2.1. Economic viability and food security

Context: Once the cotton has been grown and harvested, the last step for the farmer is to obtain a fair price at the farmgate. Cotton is a cash crop and its profit margins play an important role in reducing or increasing the level of risk of poverty and food security.

Principles: This sub-theme assessed the economic viability of the cotton farming system by looking at the price received by the farmer at the farmgate. The farmers were asked about their food consumption. These indicators were transcribed into the questionnaire (Table 6.47).

Table 6.47: List of indicators for "Economic viability, poverty reduction and food security" sub-theme, list of questions for this sub theme can be found in the appendix

2.1.Economic viability, Poverty reduction and Food Security	2.1.1. Cotton economic viability	Price received per tonne of cotton lint at farmgate (last 3 years)
	2.1.2. Food security	Number of days with food deficiency per annum in cotton-producing households

6.2.1.2.2.2. Economic Risk management

Context: "Risk management is defined as the exposure to potential damage that may arise as a consequence of a present process or a future event" (FAO and ICAC, 2015). Due to the changes in international trade policy, attention given to the issues of risk management has increased. Risk management includes the yield volatility and price volatility at the farmgate taken by the farmers. The price volatility of cotton happens due to frequent fluctuation between demand and supply, weather troubles and speculation (Lima, 2011).

Principles: One of the indicators was the yield and price volatility of the cotton. Another indicator was the farmer's understanding of price volatility and his ability to manage the multiple risks he will encounter while growing his crop. This list of indicators was integrated in the interviews with farmers in a form of simple questions. The standard cotton price of the region during that year was compared to the price the farmer received for his cotton at the farmgate (Table 6.48).

Table 6.48: List of indicators for "Economic Risk management" sub-theme, list of questions for this sub theme can be found in the appendix

2.2.Economic Risk management	2.2.2. volatility	Cotton yield volatility
		Farmgate cotton price volatility
	2.2.3. Risk management	Farmer has taken measures to manage price risks
		cotton represents the largest income of the household
	2.2.4. Payment and Prices fluctuation	Average number of days after sale that farmers receive payment
		Farmer has access to equitable credit
		Farmer is showing understanding of the factors involved in price formation or with daily access to international and domestic prices

6.2.1.2.3. Social

The indicators have been divided in 6 categories: “Labour rights and gender equality”, “business resilience”, “economic security”, worker health and safety”, “farmer organisation” and “farmers knowledge”.

The two indicators “Business resilience” and “Farmer’s knowledge” were not in the original framework, and were added as part of indicators of the social aspect.

The “Business resilience” was an indicator part of the Public Goods Tool (Gerrard et al., 2011).

For the details of the list of questions, see appendices D: Table D.92 to Table D.108

6.2.1.2.3.1. Labour rights and gender equality

Context: This section looked at the issues of working conditions, employment, social protection and child labour. Often small landholder farmers are self-employed, hire members of their family and as a last option, wage employed workers.

Principles: Education of the farmers and his children information were collected. The farmer’s health facility was considered an indicator. One indicator was about child labour, according to the United Nations Convention on the Right of the Child, no children below 15 years old should be employed in the field. The two other indicators looked at aspects of employment and the difference between male and female employees. (Table 6.49)

Table 6.49: List of indicators for “Labour rights and standards" sub-theme, list of questions for this sub theme can be found in the appendix

3.1.Labour Rights and Standards	3.1.1. education	% of children of the farmer attending and completing appropriate level of school (by gender)
		Farmer's Education
	3.1.2. Health	Farmer has effective access to health care facilities
		Farmer has access to potable water
		Farmer has access to sanitation facilities
	3.1.3. employment	Number of child labourers (by age and gender)
		% of workers with an enforceable employment contract (by age and gender)
		% of workers who are paid a minimum or living wage and who always receive their full wage in time (by age and gender)

6.2.1.2.3.2. Business resilience and economic security

Context: Worldwide, Cotton brings livelihood to millions of people (Manjunath, 2004). With climate change disruption, resilient agriculture is crucial for better livelihood. Recently the Indian government has launched a pension scheme for farmers but there was a possibility that farmers were not aware about it.

Principles: The quality of life of the farmers and how he/she thinks about his/her farm and his future in agriculture were two indicators of considering agriculture a resilient business. In the interview, the farmers were asked about their pension once they decide to retired, this was considered an indicator for economic security. (Table 6.52)

Table 6.50: List of indicators for "Business resilience" and "economic security" sub-theme, list of questions for this sub theme can be found in the appendix

3.2.business resilience	3.2.1.	Quality of life
		Future expectation
3.3.economical security	3.3.1	Farmer is contributing to a pension scheme and/or eligible to receive a pension

6.2.1.2.3.3. Health and safety

Context: Agriculture is a hazardous professional sector where farmers and workers encounter double the amount of work-related risk in comparison to any other sector. Understanding the danger of chemical products used in the field as well as taking adequate prevention to maintain a safe working place is part of indicating a sustainable level of health.

Principles: Availability of sanitation and easy access to health care were part of the sub-theme list of indicators. (Table 6.51)

Table 6.51: List of indicators for "Worker health and safety" sub-theme, list of questions for this sub theme can be found in the appendix

3.4.Worker health and safety	3.4.1.	Annual non-fatal incidences on cotton farms (total, % of workforce by age, gender)
		Total number of fatalities on cotton farms per year
		Safety of the farming system

6.2.1.2.3.4. Gender equality

Context: In Indian agriculture, male and women engage in different agrarian activities. Understanding the gap of gender-based discrimination is essential to ensure sustainability.

Principles: Men and women both play important role in Indian agriculture and are often paid differently. This indicator looked at the wage difference between the two genders. (Table 6.52)

Table 6.52: List of indicators for "Gender equality" sub-theme, list of questions for this sub theme can be found in the appendix

3.5. Gender equality	3.5.1. gender equality	Gender and age wage differentials for the same quantity of produce or same type of work

6.2.1.2.3.5. Farmer's organisations

Context: In developing countries, farmers' organisations play a major role to help farmers secure a fair price, giving technical support, facilitating access to market and understanding policies.

Principles: This sub-theme looked at farmers trainings, and organisations that help them the with getting training, technical support as well as an access to the market. Improving market access is generally a key part of a farmers' organization. Farmers were interviewed and asked if they were part of an organization and how often they received training (Table 6.53).

Table 6.53: List of indicators for "Farmer organisation" sub-theme, list of questions for this sub theme can be found in the appendix

3.6.Farmer Organization	3.6.1. Farmer Organisation	Farmer has attended training (by training type, age and gender)
		Farmer is participating in democratic organizations (by age and gender)

6.2.1.2.3.6. Farmers knowledge

Context: "*Scientia potentia est: Knowledge is Power".*

A well-informed farmer has more chance to be self-sufficient, efficient and productive than a farmer with poor knowledge. Informal and formal knowledge can help the farmer thrive in his/her environment and surroundings.

Principles: This sub-theme evaluates farmers ecological knowledge, their understanding of cotton economic as well as their knowledge on the effect of pesticides. (Table 6.54)

Table 6.54: List of indicators for "Farmer organisation" sub-theme, list of questions for this sub theme can be found in the appendix

3.7.Farmers knowledge	3.7.1. Farmers knowledge	Ecological knowledge
		Farmer's education
		Farmer is showing understanding of the factors involved in price formation or with daily access to international and domestic prices
		Knowledge on effect on pesticide on human

6.2.1.3. Step 3: Elaborating questionnaire

6.2.1.3.1. Indicators converted in questions

Once the indicators were selected from the FAO list of indicators (FAO and ICAC, 2015), they were converted into a questionnaire used to interview the farmers. Overall, the indicators were collected through farmers' interviews, ecological survey and literature. For each indicator, I developed a scoring mechanism using the OCIS Public Goods tool model. The majority of the data obtained was collected directly from primary sources (farms surveyed and interviews). A few of the indicators were general indicators which were relevant at a national level, for these indicators, online research was done, generally on government websites such as Central Institute for Cotton Research (CICR) and Indian Council of Agricultural Research (ICAR).

Empirical data used to assess the biodiversity of the farm scale systems were used to create ecological indicators which were integrated into the assessment tool.

6.2.1.3.2. Interviews

The pilot questionnaire was tested by interviewing 20 organic farmers and 20 Bt-conventional farmers from the same area. Thanks to the pilot interview, the questions were rephrased to be understood by the farmer. As the interview was happening in Hindi, which is the local language spoken in the area, the questions needed to be simple and easy to translate. The interview was designed to be carried out within one hours in order not to take up too much of the farmer's time. The whole questionnaire can be found in the appendices.

6.2.1.3.3. Scoring system

Each indicator was marked with a score between 1 and 5. 1 is the lowest performance mark, indicating that the sustainability of this particular indicator was low and could be improved and 5 was the highest sustainability score. Some indicators used a combination of questions to be evaluated. When this was the case, the questions were averaged to obtain the score of the specific indicator. A detailed list of the questions can be found in the appendix.

6.2.1.4. Step 4: Farm selection and farm's criteria

Farms were selected in a two-stage process. First, a meeting with the BioRe research and extension team was organized to select farm-scale plots that matched the below criteria. Twenty pairs were selected. On-site visits were organized for these twenty pairs and they were evaluated, the six most similar pairs were selected and surveyed.

6.2.1.4.1. Organic Farmers

- The organic farmers were part of the 4000 farmers working with BioRe(website). Organic farmers receive technical support from BioRe. BioRe are facilitating the organic certification and giving the organic farmers access to the market by buying their organic cotton with a 30% bonus.
- The organic farmers were using certified organic seeds distributed by BioRe.

6.2.1.4.2. Bt-conventional Farmers

- Farmers were selected with the help of the extension team from BioRe organisation
- The Bt-conventional farmers were not part of any organisations and were farming independently.
- The Bt-conventional farmers were using genetically modified seeds.

6.2.1.4.3. Farm scale plots selection

In order to compare different farming systems at a farm-scale, farms were selected to be as similar as possible by using the following criteria:

- The 12 farm-scale plots were growing cotton *Gossypium hirsutum*, however, the varieties of the *G. hirsutum* were different.
- Farm-scale plots were less than 2 hectares each. The owners of the plots were classified as small holder farmers.
- The crops monitored were all planted as a summer cotton crops, sowing dates were between the 29th May 2018 to 10th June 2018.

- all soils were vertisol.
- The farms were situated within a maximum radius of 35km to avoid differences in weather patterns.
- The farm-scale plots were selected as pairs. Each pair included one certificated organic farm and one Bt-conventional farm. The pairs were located at a maximum distance of 200 meters from each other to minimize variation in the type of soil and it was possible to survey the pairs on consecutive days.

6.2.1.5. Step 5: Data collection

Indicators were categorised into three categories: data obtained from the farmers' interview, the empirical data collected using the ecological survey and the data gathered through literature. The performance of 6 pairs of Bt-conventional and organic systems were evaluated in 2018.

- Ecological surveys

Ecological assessment was carried out at the farm-level. The details of the surveys and the results can be found in the two previous two chapters (Chapter 4, section 4.1 and 4.2 and Chapter 5 section 5.3 and 5.4). The optimum time to collect the ecological data was from August to October which is the peak season for insect abundance. For the economic and social aspects, the interviews were carried out after the harvest of the surveyed cotton crops when farmers had time available.

- Farmers' interviews

The social and economic indicators were assessed at the farm-level, at the land holding level through farmer's interviews. The farmers of the 6 pairs of the selected farms were interviewed in December 2018 after the ecological surveys were done and once all the farmers had harvested their cotton crops and sold them at the farmgate. The farmers interviewed owned the land they farmed.

- Literature

Through literature reviews and governmental websites, national data and information about CFS were extracted and used in this questionnaire as a benchmark to rate the sustainability of some indicators.

6.2.1.6. Step 6: Indicator scoring

Accuracy was used as a rating of the quality of the indicators, including an a measure of accuracy improves the quality of data collection by assessing the precision of indicators (Steinke et al., 2017). The data which were collected without any proof were given an accuracy score of 1, and empirical data were given the highest accuracy score of 3. Not all indicators have equal values when it comes to their “trueness” and “precision” which are the two terms which have been used to describe “accuracy” by the international Organisation for Standardisation (ISO, 1994). Once the data were collected, the accuracy score was weighted in the analysis`. The indicators with an accuracy score of 1 were counted only once, the indicators with high accuracy were considering 3 times. The detailed list of indicators and their accuracy score can be found in the Table 6.55.

To check if there was a significance difference between the scoring without accuracy in comparison the scoring with accuracy, a one tailed T-test was performed.

Table 6.55: Indicators of the sustainability framework with their accuracy score based on whether the information provided was 1.low:no proof, 2.Medium:written proof, 3.High:empirical data

Theme	Sub-theme	Sub-theme	S.N.	Selected core set of indicators from FAO guidance framework	Accuracy
I.Environment	1.1.Pest and Pesticide management	1.1.1. Pesticide application	1.1.1.1.	Quantity of active ingredients of pesticde used (kg/ha)	1
			1.1.1.2.	Quantity of active ingredients of highly hazardous pesticides used (kg/ha) pesticde used (kg/ha)	2
			1.1.1.3.	Number of pesticide applications per season	1
		1.1.2. Action to minimise pesticide	1.1.2.1.	Existence of a time-bound IPM plan	1
		1.1.3. Register Pesticide	1.1.3.1	The farm uses only pesticides which are nationally registered to use on cotton	2
			1.1.3.2.	The farmer uses pesticides which are labelled according to national standards, in at least one national language	2
		1.1.4. Pesticide safety	1.1.4.1.	The farmer uses proper disposal methods for pesticide containers and contaminated materials including discarded pesticide application equipment	1
			1.1.4.2.	The farmer is following the national recommended practices for pesticide mixing and application and cleaning of application equipment	1
			1.1.4.3.	The farmer has dedicated storage facilities that keep pesticides safely and out of reach of children	1
		1.1.5. Pesticide and health	1.1.5.1.	Total percentage of cotton area involving vulnerable persons applying pesticides	1
			1.1.5.2.	(Percentage) of workers applying pesticides that have received training in handling and use	1
			1.1.5.3.	The Farmer has access to and uses adequate /provides to the workers/ protective equipment (by type)	1
			1.1.5.4.	Knowledge on effect on pesticide on human	2
	1.2.Soil Management	1.2.1. Soil Analysis	1.2.1.1	Soil characteristics: organic matter content,	3
			1.2.1.2.	Soil characteristics: pH	3
			1.2.1.3.	Use of soil sampling for N, P, K	2
		1.2.2. Soil Fertility	1.2.2.1.	Fertilizer used by type (kg/ha) - Quantity and type of fertilizer applied can provide an indication of integrated soil fertility	1
			1.2.2.2.	Soil management	2
		1.2.3. Soil Health	1.2.3.1.	Soil Bio-indicator: earthworm diversity	3
	1.3.Biodiversity and Land use	1.3.1. Production	1.3.1.1.	Average yield (tonne of cotton lint/ha)	2
		1.3.2. Crop diversity	1.3.2.1.	Total area (ha) and % of natural vegetation converted for cotton production (ha)	1
			1.3.2.2.	Border crops	1
			1.3.2.3.	crops per 3-year period -crop rotation	1
		1.3.3. Ecosystem services	1.3.3.1.	Scoring of the Ecosystem services provided by the system (above ground ratio pest:predator)	3

2. economy	2.1.Economic viability, Poverty reduction and Food Security	2.1.1. Cotton economic viability	2.1.1.1.	Price received per tonne of cotton lint at farmgate (last 3 years)	2
		2.1.2. Food security	2.1.2.1.	Number of days with food deficiency per annum in cotton-producing households	2
	2.2.Economic Risk management	2.2.2. volatility	2.2.2.1.	Cotton yield volatility	2
			2.2.2.2.	Farmgate cotton price volatility	2
		2.2.3. Risk management	2.2.3.1.	Farmer has taken measures to manage price risks	2
			2.2.3.2.	cotton represents the largest income of the household	2
		2.2.4. Payment and Prices fluctuation	2.2.4.1.	Average number of days after sale that farmers receive payment	2
			2.2.4.2.	Farmer has access to equitable credit	1
			2.2.4.3.	Farmer is showing understanding of the factors involved in price formation or with daily access to international and domestic prices	2
3. Social	3.1.Labour Rights and Standards	3.1.1. education	3.1.1.1.	% of children of the farmer attending and completing appropriate level of school (by gender)	2
			3.1.1.2.	Farmer's Education	2
		3.1.2. Health	3.1.2.1.	Farmer has effective access to health care facilities	2
			3.1.2.2.	Farmer has access to potable water	2
			3.1.2.3.	Farmer has access to sanitation facilities	2
		3.1.3. employment	3.1.3.1.	Number of child labourers (by age and gender)	1
			3.1.3.2.	% of workers with an enforceable employment contract (by age and gender)	1
			3.1.3.3.	% of workers who are paid a minimum or living wage and who always receive their full wage in time (by age and gender)	1
	3.2.business resilience	3.2.1.	3.2.1.1.	Quality of life	2
			3.2.1.2.	Future expectation	2
	3.3.economical security	3.3.1	3.3.1.1.	Farmer is contributing to a pension scheme and/or eligible to receive a pension	3
	3.4.Worker health and safety	3.4.1.	3.4.1.1.	Annual non-fatal incidences on cotton farms (total, % of workforce by age, gender)	1
			3.4.1.2.	Total number of fatalities on cotton farms per year	3
			3.4.1.3.	Safety of the farming system	1
	3.5. gender equality	3.5.1. gender equality	3.5.1.1.	Gender and age wage differentials for the same quantity of produce or same type of work	1
	3.6.Farmer Organization	3.6.1. Farmer Organisation	3.6.1.1.	Farmer has attended training (by training type, age and gender)	2
			3.6.1.2.	Farmer is participating in democratic organizations (by age and gender)	2
	3.7.Farmers knowledge	3.7.1. Farmers knowledge	3.7.1.1	Ecological knowledge	2
			3.7.1.2.	Farmer's education	3
			3.7.1.3.	Farmer is showing understanding of the factors involved in price formation or with daily access to international and domestic prices	2
			3.7.1.4.	Knowledge on effect on pesticide on human	2

6.2.1.7. Step 7: Interpretation of graphs and results

The results were presented in a radar graph:

The graph represented the average of the assessment tool of the 6 Bt-conventional systems and 6 Organic systems surveyed including the ecological indicators.

Statistical analysis

- The significant difference between including and excluding the added ecological indicators to the overall sustainability framework has been tested using the t-test function in R studio.
- Correlation method computed the correlation between the rank of dataset including the accuracy adjustment and the rank of dataset excluding the accuracy adjustment on Rstudio using the function `cor.test()` to obtain the correlation coefficient, the R square and the p-value using the spearman's rank correlation coefficient.

6.3. Results

6.3.1. Farmer’s profiles

Information collected during the interview which have not been used for the sustainable indicators has been put in a summary table which gives information about the interviewed farmers. (Table 6.56)

Table 6.56: Farmer's profiles

		Bt-conventional farmers						Organic farmers					
	S.N	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	O1	O2	O3	O4	O5	O6
Farmer's information	**Age**	23	33	35	35	58	34	35	32	50		52	60
	Sex	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male	Male
	Village	Sadalee	JaoDa	Bable	Kakivada	Balsamadh	Satrati	Sadalee	JaoDa	Bable	Kakivada	Balsamadh	Satrati
	Cotton area	1.5	2	4 ac	4.5ac	2.87	2ac	1.5	3.5	1.5	2	4.5	4.6
	Status	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner	Land owner
Education	**Education of the farmer**	8th	7th	MA in hindi litterature	BA	11th	5th	5th	4th	master in Social Ayurverdic	4th	6th	6th
	Education of the Children (girl)	(3years)	11(7th), 8(3rd), 2		19, 17 (studying)	38,36,34,32 (all master)	8 (3rd), 15(8th), 12 (8th)	18 (9th)	13 (9th)	21 (MBA)	37 (Ba), 28 (Ba)	32 (MA)	40,38,36
	Education of the Children (boy)	(3months)	10 (5th)	9 (4th), 6 (1st)		30 (Master)	10(3rd)	16(9th), 14(9th)	12 (6th), 9 (4th)	24 (12th)	35 (10th), 30 (12th)	30 (10th), 34 (BSc.Medecine)	30 (Ba.com)
Assets	**Bullock**	2	2	0	2	2	1	4	0	0	2	2	2
	Male buffaloes	2		0	0	0	0	4	0	0	0		2
	Cows	1	1	0	1	2	0	15	4	1	2	2	2
	Female buffaloes	5		0	2	1	1	0	0	0	0	1	1
	Others (Bakri)	10	3	0	4	0	4	15	0	0	0		0
	Milk being sold per day	5	0	0	13	0	3	9	0	0	0	0	2
	Machinery	none	Tractor, cultivator,rotavator,shredder	none	tractor (2), rotavator	none	mini tractor	tractor	none	none	none	none	Tractor, trally, rotavator and cultivator (45HP)
Others	**Activity apart from farming**	Farming,selling milk	Renting out a tractor, having a small hotel, farming	farming, selling others milk	Teacher	restaurant	NA	NA	NA	Ayurvedic doctor	NA	Shop	NA

6.3.2. Indicator scoring

There was no significance difference between the scoring methods with and without the accuracy coefficient (T-test results, Figure 6.3). Therefore, to simplify the results, only the scoring without accuracy will be taken in consideration in the results of the study (Table 6.57).

Table 6.57: Average sustainability scoring given to the organic and Bt-conventional systems (farms and farmers) using the indicators without and with accuracy. The survey was done in 2018.

Sustainable scoring			
Systems	**Indicators**	**Without accuracy coefficient**	**With accuracy coefficient**
Bt-conventional systems	1.1.Pest and Pesticide management	3.3	3.24
	1.2.Soil management	3.14	3.08
	1.3.Biodiversity and Land use	2.11	2.31
	1.Environment	2.98	3.01
	2.1. economic viability,poverty reduction and food security	4.5	4.5
	2.2. economic risk management	3.44	3.47
	2. economy	3.67	3.71
	3.1. labour rights and gender equality	2.23	2.69
	3.2. Business resilience	4.56	4.56
	3.3. Economical security	2.67	2.67
	3.4. Workers safety and health	4.89	4.91
	3.5. Farmers organisation	1.38	1.38
	3.6. Farmers knowledge	2.53	2.68
	3. Social	3.26	3.37
Organic systems	1.1.Pest and Pesticide management	4.46	4.51
	1.2.Soil management	3.42	3.26
	1.3.Biodiversity and Land use	3.33	3.25
	1.Environment	3.96	3.88
	2.1. economic viability,poverty reduction and food security	5	5
	2.2. economic risk management	3.51	3.55
	2. economy	3.84	3.89
	3.1. labour rights and gender equality	2.73	3.11
	3.2. Business resilience	4.39	4.39
	3.3. Economical security	1.67	1.67
	3.4. Workers safety and health	4.83	4.81
	3.5. Farmers organisation	3	3
	3.6. Farmers knowledge	3.22	3.33

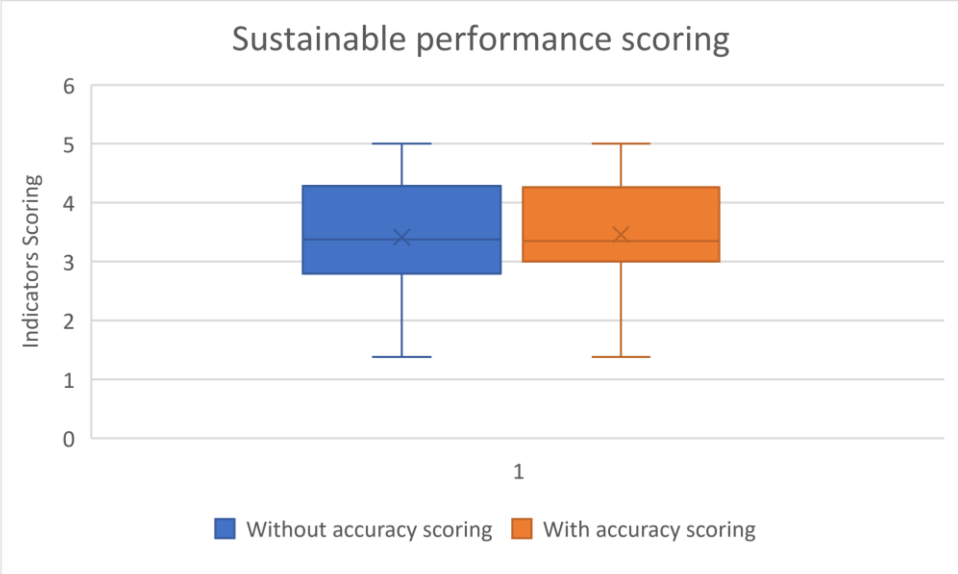

Figure 6.26: Differences in sustainable indicators scoring between the indicators used without accuracy scoring and with accuracy scoring. The P value gives the chance of equal mean obtained from Student's t test (P-value= 0.43, df=54).

6.3.3. Environment

6.3.3.1. Pest and Pesticide Management

For the "pesticide application" indicators, organic systems do not use chemical pesticides; they were using biopesticides and therefore, organic farms had the highest sustainable performance score possible of 5. For the "registered pesticide", all the chemicals used in the Bt-conventional systems were registered by the government. For "pesticide safety", Bt-conventional farmers were applying pesticides with instructions given by the shopkeepers without knowledge concerning the national recommended practices. Organic farmers were following the recommendation given by the BioRe team for the application of the bio-pesticide.

For the indicators "pesticide and safety", Bt-conventional farmers and their labourers who were applying pesticide were wearing long shirts to protect them, they were not wearing PPE as per recommendations. Knowledge on the effect of pesticides on the health of human being were not fully understood by the organic and Bt-conventional farmers (Table 6.60, Table 6.55).

Overall, for the indicators "pest and pesticide management", organic systems received a sustainable performance score of 4.62 and Bt-conventional systems received a sustainable performance score of 3.24. Pest and pesticide management indicators from organic systems were shown to significantly (n=12, p<0.01) performed better than Bt-conventional systems (Table 6.60, *Table 6.* 61).

6.3.3.2. Soil Management

Overall, for the indicators “Soil management”, organic farmers received sustainable performance score of 3.42 when Bt-conventional farmers received sustainable performance score of 3.14. Soil management indicators from organic systems (n=12, p=0,04) were shown to significantly performed better than Bt-conventional systems (Table 6.60, *Table 6.* 61).

6.3.3.3. Biodiversity and Land Use

For the indicators “production”, organic farmers had a better average yield in comparison to Bt-conventional farmers. For the indicators “Crop diversity”, both organic and Bt-conventional farmers had converted 100% of the previous natural vegetation to grow cotton. Few Bt-conventional farmers had border crops whereas 100% of the organic farmers had border crops. For the indicators “Ecosystem services”, Bt-conventional and organic systems both have their ratio “Pest: Natural enemy” above the general threshold. During the last survey, Bt-conventional systems had their ratio “Pest: Natural enemy” ten times above the general threshold giving them a lower scoring than organic systems (Table 6.58, Table 6.59).

Overall, for the indicators “Biodiversity land use”, organic farmers received a sustainable performance score of 3.33 when Bt-conventional farmers received a sustainable performance score of 2.11. Biodiversity and land use indicators from organic systems (n=12, p<0.01) were shown to significantly perform better than Bt-conventional systems (Table 6.60, *Table 6.* 61).

Table 6.58: “Pest: Natural enemy” ratio in two farm-scale farming systems in 2018

	Jul-18	**Aug-18**	**Sep-18**
Bt-conventional	9.9:1	2.9:1	19.5:1
Organic	6.5:1	3.4:1	6.8:1

Table 6.59: Converting Pest: Natural enemy ratio into scoring to evaluate each farming system with 2016,2017 and 2018 dataset (Rating score: below jassids threshold level (1:5):5, between the jassids and general threshold level:4, above general threshold level:2, ten times above the threshold level:1)

2018	May	June	July	August	September	October	November	December	Average
Bt-conventional	-	-	2	2	1	-	-	-	**1.67**
Organic	-	-	2	2	2	-	-	-	**2.00**

6.3.3.4. Environment indicators summary

Organic systems received a sustainable performance score of 3.79 taking in consideration the added ecological indicators. Organic systems received a sustainable performance score of 2.83 with the ecological added indicators. Overall, the environment indicators have shown that organic systems (n=12, p<0.01) in comparison to Bt-conventional systems have scored a significantly higher score in sustainability (Table 6.60, Table 6. *61*, Figure 6.27).

6.3.4. Economy

6.3.4.1. Economic viability, poverty reduction and food security

“Cotton economic viability” was the highest (5) for the organic systems as farmers were receiving a bonus due to the organic certification in addition to the normal price of the cotton at the farmgate.

The indicator “food security” was the highest for both Bt-conventional and organic systems as farmers were eating to meet with their needs.

Overall, for the indicators “economic viability, poverty reduction and food security”, organic systems (n=12, p=0.04) got the highest sustainable achievable score (5) and were significantly more sustainable than Bt-conventional systems (Table 6.60, *Table 6. 61*).

6.3.4.2. Economic risk management

For “Volatility”, results have shown that Bt-conventional systems yield (3.20) and price (4.75) were slightly more volatile than organic systems, respectively 3.67 and 4.83.

For the indicator “risk management”, in Bt-conventional systems, often farmers were practising other activities apart from farming which made cotton farming a secondary income when organic farmers were farming cotton as their main income activity.

For the indicator “Payment and prices fluctuation”, both Bt-conventional systems and organic systems had received payment shortly after selling their cotton at the farm gate. According to the results, organic farmers had a better understanding of the factors which are involved in price formation.

Overall, for the indicators “Biodiversity land use”, organic farmers received a sustainable performance score of 3.51 and Bt-conventional farmers received a sustainable performance score of 3, making the sustainable performance score very similar for both systems in the economic scoring indicators of the sub-theme “economic risk management” (Table 6.60).

6.3.4.3. Economic indicators summary

Overall, the data have shown that organic systems in comparison to Bt-conventional systems have scored a slightly higher sustainable performance score for the economic risk management indicators combined together but not significant. Organic systems received a sustainable performance score of 3.51 when Bt-conventional systems received a score of 3.44 (Table 6.60, Table 6. 61, Figure 6.27).

6.3.5. Social

6.3.5.1. Labour Rights and gender equality

For "Employment", my results have shown that Bt-conventional farmers hire children more often than organic farmers. None of the workers on the farms had a contract. For the indicators "Gender equality", All women workers were paid a lower daily wage than the men. All the children of the farmers, girls and boys were attending school. There was no significant in between the sustainable performance core between the two systems (Table 6.60, Table 6. 61).

6.3.5.2. Business resilience

For "Business resilience ", which was an added indicator to the framework, there were no significant differences between the Bt-conventional and organic systems (Table 6.60, *Table 6.* 61).

6.3.5.3. Economic security

For "economic security", organic farmers were older than the Bt-conventional farmers and therefore only few of the organic farmers were eligible to receive a pension. There were no significant differences between the Bt-conventional and organic systems (Table 6.60, Table 6. 61).

6.3.5.4. Worker health and safety

For "worker's safety", both of the cotton farming system obtained a similar sustainability score as there was no significant difference between the safety of the farm and the access to health care facilities (Table 6.60, Table 6. 61).

6.3.5.5. Farmers organization

For “farmer’s organisation” Bt-conventional farmers obtained a very low sustainability score as they were not part of any organisation in comparison to the organic farmers who were part of the BioRe organisation. There was a significant difference between the Bt-conventional and organic systems ($n=12, p<0.01$) (Table 6.60, Table 6. 61).

6.3.5.6. Farmers’ knowledge

For “farmer’s knowledge”, my results have shown that organic farmers had better ecological knowledge than Bt-conventional farmers. The type of farming did not make a difference to the farmers’ education as both systems obtained the same sustainability score to farmer’s education. Organic farmers had a better understanding of the fluctuation of the cotton price and a better understanding of the effect of pesticides on human health. There were no significant differences between the Bt-conventional and organic systems (Table 6.60,Table 6. 61).

6.3.5.7. Social indicators summary

Overall, my results have shown that there was a significant difference in between the social sustainability of the organic systems in comparison to Bt-conventional. Organic systems received a sustainable performance score of 3.18 and Bt-conventional systems received a sustainable performance score of 2.84 (Figure 6.27).

6.3.6. Overall sustainability

Overall, the organic cotton farming systems ($n=12$, $p<0.01$) received a significantly higher performance score than Bt-conventional systems (Table 6.60, Table 6. 61).

Table 6.60: Scores from 6 pairs of Bt-conventional and organic cotton farming systems with standard deviation and means from a survey carried out in 2018, in Madya Pradesh)

	Bt-conventional systems									**Organic systems**								
Sustainable Indicators	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**Means**	**Standard Deviation**	**Standard Error**	**O1**	**O2**	**O3**	**O4**	**O5**	**O6**	**Means**	**Standard Deviation**	**Standard Error**
1.1.Pest and Pesticide management	3.10	2.77	2.82	4.02	3.58	3.21	3.24	0.48	0.20	4.27	4.39	4.77	4.77	4.68	4.82	4.62	0.23	0.09
1.2.Soil management	3.03	3.43	3.07	2.68	3.37	3.27	3.14	0.28	0.11	3.17	3.21	3.69	3.30	3.47	3.67	3.42	0.23	0.09
1.3.Biodiversity and Land use	2.00	2.63	2.10	2.63	1.83	1.47	2.11	0.46	0.19	3.30	3.70	2.90	3.40	3.30	3.40	3.33	0.26	0.11
1.Environment	2.85	2.90	2.73	3.40	3.16	2.85	2.83	0.25	0.10	3.75	3.91	4.05	4.06	4.04	4.18	3.79	0.15	0.06
2.1. Economic viability,poverty reduction and food security	5.00	5.00	4.00	4.00	5.00	4.00	4.50	0.55	0.22	5.00	5.00	5.00	5.00	5.00	5.00	5.00	0.00	0.00
2.2. Economic risk management	3.29	3.19	2.39	4.05	4.00	3.38	3.44	0.61	0.25	3.57	2.57	4.24	3.14	4.24	3.29	3.51	0.65	0.27
2. Economy	3.67	3.59	2.79	4.04	4.29	3.52	3.97	0.51	0.21	3.89	3.11	4.41	3.56	4.41	3.67	4.26	0.51	0.21
3.1. Labour rights and gender equality	3.43	3.25	3.50	3.88	3.38	4.13	3.56	0.34	0.14	3.00	4.13	4.50	3.63	4.00	3.75	3.83	0.51	0.21
3.2. Business resilience	4.75	4.75	4.75	3.59	3.75	4.75	4.39	0.56	0.23	4.75	4.75	4.34	4.75	3.75	5.00	4.56	0.45	0.18
3.3. Economical security	3.00	3.00	3.00	3.00	1.00	3.00	2.67	0.82	0.33	3.00	3.00	3.00	3.00	1.00	3.00	1.67	0.82	0.33
3.4. Workers safety and health	5.00	5.00	5.00	5.00	5.00	4.33	4.33	0.27	0.11	5.00	5.00	5.00	5.00	5.00	5.00	5.00	0.00	0.00
3.5. Gender equality	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00
3.6. farmers organisations	1.25	1.25	1.25	2.25	1.00	1.25	1.38	0.44	0.18	2.00	2.00	2.50	2.50	4.50	4.50	3.00	1.18	0.48
3.7. Farmers knowledge	2.50	1.75	1.50	3.75	4.25	1.42	2.53	1.21	0.50	2.13	2.25	4.33	4.08	4.00	2.88	3.22	0.98	0.40
3. Social	3.37	3.05	3.10	3.65	3.36	3.22	2.84	0.22	0.09	3.10	3.55	3.98	3.66	3.88	3.69	3.18	0.31	0.13
Overall sustainability	**3.11**	**3.09**	**2.86**	**3.32**	**3.10**	**2.93**	3.07	0.16	0.06	**3.35**	**3.42**	**3.77**	**3.63**	**3.66**	**3.77**	3.60	0.18	0.07

Table 6. 61: Mean difference between Bt-conventional systems and organic cotton farms with degree of freedom (df), number of observations (n), F-statistic and significance (p-values).

Variables	means Bt-conventional systems	organic systems	n	df	F value	P-value
1.1.Pest and Pesticide management	3.24	4.62	12	7	4.39	<0.01*
1.2.Soil management	3.14	3.42	12	10	1.50	0.04*
1.3.Biodiversity and Land use	2.11	3.33	12	8	3.16	<0.01*
1.Environment	2.83	3.79	12	8	2.77	<0.01*
2.1. Economic viability, poverty reduction and food security	4.50	5.00	12	5	0.00	0.04*
2.2. Economic risk management	3.44	3.51	12	10	0.87	0.37
2. Economy	3.97	4.26	12	10	1.02	0.27
3.1. Labour rights and gender equality	3.56	3.83	12	9	0.43	0.18
3.2. Business resilience	4.39	4.56	12	10	1.56	0.29
3.3. Economical security	2.67	1.67	12	10	1.00	0.5
3.4. Workers safety and health	4.33	5.00	12	5	0.00	0.18
3.5. Gender equality	1.00	1.00	12	NA	0.00	NA
3.6. farmers organisations	1.38	3.00	12	6	0.14	<0.01*
3.7. Farmers knowledge	2.53	3.22	12	10	1.52	0.13
3. Social	2.84	3.18	12	9	0.50	0.03*
Overall Sustainability	3.07	3.6	12	10	0.78	<0.01*

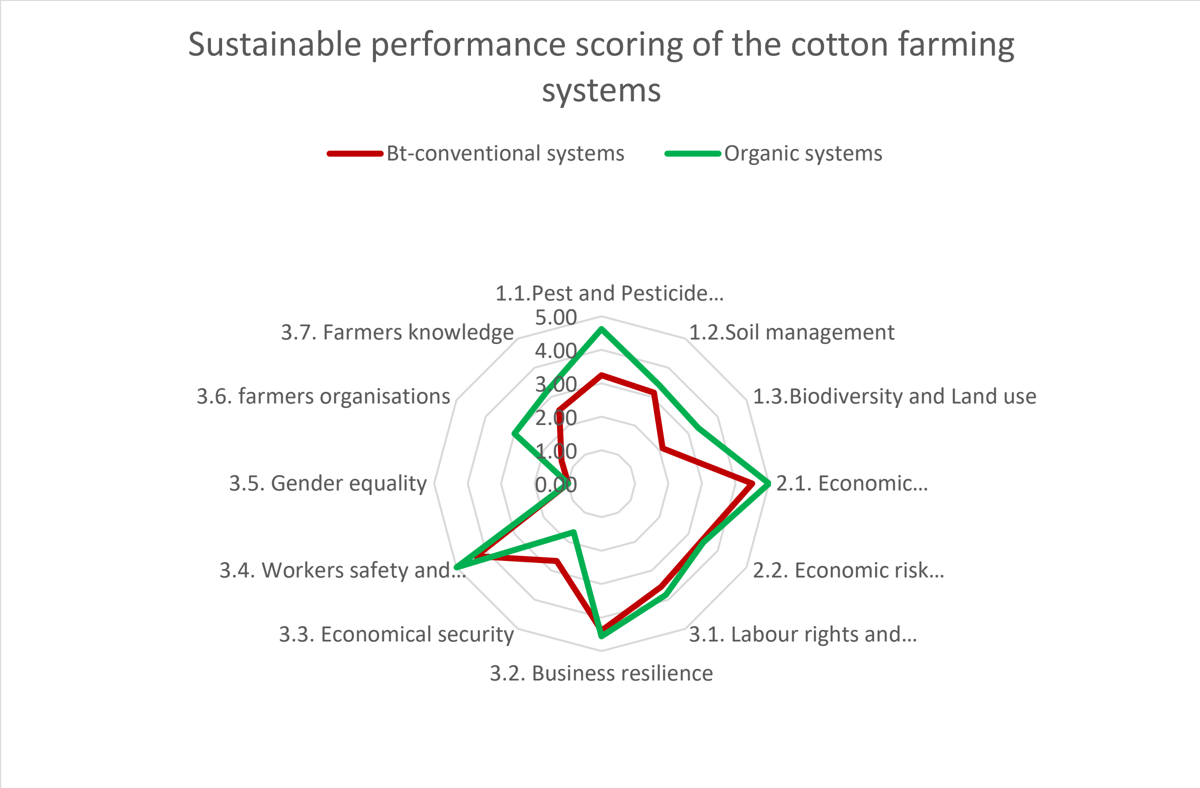

Figure 6.27: Spider radar comparing scores of organic and Bt-conventional cotton farms (mean score across 6 farms)

6.3.7. Ecological indicators and the overall sustainability indicators

Overall, there were a significant difference (n=12, p=0.01) between the results of the framework including and excluding the ecological indicators (Table 6. 62, Table 6.63). The ecological indicators were significantly and positively correlated to the results of the overall sustainability and environmental sustainability performance score (Table 6.64, Table 6.65) but not to the economy and social sustainability performance score.

Table 6. 62: Descriptive statistic of the overall sustainable performance scoring of 6 Bt-conventional and 6 organic systems including and excluded the ecological indicators

	Bt-conventional		Organic		All systems	
	Including ecological indicators	Excluded ecological indicators	Including ecological indicators	Excluded ecological indicators	Including ecological indicators	Excluded ecological indicators
System 1	3.11	3.21	3.35	3.56	3.23	3.39
System 2	3.09	3.09	3.42	3.62	3.25	3.36
System 3	2.86	2.91	3.77	4.05	3.32	3.48
System 4	3.32	3.59	3.63	3.79	3.48	3.69
System 5	3.10	3.35	3.66	4.01	3.38	3.68
System 6	2.93	3.11	3.77	3.93	3.35	3.52
means	3.07	3.21	3.60	3.83	3.33	3.52
standard deviation	0.16	0.23	0.18	0.20	0.09	0.14
standard error	0.06	0.10	0.07	0.08	0.04	0.06

Table 6.63: Statistical analysis of all systems comparing the significance difference between the sustainability performance scoring including and excluding the ecological indicators

Systems	df	n	F value	p-value
All systems	9	12	0.41	0.01*
Bt-conventional	9	12	0.46	0.25
Organic	10	12	0.39	0.04*

Table 6.64: Details of the ecological indicators added to the sustainable framework

S.N	Added Ecological Indicators	B1	B2	B3	B4	B5	B6	Means	Standard deviation	Standard error	O1	O2	O3	O4	O5	O6	Means	Standard deviation	Standard error
1.2.3.1.	Soil Biodiversity (earthworm survey)	2.00	3.00	1.00	1.00	1.00	2.00	1.67	0.82	0.33	2.00	2.00	3.00	3.00	3.00	3.00	2.67	0.52	0.21
1.3.3.1.	Scoring of the Ecosystem services provided by the system (above ground ratio pest:predator)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	0.00	0.00	2.00	4.00	2.00	2.00	2.00	2.00	2.33	0.82	0.33
3.7.1.1	Ecological knowledge	3.00	2.00	2.00	2.00	3.00	1.67	2.28	0.57	0.23	2.50	3.00	3.50	4.33	3.00	2.50	3.14	0.69	0.28
	Average of Ecological indicators	2.33	2.33	1.67	1.67	2.00	1.89	1.98	0.30	0.12	2.17	3.00	2.83	3.11	2.67	2.50	2.71	0.35	0.14

Table 6.65: Correlation between the average of the added ecological indicators and the developed sustainable indicators

	Correlation	R^2	Regression p-value
1.Environment	0.71	0.50	>0.01*
2.Economy	0.24	0.06	0.40
3.Social	0.52	0.27	0.06
Overall sustainability	0.75	0.57	>0.01*

6.5. Discussion

Overall organic systems are more environmentally, socially and economically sustainable than Bt-conventional systems. Using this framework, three key aspects of cotton sustainability in need of attention have emerged: plant protection, soil management and production, and incomes. This discussion clusters together different indicators to examine these three key aspects.

6.5.1. Plant protection

Plant protection is the weakest link in the production process (Ramasundaram, 2001). These results showed that the way farmers managed their systems to deal with pest attacks had an impact on environmental sustainability., The organic farmers eschewing chemical pesticides on their cotton systems obtained the highest sustainability score in this category.

6.5.1.1. Pesticides effect on biodiversity

Organic farmers were trained with BioRe association and used biopesticides (see methodology chapter) while Bt-conventional farmers were applying pesticides containing the following active ingredients: Acephate, Imidacloprid, Monocrotophos.

When Acephate (which is a broad-spectrum pesticide/wide-spectrum insecticide) is used frequently, it has been observed to create insect resistance that contributes to pest resurgence, spurring some concerns within the scientific community (Obrycki and Kring, 1998). In the US, this active ingredient is not recommended in the growth of cotton crops as it negatively impacts natural enemies (Naranjo and Ellsworth, 2009).

“Imidacloprid is a neonicotinoid insecticide and is an agonist of insect nicotinic acetylcholine receptors. The toxicity symptoms in insects include loss of coordination, tremors and paralysis” (Xiao et al., 2016). Imidacloprid is toxic to non-target pollinators and highly toxic to soil invertebrates, earthworms, fungi and predators found in cotton crops (Lima e Silva et al., 2017; Obrycki and Kring, 1998; Xiao et al., 2016). There is evidence that Imidacloprid is responsible for the loss of honeybees (Woodcock et al., 2016). The Bt-conventional system farmers surveyed used seeds treated with Imidacloprid. This could explain the findings in the previous results chapters: the number of coccinellidae and spiders (natural enemies) was lower in the Bt-conventional systems in comparison to organic systems (Chapter 4).

Studies show that pesticides have a negative effect on natural enemies through different processes: reduction of fecundity (Carvalho et al., 2003), deformation during their development (Krespi et al., 1991; Qi et al., 2001), reduction of their life span (Hamilton and Lashomb, 1997; Liu and Stansly, 2004), as well as many other sub-lethal negative effects (Desneux et al., 2007). One of the added indicators of the sustainability framework from this study was the conversion of the above ground biodiversity into the ratio of pests: natural enemies to assess the ESs provided by the methods. This specific indicator obtained a higher score among organic systems in comparison to Bt-conventional systems which means that there are more natural enemies for the same number of pests in organic systems in comparison to Bt-conventional systems. As other studies suggest, a decrease in natural biodiversity can lead to the decline in natural pest control, leading to an increase in pest damage (Jonsson et al., 2012; Mkenda et al., 2019). In consequence, the reduction in ESs provided by natural functional biodiversity negatively affects the sustainability of the agrosystem (Lammerts van Bueren et al., 2002).

The application of neonicotinoids has not shown an effect in increasing crop yields (Seltenrich, 2017), though farmers' communities strongly believe this (NFU, 2015). In March 2017, the European Commission suggested a ban on the three following neonicotinoids: Imidacloprid, Clothianidin and Thiamethoxam, but they are still used in many crops (Veres et al., 2020). Monocrotophos (Booth and O'Halloran, 2001; Zhou et al., 2007) and Imidacloprid (Dittbrenner et al., 2011; Faheem and Khan, 2014) have a negative impact on earthworm populations. The negative effects of Monocrotophos is recognised in many countries and, despite research from India showing the harmful effects of these chemicals on soil bio-indicators such as earthworms, it is still legally available (Abbiramy et al., 2018; Bharathi and Subba Rao, 1986). When a pesticide is applied to the foliage, it eliminates arthropod pests but the natural enemies of those pests are also directly or indirectly exposed (Desneux et al., 2007). Studies show that farmers who receive training spend less money on pesticides (Ranganathan et al., 2018a). None of the Bt-conventional farmers interviewed received specific training from the government in order to learn the protocols required in the application of these toxic chemicals.

6.5.1.2. Farmers exposure to pesticides

In 2002, 500 cotton farmers died of overexposure to pesticides in Andhra Pradesh because they took no safety measures such as wearing protective equipment during the hottest period of the day (Chari and Govindarajan, 2018). The Bt-conventional farmers interviewed did not wear personal protective equipment (PPE) and had their skin directly exposed to the pesticide they applied. Working in these primitive conditions exposes farmers directly to acute toxic pesticides. However, none of interviewed farmers or their workers have encountered a fatality and insisted that the farms had safe working conditions. In 2017, more than 1000 Bt-conventional cotton farmers experienced chemical exposure, 23 of whom died due to the toxic compounds inhaled from the pesticides (Kumar, 2018). The FAO has developed the "International Code of Conduct on the Distribution and Use of Pesticides" (FAO, 2003) and recommends small-scale users in hot climates use pesticides which do not require the use of PPE (Mancini et al., 2009). All pesticides and insecticides under the Insecticides Act of 1968 have labels with directions for use (Kyndiah, 2002). In India, 50% of farmers are illiterate and can't read the directions provided (CSA, 2006). I have discovered during the interview process that farmers follow the instructions communicated by retailers. This is a common practice in India (Satya Sai et al., 2019). In May 2020, the Indian Government issued a draft order banning 27 pesticides including Acephate and Monocrotophos (Chandra, 2020). In June 2020, the Minister of Chemicals and Fertilisers, agrochemical associations and trade organisations opposed the bill and therefore the Department of Agriculture could not implement the draft order. Until a new expert committee is formed to assess the possible threat and impact of these pesticides on the environment, society and economy of the agricultural sector, these agrochemicals products can be used in the domestic Indian market (LLP, 2020).

6.5.1.3. Integrated Pest Management (IPM)

The long-term goal of Integrated Pest Management (IPM) is to reduce the cost of pest management economically and environmentally. Research has shown training creates awareness and encourages farmers to use alternatives to chemical pesticides. For example, in Arizona, US, educating farmers led to the adoption of Integrated Pest Management in the whole community (Naranjo and Ellsworth, 2009). In that particular case study, broad-spectrums such as Acephate have been downgraded to act as a last resort (Naranjo and Ellsworth, 2009). As a result, the ESs stabilised and there were major economic and environmental gains in the Arizona cotton agro-ecosystem (Naranjo and Ellsworth, 2009).

In India, Integrate Pest Management is supposed to be part of the central government agenda (ICAR, 2020). The government has a scheme dedicated to "Sub Mission on Plant Protection and Plant Quarantine" which includes "Implementation of Insecticides Act", "Integrated Pest management" and "Locust Control and Research" (Agricoop, 2020). The Indian government is aware of the importance of IPM in promoting sustainable agriculture. However, none of the farmers interviewed have received IPM training or participated in any schemes. Further research to explore how wide-spread this lack of training is would be useful.

6.5.1.4. Farmers knowledge

During interviews, the extended ecological knowledge of farmers was assessed. The results highlighted their lack of ecological knowledge. This indicator was not part of the original framework. However studies have shown the importance of traditional ecological knowledge for the sustainability of farming practices (Anderson et al., 2021). Both conventional and organic farmers were able to recognise jassids, the main pest in the fields responsible for low yield. Honeybees, important for pollination, were better known to organic farmers than Bt-conventional ones. Important natural enemies operating in cotton systems such as ladybirds and Chrysopidae were unknown to the both organic and conventional farmers. IPM training strengthened both their ecological knowledge and appreciation of natural enemies, which encourage farmers towards natural enemy conservation methods (Wyckhuys and O'Neil, 2007). Studied have shown that this traditional ecological knowledge was inherited generationally, forming the basis of agriculture practices (Pilgrim et al., 2007). Traditional ecological knowledge is defined as '*a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment'* (Berkes, 1999; Rakshit et al., 2017). Traditional knowledge has shown to have the potential to reinforce agricultural sustainability (Sumane,2018).

Increasing farmers' dependency on agro-chemicals has been trending worldwide (Kranthi and Stone, 2020; Wyckhuys and O'Neil, 2007). Indian governmental policies have promoted the intensive use of chemicals through subsidised prices in agricultural management through the last forty years. Consequently, Bt-conventional farmers have used pesticides and fertilisers injudiciously (Pesticide Action Network UK, 2017) leading to a near loss of their traditional ecological knowledge (Rakshit et al., 2017; Wyckhuys and O'Neil, 2007).

In India, the majority of farmers are illiterate (Khandare, 2015). "The progress of a country's agriculture depends on millions of farmers who shall keep pace with the changing technology" (Sirisha et al., 2016). Unfortunately Indian farmers have little access to information and efficient methodology (Khandare, 2015).

Due to their lack of education, farmers often seek to eliminate all the wild species present in their agrosystems because they see them as pests that, in their words, have a negative effect on crop productivity (Scherr and McNeely, 2008). However, Millennium Assessment has suggested that the future of agricultural production should focus on more ecologically sustainable management to conserve function biodiversity and increase production without degrading the agricultural land (Millennium Ecosystem Assessment, 2005). Land depletion is a recurrent problem and applying ecological intensification on agrosystems would help increase productivity without damaging the ecosystems.

Focusing on improving farmers' knowledge should be a priority in order to empower them and tilt the scales towards ecological and socio-economically sustainable agriculture (Chand, 2019). Ground level organisations such as BioRe help create awareness amongst farmers. They work with farmers and are present all over India in small pockets (Bahuguna, 2019; Black, 2000). The key point of success for these organisations is to technically support farmers and facilitate access to the market. These initiatives have proved successful over the years and the research recommendations are well-positioned to be promoted by the government on a national level.

6.5.1.5. Effect of pesticides on soil biodiversity

I observed that earthworm populations were lower in Bt-conventional systems than in organic systems — a result in agreement with other studies (Dittbrenner et al., 2011; Faheem and Khan, 2014). My study suggests that in long-term experimental Bt-conventional systems, the fungal community in non-rhizosphere soil was negatively affected by pesticide-coated seeds (chapter 5 section 5.6).

6.5.2. Soil fertility

Soil fertility is a crucial factor in the productivity of cotton crops (CRDC, 2014) and in supporting highly functional biodiversity (Jeanneret et al., 2008). This study, Chapter 5 sections 5.4, demonstrated that the abundance and biomass of earthworms were significantly higher in organic systems in comparison to Bt-conventional systems. This has been construed as one of the sustainability indicators for soil management and has been integrated into the sustainability framework. The results suggest that the application of chemical fertilisers and pesticides could be linked to the lower population of earthworms in Bt-conventional systems (See Soil Bio-indicators chapter). Organic farmers apply farmyard manure as fertiliser to their crops while Bt-conventional apply FYM as well as urea (see Chapter 3). Based on (Dwivedy, 2011) I suggest that their use of farmyard manure in tandem with chemical fertiliser is a remnant of their indigenous knowledge from when agriculture was thriving. When asked about their ecological knowledge, all the farmers interviewed knew the benefits that earthworms bring to the soil. They were aware of the earthworm’s ability “to make the soil soft,” which is the vernacular that farmers use to describe fertile soil.

6.5.2.1. Crop residue management

The way the farmers managed crop residue after the last cotton harvest was unrelated to the type of farming they practiced (organic or Bt-conventional). Crop residue management plays an important role in protecting the soil surface from wind and water erosion (USDA, 1997). There were three different ways of managing the crop after harvesting. First, farmers hired shepherds and let the sheep feed on the unpicked bolls and the remaining leaves. Nomadic pastoralists from Rajasthan called the Raikas migrate yearly to Madhya Pradesh during this period. They have a relationship with the farmers wherein the herds graze the harvested field and manure the soil in exchange (Ballantine et al., 2020). The removal of unplugged bolls by sheep and goats is considered a part of IPM practices and helps control the damage done by pink bollworms by destroying any remaining caterpillars in the unplugged bolls (Arora et al., 2006). Animals that graze on Bt-cotton have been observed to fall sick or die in the aftermath (Sagari, 2010). The ones previously exposed to Bt-cotton appear to have a higher rate of morbidity in comparison to animals exposed for the first time. These symptoms are known as the “Bt Cotton Syndrome” (BCS) (Sagari, 2010). There is evidence that sheep feeding on Bt-cotton plants are affected by the Bt toxin (Hashim et al., 2017). Another study shows that Bt-cotton contained residues of organophosphate (a compound of pesticides), an excess quantity of nitrates as well as Bt-protein (Sagari, 2010). This cocktail could explain why sheep that feed on Bt-cotton fall sick. It is disturbing that even after many years, there are no regulations relating to the safety of the animals grazing on Bt-cotton (Sagari, 2010).

Secondly, farmers hire a machine to shred the cotton stalk and incorporate the biomass back into the soil. Returning these elements to the soil increase the content of organic matter, acting as protection against nutrient loss and consequently improving soil fertility (Nguyen et al., 2015). High yield cotton varieties require more nutrients including potassium (K). However, K deficiency is a common problem in cotton farming as the plant absorbs a considerable amount. Potassium is important as it can significantly affect the quality and the length of the cotton fibre (Zimmer, 2017). By reincorporating the cotton stalk into the soil, a nutrient like potassium is replenished. Crop residues are also a good source of nutrients like carbon (Sharma et al., 2018). Finally, some farmers save any remaining stalks and the body of the dead plant to use as firewood in the winter season. Using crop residues as household fuel is a common practice in low-income countries such as India (Smil, 1999).

Crop residues should not be seen as waste but as a nutrient source and this should be communicated to the farmers.

6.5.2.2. Soil fertility linked to yield

This study shows that the soil management of Bt-conventional systems was less sustainable than organic systems. Soil fertility is a major factor responsible for the low yield of CFS in India and farmers should be aware of the best management practices — such as crop residues and the application of (bio) fertilisers — to improve fertility. With the introduction of Bt-cotton, Indian agricultural institutes recommended applying the double amount of fertiliser to increase yields (Kranthi and Stone, 2020). However it is known that increasing the application of fertiliser has a negative effect on the soil health (Lupatini et al., 2019). Furthermore, my study, as well as a few others, has shown that in India, there is little difference between organic and Bt-conventional yields (Patil et al., 2014a), which questions the efficacy of applying such high amounts of chemical fertilisers in Bt-conventional cotton systems. As mentioned previously, India has one of the lowest cotton yields per hectare in the world (Choudhary and Gaur, 2015). Therefore there is a need to focus on closing the yield gap without compromising the health of the soil to reach economic and ecological sustainability.

6.5.3. Production and incomes

My work showed that the sustainable performance score of economic indicators were slightly better in organic systems in comparison to Bt-conventional systems. The fact that organic farmers were working in collaboration with BioRe organisation insured them a stable market for their organic cotton (see methodology) at the farmgate. at the same time, Bt-conventional farmers sell their produce to traders at the mandis (government regulated wholesale agricultural market) (DACW, 2020). It has been recognised by economists that farmers are often exploited by these traders (Goyal, 2010). According to the minimum support price (MSP) fixed by the government, the price of the cotton has been increasing yearly. However, according to my interviews, none of the farmers received the minimum support price when they were selling their cotton at the mandis. Only around 20 per cent of farmers in India are aware of the minimum support price of cotton (Geetha and Mahesh, 2019). Farmers need to be informed and need support to be able to get a fair price when it comes to sell their cotton at the farmgate. Recently, the government has put in place three farm bills which will allow the farmers to sell their crop legally in other states and to private companies (Mustafa, 2020). Farmers have been protesting against these bills because they know that without any regulation, they will not get a higher price, but they will have to compete with each other, and private companies will be able to buy their produce at a lower price than the MSP. Farmers all over the country have been protesting and have been asking for these three laws to be removed as well as for the MSP to be implemented properly in mandis (Times of India, 2020).

This study showed that for the majority of the organic farmers, cotton represented the largest income of the household, making it a major risk to rely on one source of income. Bt- conventional farmers tended to have other sources of income to sustain themselves and their family. The activities they were practicing include selling milk, teaching or having a side business. Taking up a second activity as a source of income could be linked to the fact that the price of the cotton fluctuates much more for the Bt-conventional cotton farmers when the organic cotton farmers have a yearly stable source of income from selling their organic cotton to BioRe limited.

There is a misapprehension that conventional farming requires more labour than organic farming but it has been proven that in India the labour requirements do not vary much between these two systems (Patil et al., 2014b). My study, in accordance with other studies, showed that the difference in labour is not between systems but the inequality which exist between female and male workers who were not paid equally (Pushpa et al., 2016).

In terms of age, Bt-conventional farmers were on average younger than the organic farmers which indicate us that the new generation are preferring conventional farming than organic farming. In 2019, the government has put in place a new scheme called Pradhan mantra Kisan Maandhan Yojana for older farmers to be eligible to receive a pension at the age of 60 years old. Farmers falling into the age group of 18 to 40 will be eligible for a monthly pension of 3000 Indian rupees when they will attain 60 years. Majority of the organic farmers interviewed were above 40 and will not be eligible to receive a pension when they will attain 60 years old when on the other side majority of the Bt-conventional farmers were below 40 years old.

Apart from the type of farming management they decided to practice, organic farmers and Bt-conventional farmers had a very similar lifestyle with similar principles. Organic farmers can economically be sustainable when they are linked to an organisation which provide them with organic certification and technical support as well as a premium price for their cotton. This type of model has been shown to work successfully with other organisations (Bahuguna, 2019).

6.5.4. Action for sustainability in Indian cotton farming system: what's next?

In cotton crops in India, 32% of all external cost occurs during the cultivation phase (Grosscurt et al., 2016). To reduce these external costs and increase farmers income, reducing the use of chemical fertiliser and pesticide should be encouraged. Ecologists should be involved to provide solutions and guidance to the farmers by increasing their ecological knowledge and their understanding of ecosystem services provided by the functional biodiversity. Promoting ecological intensification will be a huge asset for the farmers to be able to improve crop productivity, to reduce pesticides loads and by consequence to reduce agricultural growing costs (Mall et al., 2018). Creating awareness among farmers on up-to-date technics to increase productivity is fundamental. For example, spacing adequately the cotton plants is a technic which has shown positive results and has been encouraged by scientists and organisations (Chapepa et al., 2020).

During my research for this chapter, I found that many agricultural schemes provided by the government were available, the problem is that only few of them are being implemented and few of them manage to reach the marginal farmers.

There is enough agricultural land but the productivity per hectare needs to be improved (Talukder et al., 2020). One of the government targets is to double farmers income by 2022 (Talukder et al., 2020). If Indian farmers manage to double the cotton yield per hectare, it will help them to double their income and reach this target which seems until now to be an obtuse aim (Sengupta, 2021). The government should transition from an agribusiness-oriented model toward a knowledge-based agriculture model by focusing on local knowledge, cultural services and diversity as well as up-to-date technology (IAASTD, 2009). For Indian agriculture to become resilient, there is a need to start thinking about “climate change impacts, water scarcity and other challenges” (Giovannucci et al., 2012).

During the Covid-19 pandemic, many labours working in the cities returned to their village. This could be seen as an opportunity for the government to focus on empowering/skilling them and on revitalising agriculture by organising trainings and giving them access to knowledge. With the pandemic Indian GDP has fallen by 7.3% for the whole financial year 2020-2021, facing the worst economic crisis since independence (Dhingra and Ghatak, 2021). During the Covid-19 crisis, the number of poor people has more than doubled. Agriculture in India represents 43% of the employment sector (World Bank, 2020b). Focusing on agriculture could play an important role in national resilience against the nation economic and financial turmoil. Agriculture represents 20% of the gross domestic product (World Bank, 2020a), for this reason, agriculture activities should become a focus to boost the economy. If the government focuses on giving technical support at the ground level as well as facilitate access to market for farmers, it would be possible to shift toward a more sustainable type of farming system while increasing crops productivity and farmer’s incomes. Being able to link agri-products processing to production using efficient value chain could offer substantial scope for rural employment and increasing farmer's income (Chand, 2019).

6.5.5. Limits of this study

There has been considerable work on investigating sustainability cotton systems in India on a large scale such as producer groups (Textile Exchange, 2015) or using data from Indian Human Development Survey (De Hoop, 2018). To my knowledge, there is no comprehensible and easily replicable assessments done at the farm-level in India.

This assessment tool has the potential in the future to be used in other studies to assess more cotton systems in the same region or even at a national level as many Indian cotton farmers are facing the same challenges while farming cotton crops in India. This assessment tool which I have developed adopted a wider list of indicators than the original framework.

Only a few indicators were selected from the total indicators presented by the FAO framework, partly based on what was feasible for the auditor to get an answer and answer available in the context specific.

The social aspect did not include an assessment of the role of women in farming systems and compare their role and the status they have in the different farming systems. Including this in future studies would be a positive next step. Studies have shown that women have more responsibilities within organic systems than in conventional systems. In the assessment, indicators did not assess if women are being empowered by a system more than another one (Chopin et al., 2021).

The interview was finalised using pilot interviews with organic and conventional farmers. However, farmers were not asked their interpretation of sustainability, although farmers were interviewed and present during the ecological surveys on their farm on a voluntary base. The questionnaire was a quantitative with multiple choices questions and benchmark questions, not qualitative to make the indicators easily scorable.

I suggest, if replicated, this assessment tool could be improved by encouraging the farmers to participate at the ecological survey. I suggest that the assessment tool could be refined by visiting the surveyed farmers and discussing with them the indicators and the obtained performances (Coteur et al., 2020).

A correlation was found in between the added ecological indicators and the overall sustainability indicators. Among these three added ecological indicators, two (earthworms' population and ecological farmer knowledge) were easy to collect. They could be used by further studies to assess environmental sustainability. However, the third added ecological indicator (ratio pest: natural enemies) require time and expertise which is not always easy to find.

Agricultural sustainability is a complex issue which requires multiple factors within economic, social and environmental sectors to be implemented. I have identified factors that could be taken into consideration when assessing cotton farming systems. A summary of these factors to be addressed can be found in the literature (Table 7.66) (Talukder et al., 2020).

Table 7.66: Various capitals for agricultural sustainability, source Talukder et al.,2020

Source: Based on vanLoon et al., 2005 :48; Pretty, 1999

6.6. Conclusion

Based on the FAO guidance framework, I developed an assessment tool to integrating ecological indicators . This tool was used to evaluate and compare the sustainability of the two main cotton farming systems in Madhya Pradesh (organic and Bt-conventional). By combining the empirical data from the ecological survey and the data obtained through farmer's interviews, this framework has shown us that in this specific context, organic farming systems were, overall, ecologically, environmentally, socially and economically significantly more sustainable than Bt-conventional systems.

Adding ecological empirical data to the framework didn't make a difference in determining which of the two systems were the most sustainable. However, integrated the ecological indicators facilitated insightful understanding of farmers management choices and highlighted the contextual problem that farmers face while growing cotton in Central India. The added ecological indicators were significantly correlated to the general sustainable performance score of the farming systems. This specific framework could be refined and has the potential to assess the sustainability of cotton farming systems in India. There is a need to assess more farming systems all over India to understand how they perform and how their sustainability can be improved.

Chapter 7. Discussion and Conclusion

Aims and objectives

The main aim of this study was to assess the socio-ecological sustainability of the cotton farming system in central India. To meet this aim, I have studied a long-term trial (with four farming systems (Organic, biodynamic, conventional and Bt-conventional) and 12 farms (6 organic and 6 Bt-conventional).

The first objective was to develop a methodological approach to explore sustainability in Indian cotton systems. This study compared the above-ground and below-ground biodiversity, at the plot-scale and farm-scale, of organic and conventional systems. In this comparative study, I have used the Food and Agriculture Organization (FAO) framework (FAO, 2015) which has a list of comprehensive indicators based on previous frameworks and initiatives. To compare and assess the sustainability performance of cotton at the farm-level, It was key to develop a dynamic framework (Binder et al., 2013). I developed an innovative methodology integrating ecological indicators into the existing framework which was largely focused on the environmental, social and economic indicators. This assessment tool was developed to assess Indian cotton farming in Madhya Pradesh while keeping in mind that sustainable agriculture differs based on varied regional contexts (Kuehne, 2016; Syswerda and Robertson, 2014). I developed a step-by-step methodology integrating the created assessment tool's ecological-centred impact indicators.

The second objective was to compare the long-term impact of four plot-scale cotton and two farm-scale farming systems on functional biodiversity with a focus on crop protection. In this comparative study, the number of natural enemies (Spiders) was statistically higher in the conventional systems as compared to the organic systems, and the main secondary pest (Jassids) abundance was similar in the conventional systems than in the organic systems. This study has demonstrated that organic systems were doing as well as conventional systems when it comes to pest control with less damage to natural enemies and non-target invertebrates.

The third objective was to compare the long-term impact of four plot-scale cotton farming systems and two farm-scale farming systems on functional biodiversity with a focus on soil health. To determine the 'health' of the soil ecosystem, I chose earthworms and fungi as bio-indicators. Soil biodiversity can be negatively impacted by farming practices; soil biodiversity is essential for soil fertility and crop productivity (Edwards, 1984; Zhang et al., 2007). This study showed that earthworm biomass and density were higher in organic systems than in conventional systems at both the plot- and farm-level. Earthworms are valuable indicators as they are easy to monitor and identify (Pelosi and Römbke, 2016; Smith et al., 2008; Stork and Eggleton, 1992). The presence of earthworms in higher numbers gives a fairly accurate indication that the soil in both organic systems was less degraded in comparison to both conventional systems.

As far as I am aware, this study is the first to examine fungal communities in comparative farming systems in India. Here, I focussed on looking at the fungal community composition and I considered the fungal guild. The fungal community was previously unknown in this area, consequently, this study adds new knowledge to the evidence base. The results of my study showed that the fungal community was more diverse in organic systems when compared with conventional systems. This is in agreement with a recent study (Lupatini et al., 2019). This study has observed that species such as *Trichoderma* have been recognized as indicators of soil health in other studies. The results in Chapter 5 showed that the presence of *Trichoderma* was higher in the organic systems than in conventional systems. *Trichoderma,* which is one of the most studied genus of fungi in agriculture, has been categorized as an antagonist fungal agent (Calistru et al., 1997).

To conclude, my findings have confirmed that the soil biodiversity of organic soil systems was higher than for conventional systems, both at the plot- and farm-scale.

The fourth objective was to investigate if Bt-transgenic cotton crops have a long-term impact on biodiversity. This study showed no significant difference between Bt-conventional systems and the non-Bt-conventional system on either above- or below-ground biodiversity in the long-term trials.

The fifth objective was to integrate the measurement of functional biodiversity into whole farm sustainability assessments and compare the two major farming systems currently practised in India. Based on the FAO guidance framework, I developed an assessment tool to integrating ecological indicators. The added ecological indicators were significantly correlated to the general sustainable performance score of the farming systems but did not directly affect the sustainability performance score, rather they provided insightful information on the impact of cotton farming practices on biodiversity and highlighted the lack of ecological knowledge among farmers. This study has shown that organic systems scored a higher sustainability performance score than the Bt-conventional systems. However, both systems could improve their economic and social sustainability performance score.

The link between above ground and below-ground biodiversity

Biodiversity plays an important role in providing ecosystem services which play an essential role in ensuring the health of agroecosystems. The bio-indicators that I selected all exhibited a similar response to farm management. To clarify, a useful bio-indicator species is moderately sensitive to environmental changes and can reveal specific stress (Schwerdt et al., 2018). In such cases, when the species in question is affected, it alters the population dynamic and disrupts the community as a whole (Holt, 2010). The bio-indicators I selected were from different trophic levels. My work showed that beneficial arthropods above ground, earthworms and fungal communities below ground were affected more negatively by conventional farming management than organic management. In agreement with other studies, my research on biodiversity has suggested that conventional systems reduced ecosystem services in comparison to organic systems (Curran et al., 2020; Kremen, C. & Miles, 2012; Sandhu et al., 2015; Tscharntke et al., 2005). Both fertilisers and pesticides have been identified as negatively impacting above and below-ground biodiversity (Gunstone et al., 2021). Loss of soil biodiversity due to agricultural intensification reduces soil ecosystem services and agriculture sustainability (Veresoglou et al., 2015). Ecosystems and the services that biodiversity provide contribute to ecological sustainability. There is a need to distinguish between ecologically sustainable and ecologically resilient. These two principles are not always correlated (Volkov et al., 2022). For cotton farming systems to be considered sustainable and resilient, they must have the capacity to cope with external stress factors without collapsing (Walker and Salt, 2006). With the increase in weather fluctuations and unpredictable weather events, as a result of the climate crisis, a higher number of predators in a farming system might not be enough to be able to ensure an ecologically stable farming system. A genuinely resilient system is one capable of lasting over time and adapting, so the whole system does not collapse (Johansson et al., 2005). Further research

should investigate possible indicators related to both ecological sustainability and resilience (Volkov et al., 2022).
Understanding above and belowground ecology is important to understand how plants interact with decomposers, mutualists and enemies. My study has looked at the above and below ground separately, giving a good overview of how the entire communities respond to the different farming systems. Plants are the link between the two subsystems as they connect the herbivores, pathogens, and their natural antagonists to the soil. Research is now moving from looking at a few species to observing species assemblages to which plants are interacting, both belowground and aboveground. For example, in recent studies, earthworms have been shown to have a reciprocal relationship with earth microbiota (Ahmed and Al-Mutairi, 2022). Earthworms impact directly and indirectly the plant growth through the microbial community. Several recent studies have shown that earthworms increase available nutrients (eg, nitrogen, phosphorus) and indirectly play a role in the growth of plants. Furthermore, a meta-analysis has shown that earthworms play a role in plant resistance to herbivores such as thrips (cell-feeders) and root-feeding nematodes (Xiao et al., 2018).

Specific network types based on correlations has gained popularity in ecological studies. Correlational networks have gained popularity as they can accommodate many data types. Network analysis using correlation is a new step to understand species interaction. Correlational networks are flexible and can accommodate many data points (Ramirez et al., 2018). The future of aboveground and belowground ecology will involve transdisciplinary and interdisciplinary research and has the potential to explore the functional role of species, communities and ecosystems (Ramirez et al., 2018). These types of studies are extremely resource intensive, however studying the complex functional structure of community webs can help reveal direct and indirect species interactions (Schuldt et al., 2017).

In this study, the cotton farming system has been simplified and narrowed down to a handful of ecological indicators. However, ecological systems are very complex systems which are influenced by biodiversity from the molecular system level to the landscape system level. In this study, we need to underscore that we have simplified the system through standardised imposed indicators to be able to assess it. This may not give us an accurate representation, but according to available literature, provide a good approximate representation of the overall system (Kakabadse and Khan, 2016).

BT-cotton

The Bt-cotton was introduced in 2002 and accounts for more than 95% of the total area of cotton grown in India. With the introduction of Bt-cotton, doubts arose over the long-term sustainability of cotton farming. However, the concerns around Bt technology do not stem from economic performance or associated indicators. Rather, they have centred on its ecological impact in the long term (Ramani and Thutupalli, 2015b). My study indicated that in the long term, the planting of transgenic cotton does not significantly affect the most common taxa of above- and below-ground invertebrates. These results were at variance with long-term laboratory studies (Liu et al., 2009; Zwahlen et al., 2003) showing the importance of having on-site studies. Field results can be significantly different from laboratory studies due to external factors.

These results do not indicate, however, that there are no problems with the adoption of Bt-cotton in India. Where Bt-cotton was supposed to reduce the use of pesticides in the field, the opposite has happened (Ranganathan et al., 2018b). As mentioned in previous chapters, the amount of pesticide applied in cotton fields had increased since the introduction of Bt-conventional cotton (Kranthi and Stone, 2020) India is ranked 36th globally on yield per hectare (IndexMundo, 2021). It is important to note that among the countries which yield more than India, only 8 are using Bt-cotton. The rest use non-Bt cotton seeds and it’s also worth noting that India uses more fertiliser than countries that are more productive (ASHA and Kranthi, 2020). It has been suggested that the new hybrid cotton seeds developed by the Central Institute for Cotton Research (CICR) have greater biomass which attracts more sucking pests. With the increase of sucking pests, farmers had increased their use of pesticides (Kranthi and Stone, 2020). In other countries, Bt cotton hybrids represent only 5% of the area under cotton cultivation where they have been in favour of non-Bt hybrid varieties (Kranthi, 2012). In India more than 95% of the seeds developed by government research are Bt and India has positioned itself as the pioneer of cotton hybrids in commercial cultivation, claiming that hybrids have “50% higher productivity than other varieties”, a ”high degree of resistance to biotic and abiotic stresses” and “better fibre quality” (Sabesh, 2008). The first hybrid cotton was released in 1970. By 2008, hybrids accounted for more than 50% of the cotton area sown (Sabesh, 2008). Today, the majority of conventional farmers (>95% of cotton farmers) use hybrid seeds (Gutierrez et al., 2020). Farmers were channelled into GM technology, and the subsequent use of insecticides, as access to viable non-GM seeds, fell considerably (Gutierrez et al., 2020). Furthermore, there is some circulation of illegal genetically-modified seeds (Manjunath, 2007).

In India, only the government has the legal right to authorise Bt-seeds. However, in the past few years, new genetically-modified illegal hybrid seeds have been circulating among farmers, known as the "HT BT" cotton seed. The HT BT cotton is engineered to be resistant to bollworms as well the herbicide glyphosate. This allows farmers to apply the herbicide directly onto the cotton crop to remove weeds. In 2018, "*the Centre* [State agriculture department*] had constituted a special committee to study the problem. The committee estimated a sale of 30-33 lakh packets of the illegal hybrid*." (Biswas, 2021).

Although many reports highlight the importance of hybrids in increasing India's cotton yields, data has shown that since 2006, yields have been stagnant at the national level (Kranthi and Stone, 2020; Suresh et al., 2013). There is clear evidence that the introduction of drip irrigation and fertiliser applications played an important role in the increase of yield per hectare (Suresh et al., 2013). Reports are crediting the increase in yield to Bt-cotton adoption (Kathage and Qaim, 2012). However, when one looks at the key factors, one can see that in 2002, when Bt-cotton was only covering 0.38% of the total area, cotton yield increased from 302kg/ha to 399kg/ha due to the increase in fertiliser use (Kranthi, 2016). There is a very tenuous correlation (0.26) between the adoption of Bt-cotton and an increase in yield while there was a strong positive correlation (0.42) between increase in fertiliser use and an increase in yield between 2003 and 2011 (Kranthi and Stone, 2020). Kranthi (Kranthi and Stone, 2020) showed, using the regression-correlation analysis over 20 years, that it was the adoption of fertiliser and irrigation and not Bt-cotton adoption which was responsible for the increase in yield in cotton farming systems.

A focus on soil health

With the introduction of Bt-conventional systems, the amount of fertiliser used doubled (Kranthi and Stone, 2020). Studies have shown that the increase in fertiliser application harms soil health (Lupatini et al., 2019). Even if my study has shown that soil health was better in organic systems in comparison to Bt-conventional systems, studies have shown there is not much difference between organic and Bt-conventional yield in India (Patil et al., 2014a) while others have observed a significant difference (Riar et al., 2020). In both sets of studies, it has been observed that the yield of Indian cotton systems was lower than the yield potential of cotton (Constable and Bange, 2015). Soil fertility and soil health are important factors responsible for the low yield of Indian cotton. There is a need to focus on closing the yield gap without compromising the health of the soil to attain economic and ecological sustainability (Cunningham et al., 2013),

Assessing Sustainability at the farm level

Multidisciplinary approaches are crucial to understanding the sustainability of a farming system as a whole (Lescourret et al., 2015; Zhang et al., 2007). There are many frameworks and initiatives which have been created to assess sustainable agriculture globally which has been discussed in chapter 6 (BCI, 2013; CmiA, 2014; COSA, 2013).

Assessing sustainability at the farm level is complex and there are limitations in this study when it comes to the use of the FAO sustainability framework.

This was a very specific case study of organic farmers who were linked with an organisation. In the area studied, all the organic cotton farmers were linked to this single organisation (Biore). The survey could have been done with farmers linked to another organisation as well. However, this would not have been feasible in the timeframe that I had as organic farmers from another organisation were too far away from the BioRe centre where I was staying during the study.

In this study, information was taken from farmers and very little was given back. This has been one of the critiques of literature gathered through a questionnaire survey. Through the questionnaire, information was obtained, taken away and analysed. This is still a valid activity which has been done in the past and will continue in future (Chambers, 1992). In this study, the only real exchange which was done was due to the added ecological indicator of the farmers identifying the arthropods shown to them to test their ecological knowledge. After each interview, time was taken with farmers to discuss the role of each of the arthropods observed and the role they play in the farming systems.

This study did not explore the political economy of cotton cultivation in India and how farmers take decisions on selecting new seeds or making planting and practising choices. There is interesting research done by Flachs which has shown how farmers have learned to perceive cotton seeds (hybrids seeds) as a branded commodity (Flachs, 2019). Indian research has been focusing on developing hybrid seeds which have shown no significant benefit in increasing Indian cotton productivity when compared with the average world productivity (Daisen, 2020). To reduce the yield gap and the cost of growing, there is a need to focus research on local seeds (Kranthi, 2015). Researchers have recently developed local varieties with standard 32 mm fibre (ASHA and Kranthi, 2020). These local varieties (such as PA812) are much more pest-resistant and drought-resistant than the hybrid Bt-cotton varieties developed by the government (Chinchane et al., 2018). These local seed varieties have also been performing better during spinning tests (Chinchane et al., 2020). In the current agrarian system, farmers have a disconnected relationship with their seeds. In a sustainable farming system, farmers produce and keep their own seeds (CSUN, 2015). Today, even seeds are selected by organic certifiers and development projects. Private seed companies have proliferated with no regulation of quality and sustainability (Revathi and Ramana, 2005). The farmers' choice of their seeds has become "a matter of hope more than anything else" (Flachs, 2019). In my study, both seeds used by organic and Bt-conventional farmers were hybrid seeds. This shows how in a capitalist system, seed production, both in the context of organic or Bt-conventional systems, can transform a farmer's right into an opportunity to make money.

There are multiple and layered linkages that connect the farmers/villages to the larger economic political and socio-cultural worlds which have not been looked at in this framework. However, they are intertwined to impact the lives of agriculturists (Vasani A.R., 2013). In their studies, Flachs and Vasani both refer to the neo-liberal system which has made farmers seek higher levels of aspiration. The neoliberal economic system has changed the way farmers are thinking of sustainability where productivity has been privileged over all other aspects of agriculture (Flachs, 2019; Vasani A.R., 2013). The agrarian systems have now shifted from the local, ecological embeddedness of agriculture to a template of uniformity of practices. In Indian agriculture today, local knowledge is considered archaic and the production system has been dis-embedded from its ecological base. The Green Revolution has been encouraging water-intensive crops, unseasonal crops, and many more examples of farming practices which show that agriculture is largely divorced from ecology. To add to this, with changing climatic conditions which have disrupted the established bodies of knowledge of farmers, many have been facing the loss of crops or drops in yield. For a more sustainable agricultural system and as a means to stop the agrarian crisis in India, there is an urgent need for an alternative model. An agroecological alternative, based on local knowledge, innovative farming methods and modern agricultural research could be the solution (Wani, 2014).

Recommendation and next steps for researchers and farmers

The study entailed large-scale sampling of invertebrates (a total of 23,123 specimens were identified) - for many of which there is poor taxonomic resolution in India. Furthermore, there was no apriori crop-specific knowledge that allowed us to know which taxa would respond to cotton crop management in the region. Therefore, I took a broad approach, collecting a wide range of taxa and identifying them according to order or family; the appropriate taxonomic level was based on 1) the minimum level necessary to infer function and 2) what it was practical to identify. My approach was to focus on the broad impact of crop management rather than the ecology of farmland invertebrates. However, there are specific ‘next steps’ that this research suggests, one of which is to go beyond the taxonomic resolution that was applied. For example, my research showed that spiders responded to management--the next step is to understand how the different families respond, as different families can be excellent indicators in evaluating the anthropogenic disturbance impact on the ecosystem and its food chain (Menta and Remelli, 2020).

Assessing ecological sustainability can be challenging. There is no standard biodiversity reference, as it varies according to the location and environment. To assess the biodiversity of a specific type of agroecosystem, comparative studies are the most appropriate, therefore integrating ecological data with environmental indicators of the assessment tool was challenging.

Soil biodiversity (including ground-dwelling and below-ground biota) is the most diverse ecosystem in comparison to any other system. In the past two decades, research has developed several indicators based on soil fauna. The taxonomic groups

I have surveyed have recently been used in literature as soil health indicators (Menta and Remelli, 2020). However, other groups such as Collembola and Acari which are considered the two most important groups in relation to diversity and abundance (Menta and Remelli, 2020) have not been looked at in my study. Soil nematodes are useful bio-indicators for soil health and have been increasingly used as biological indicators over the years(Lu et al., 2020).

An interesting integrative approach named Indice Biotique de la Qualité du Sol (IBQS) has been developed by Nuria et al (Nuria et al., 2011) by assessing the macro-invertebrate diversity which is involved in soil processes. One of the indices developed among the others is QBS-ar ("Soil Biological Quality- arthropods based on Biological Forms approach") which "links biodiversity of soil microarthropod community to the degree of soil vulnerability"(Menta et al., 2018). These two indices have documented a similar trend to that in my study, observing a less stressed soil condition in organic systems in comparison to conventional systems. For a further in-depth study of soil quality, we recommend using the methodology developed by Nuria et al. (Nuria et al., 2011).

In this study, I focused on two singular ecosystem services provided by a part of the whole biodiversity. However, there are trade-offs and synergies among ecosystem services (Bennett et al., 2009). A further study could examine this in greater detail, for example, the life cycle of beneficial species could be surveyed regularly to better understand the impact of pesticide application on the life cycle of the different bio-indicators (Santos et al., 2007).

This study had limited efficacy due to the exclusive use of quantitative methods. This study has not been complemented by qualitative research which is generally used to classify the underlying explanations of the data received from interviewees (Adato, 2011). When it comes to indicators for gender equality and the status of women, this study was lacking an in-depth understanding as both organic and conventional systems scored the lowest sustainability performance for the gender equality indicators of sustainability. These understandings could have been gained through qualitative methods. I suggest that with more time and funding, a mixed-method approach combining qualitative and quantitative data could be explored for a more in-depth study to explain social phenomena within agrarian settings (Sattar et al., 2017).

This assessment study stopped largely at the farm gate; a full life cycle assessment which could consider ginning, processing and marketing of the final cotton product (FAO and ICAC, 2015) would add value to the study.

To shift towards sustainability, there is a need to go beyond the individual farm. This means involving the government and decision-making stakeholders on a landscape scale (Dicks et al., 2013; Schader et al., 2016). Lastly, a larger multiple farm-scale studies would scale-up the impact of the research.

Conclusion

This thesis aimed to assess the sustainability of cotton farming systems in Central India. By integrating ecological indicators, my study has shown that there is an opportunity for improvement in both organic and Bt-conventional systems. Overall, my study has shown that organic systems were environmentally, socially and economically performing better than Bt-conventional systems. My findings have demonstrated that the biodiversity in above- and below-ground habitats have been more degraded by conventional than organic management. From an ecological point of view, the study suggests that the problem is not directly related to transgenic cotton, but rather to conventional management.

Although this study demonstrates that organic systems support ecosystem services more readily than conventional management, the socio-ecological assessment has shown that both organic and Bt-conventional systems needed improvement. There are alternative strategies available that are less commonly used in India. Ecological solutions can be provided to farmers to increase productivity while conserving functional biodiversity (Mall et al., 2018; Scherr and McNeely, 2008). Traditional ecological knowledge is an important factor in the transition towards ecological sustainability and should be a priority when looking at challenges in farming.

Agroecology is based on a socio-ecological management approach to farming systems (Cammarata et al., 2021). To transit toward sustainable agriculture, farmers must be involved in agroecological science. More than organic, agroecology practices are needed to restore ecosystem services aimed at achieving high crop production while conserving biodiversity (Garbach et al., 2014; Scherr and McNeely, 2008)

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Appendices

Figures

Tables

Appendices A

Table A.1: Details of the pollinator surveys with methodology, results and discussion

Pollinator survey

Introduction

Pollinators play an important role in cotton. A tentative to study the long-term effect of cotton farming systems on pollinators at the plot scale level was adempted.

Methods

The survey was done in the intension to survey the pollinator species, their abundance, their activity and their flower visitations. During the year 2017, the survey was done with the assistance of Fairlie Kirkpatrick Baird, a MSc student from Oxford University. The survey was done during the pick flowering season of the cotton plants in August. Two methods were used to gather data on pollinator species, abundance, activity and flower visitations. The first survey was done using transects method with the objective to observe and identify primary pollinator species and their abundance. Eight rows evenly spaced in each plot were walked for one minute resulting in total observations of eight minutes per plot. Any pollinators observed within the net plot were identified and recorded. This survey was carried out in every plot a total of four times throughout a five-week period. The second survey was the plot observation to gather data on pollinator activity. Each net plot was observed for ten minutes. When a pollinator was observed, the species was identified, and the length and number of flower visitations carried out within one minute was recorded. This survey was also conducted in every plot a total of four times throughout the five-week period.

Results

The student observed a total of five pollinator species actively pollinating cotton flowers. The most abundant species was *Oxycetonia versicolor*, the flower chafer beetle, which was observed 27 times over the course of the surveys. Three of the other species were bees; *Apis florea* was observed 7 times, [solitary bee species] was observed 5 times, and *Apis dorsata* was observed 3 times. A pollen beetle of the *Mylabris* genus was observed once, although this species was also seen frequently outside of survey times, usually between 07.00 and 09.00 before the surveys began.

Discussion

The number of observed pollinators was too low to be statistically valid and therefore it was not possible to compare the effect of farming systems on pollinators species and abundance. It is possible that the plot trials were too small and too fragmented to be attracting pollinators. Pollinators can travel across different habitats, therefore surrounding landscapes have a strong impact on the pollinator population (Brittain et al., 2010). The plot trials were surrounding by vast fields of Bt-conventional systems which could have potentially had a negative effect on pollinators visiting the trial (Holzschuh et al., 2008). For better representation of activity of pollinators in cotton farming systems, we have suggested that the survey should be taken directly at the farmers field.

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Figure A.1: Article from The Bulletin by British Ecological Society written by Fairlie Kirkpatrick Baird

Appendices B

Canopy-dwelling arthropods community during the survey 2016

Table B.2: Results of generalised linear mixed effect model comparing Araneae taxonomic group of the canopy- dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Araneae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.38	-2.65	<0.01
Conventional Biodynamic	-0.33	-2.24	0.03
Organic Biodynamic	0.18	1.28	0.31
Conventional Bt-conventional	0.06	0.41	0.54
Organic Bt-conventional	0.57	3.95	<0.01
Organic Conventional	0.51	3.53	<0.01

Table B.3: Results of generalised linear mixed effect model comparing Araneae taxonomic group of the canopy- dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Blattodae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	0.06	1.13	0.23
Conventional Biodynamic	0.03	0.57	0.55
Organic Biodynamic	0.02	0.45	0.63
Conventional Bt-conventional	-0.03	-0.56	0.58
Organic Bt-conventional	-0.03	-0.68	0.55
Organic Conventional	-0.01	-0.12	0.94

Table B.5: Results of generalised linear mixed effect model comparing Cicadellidae taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Cicadellidae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	1.67	1.85	0.11
Conventional Biodynamic	-2.17	-2.30	<0.01
Organic Biodynamic	0.59	0.65	0.50
Conventional Bt-conventional	-3.84	-4.27	<0.01
Organic Bt-conventional	-1.08	-1.20	0.30
Organic Conventional	2.76	3.06	<0.01

Table B.4:Results of generalised linear mixed effect model comparing Coleoptera taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Coleoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.37	-2.51	<0.01
Conventional Biodynamic	-0.31	-2.09	0.05
Organic Biodynamic	-0.16	-1.09	0.30
Conventional Bt-conventional	0.06	0.15	0.66
Organic Bt-conventional	0.21	0.15	0.14
Organic Conventional	0.14	0.15	0.30

Table B.7: Results of generalised linear mixed effect model comparing Diptera taxonomic group of the canopy- dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Diptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.23	-1.32	0.14
Conventional Biodynamic	-0.15	-0.84	0.36
Organic Biodynamic	0.21	1.20	0.30
Conventional Bt-conventional	0.08	0.48	0.57
Organic Bt-conventional	0.44	2.54	0.02
Organic Conventional	0.35	2.05	0.07

Table B.8: Results of generalised linear mixed effect model comparing Others taxonomic group of the canopy- dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Others			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.23	-1.61	0.07
Conventional Biodynamic	0.08	0.57	0.61
Organic Biodynamic	-0.06	-0.42	0.69
Conventional Bt-conventional	0.31	2.18	0.02
Organic Bt-conventional	0.17	1.19	0.18
Organic Conventional	-0.14	-0.99	0.37

Table B.6: Results of generalised linear mixed effect model comparing Orthoptera taxonomic group of the canopy- dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Orthoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.06	-1.56	0.10
Conventional Biodynamic	-0.06	-1.39	0.14
Organic Biodynamic	0.04	1.01	0.41
Conventional Bt-conventional	0.01	0.17	0.81
Organic Bt-conventional	0.1	2.58	0.02
Organic Conventional	0.09	2.40	0.03

Ground-Dwelling arthropods community during the survey 2016

Table B.10: Results of generalised linear mixed effect model comparing Araneae taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Araneae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	0.07	0.13	0.75
Conventional Biodynamic	-0.05	-0.09	0.82
Organic Biodynamic	0.84	1.51	0.26
Conventional Bt-conventional	-0.13	-0.22	0.61
Organic Bt-conventional	0.77	1.38	0.31
Organic Conventional	0.89	1.60	0.24

Table B.9: Results of generalised linear mixed effect model comparing Blattodae taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Blattodae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.04	-1.66	0.06
Conventional Biodynamic	-0.01	-0.41	0.32
Organic Biodynamic	-0.05	-2.07	0.04
Conventional Bt-conventional	0.03	1.24	0.15
Organic Bt-conventional	-0.01	-0.41	0.76
Organic Conventional	-0.04	-1.66	0.18

Table B.12: Results of generalised linear mixed effect model comparing Coleoptera taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Coleoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.16	-1.04	0.37
Conventional Biodynamic	-0.39	-2.57	0.01
Organic Biodynamic	-0.38	-2.5	0.02
Conventional Bt-conventional	-0.23	-1.53	0.12
Organic Bt-conventional	0.01	-1.46	0.13
Organic Conventional	-0.39	0.07	0.93

Table B.11: Results of generalised linear mixed effect model comparing Dermoptera taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Dermoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	6.30E-17	0.00	1.00
Conventional Biodynamic	2.09E-02	1.16	0.31
Organic Biodynamic	7.51E-18	0.00	1.00
Conventional Bt-conventional	2.08E-02	1.16	0.31
Organic Bt-conventional	5.55E-17	0.00	1.00
Organic Conventional	2.08E-02	-1.16	0.31

Table B.14: Results of generalised linear mixed effect model comparing Diptera taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Diptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-3.13E-02	-0.37	0.70
Conventional Biodynamic	-4.18E-02	0.49	0.62
Organic Biodynamic	1.03E-15	0.00	1.00
Conventional Bt-conventional	-1.04E-02	-0.12	0.89
Organic Bt-conventional	3.13E-02	0.37	0.71
Organic Conventional	4.17E-02	0.49	0.63

Table B.13: Results of generalised linear mixed effect model comparing Isopoda taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Isopoda			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.02	-0.26	0.80
Conventional Biodynamic	0.04	0.52	0.65
Organic Biodynamic	-0.08	-1.04	0.28
Conventional Bt-conventional	0.06	0.78	0.45
Organic Bt-conventional	-0.06	-0.78	0.34
Organic Conventional	-0.13	-1.56	0.10

Table B.15: Results of generalised linear mixed effect model comparing Orthoptera taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Orthoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.09	-0.26	0.80
Conventional Biodynamic	-0.11	-0.31	0.76
Organic Biodynamic	-0.29	-0.79	0.41
Conventional Bt-conventional	-0.02	-0.06	0.96
Organic Bt-conventional	-0.19	-0.54	0.58
Organic Conventional	-0.18	-0.48	0.63

Table B.16: Results of generalised linear mixed effect model comparing Others taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2016

Others			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Bt-conventional Biodynamic	-0.28	-0.94	0.36
Conventional Biodynamic	-0.13	-0.42	0.72
Organic Biodynamic	-0.31	-1.04	0.28
Conventional Bt-conventional	0.15	0.52	0.61
Organic Bt-conventional	-0.03	-0.10	0.89
Organic Conventional	-0.18	-0.63	0.52

Canopy-Dwelling arthropods community during the survey 2017

Table B.18: Results of generalised linear mixed effect model comparing Araneae taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Araneae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	-0.38	-2.46	0.04
Organic Bt-conventional	0.17	1.15	<0.01
Organic Conventional	0.24	1.67	0.02
Bt-conventional Biodynamic	-0.56	-3.6	<0.01
Conventional Biodynamic	-0.63	-4.06	<0.01
Conventional Bt-conventional	-0.07	-0.46	0.38

Table B.17: Results of generalised linear mixed effect model comparing Blattodae taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Blattodae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	0.06	1.04	0.11
Organic Bt-conventional	0.15	2.45	0.01
Organic Conventional	0.07	1.11	<0.01
Bt-conventional Biodynamic	-0.09	-1.41	0.33
Conventional Biodynamic	-0.004	-0.07	0.07
Conventional Bt-conventional	0.08	1.34	0.40

Table B.20: Results of generalised linear mixed effect model comparing Cicadellidae taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Cicadellidae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	-1.11	-0.60	0.72
Organic Bt-conventional	0.59	0.32	0.06
Organic Conventional	1.08	0.58	0.30
Bt-conventional Biodynamic	-1.70	-0.92	0.03
Conventional Biodynamic	-2.19	-1.19	0.17
Conventional Bt-conventional	-0.49	-0.26	0.39

Table B.19: Results of generalised linear mixed effect model comparing Coleoptera taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Coleoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	-0.09	-0.86	0.09
Organic Bt-conventional	0.02	0.23	0.19
Organic Conventional	-0.03	-0.35	0.15
Bt-conventional Biodynamic	-0.11	-1.08	0.01
Conventional Biodynamic	-0.05	-0.51	<0.01
Conventional Bt-conventional	0.06	0.57	0.89

Table B.22: Results of generalised linear mixed effect model comparing Diptera taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Diptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	-0.08	-0.11	0.52
Organic Bt-conventional	-0.15	-0.21	0.01
Organic Conventional	-1.10	-1.61	0.24
Bt-conventional Biodynamic	0.07	0.10	0.04
Conventional Biodynamic	1.03	1.50	0.59
Conventional Bt-conventional	0.95	1.40	0.09

Table B.21: Results of generalised linear mixed effect model comparing Miridae taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Miridae			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	0.01	0.40	0.99
Organic Bt-conventional	-0.09	-0.36	0.34
Organic Conventional	-0.11	-0.41	0.08
Bt-conventional Biodynamic	0.11	0.40	0.31
Conventional Biodynamic	0.13	0.45	0.06
Conventional Bt-conventional	0.01	0.05	0.42

Table B.24: Results of generalised linear mixed effect model comparing Hemiptera taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Hemiptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	-0.08	-0.85	0.22
Organic Bt-conventional	-0.02	-0.19	0.25
Organic Conventional	0.002	0.02	0.18
Bt-conventional Biodynamic	-0.06	-0.67	0.11
Conventional Biodynamic	-0.08	-0.88	0.10
Conventional Bt-conventional	-0.02	-0.21	0.79

Table B.23: Results of generalised linear mixed effect model comparing Orthoptera taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Orthoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	0.61	1.27	0.23
Organic Bt-conventional	0.41	0.85	0.18
Organic Conventional	0.49	1.02	0.52
Bt-conventional Biodynamic	0.20	0.42	0.75
Conventional Biodynamic	0.12	0.25	0.48
Conventional Bt-conventional	-0.08	-0.17	0.37

Table B.25: Results of generalised linear mixed effect model comparing others taxonomic group of the canopy-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Others			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	0.04	1.33	0.42
Organic Bt-conventional	0.03	0.93	0.36
Organic Conventional	0.02	0.66	0.06
Bt-conventional Biodynamic	0.01	0.39	0.96
Conventional Biodynamic	0.02	0.66	0.39
Conventional Bt-conventional	0.01	0.27	0.40

Ground-Dwelling arthropods community during the survey 2017

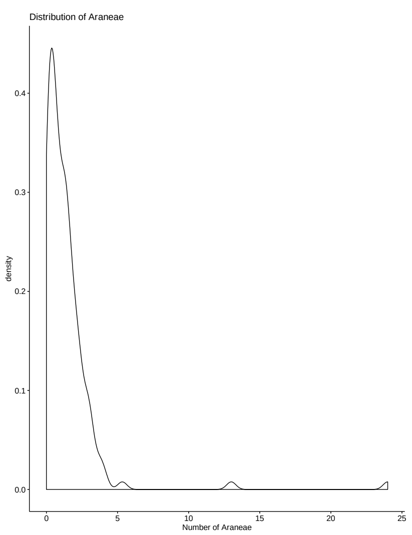

Figure B.4: Density plot analysing the Distribution of Araneae of the ground dwelling arthropods survey of 2017 generated in R

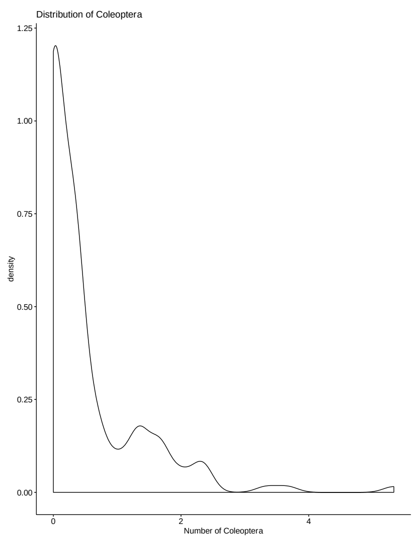

Figure B.3: Density plot analysing the Distribution of Coleoptera of the ground dwelling arthropods survey of 2017 generated in R

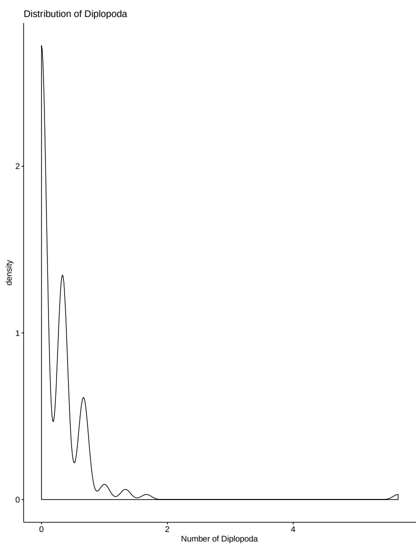

Figure B.2: Density plot analysing the Distribution of Diplopoda of the ground dwelling arthropods survey of 2017 generated in R

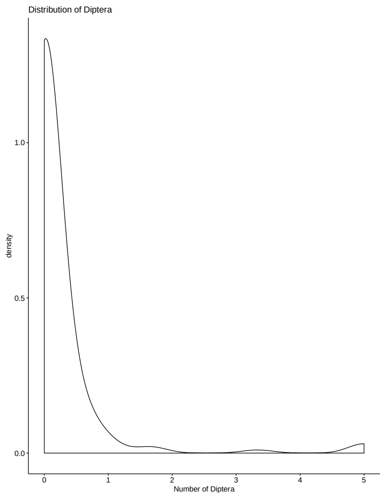

Figure B.7: Density plot analysing the Distribution of Diptera of the ground dwelling arthropods survey of 2017 generated in R

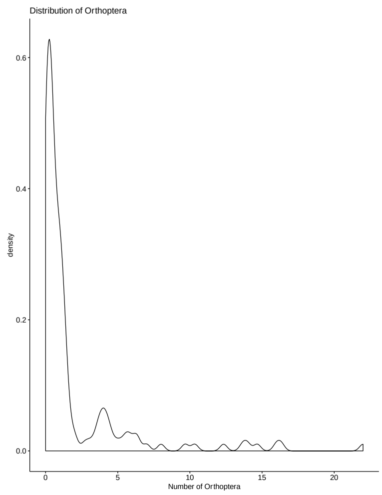

Figure B.6: Density plot analysing the Distribution of Orthoptera of the ground dwelling arthropods survey of 2017 generated in R

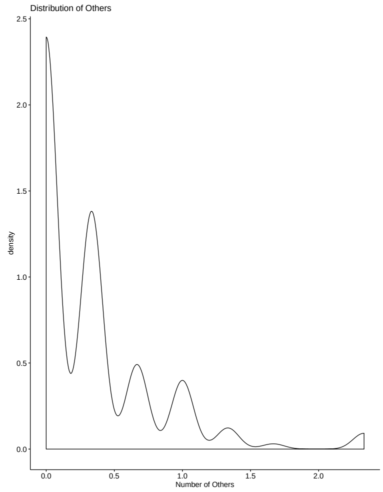

Figure B.5: Density plot analysing the Distribution of Others of the ground dwelling arthropods survey of 2017 generated in R

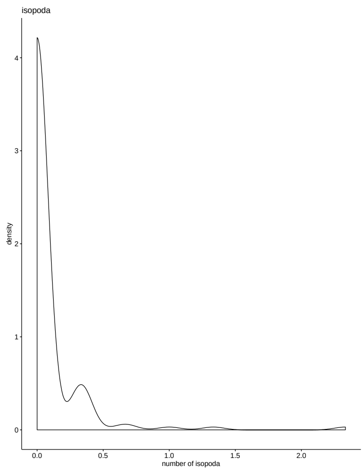

Figure B.9: Density plot analysing the Distribution of Zygentoma of the ground dwelling arthropods survey of 2017

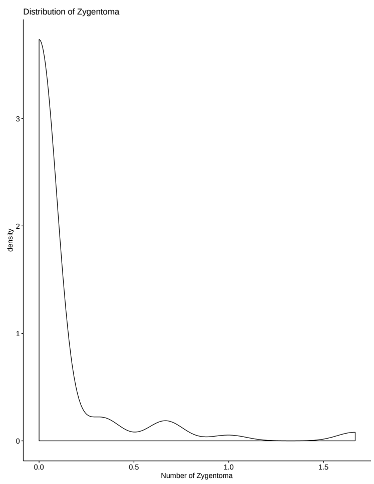

Figure B.8: Density plot analysing the Distribution of Isopoda of the ground dwelling arthropods survey of 2017

Table B.27: Results of generalised linear mixed effect model comparing Araneae taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Araneae			
Fixed effects	**Estimate**	**z value**	**Pr(>Izl)**
Organic Biodynamic	-0.08	-0.14	0.12
Organic Bt-conventional	-0.78	-1.42	0.46
Organic Conventional	-0.53	-0.98	0.14
Bt-conventional Biodynamic	-0.7	-1.28	0.91
Conventional Biodynamic	-0.46	-0.84	0.02
Conventional Bt-conventional	0.24	0.97	0.25

Table B.26: Results of generalised linear mixed effect model comparing Coleoptera taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Coleoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>Izl)**
Organic Biodynamic	0.1	0.451	0.38
Organic Bt-conventional	-0.09	-0.41	0.36
Organic Conventional	0.04	0.19	0.15
Bt-conventional Biodynamic	-0.19	-0.86	0.27
Conventional Biodynamic	-0.06	-0.26	0.24
Conventional Bt-conventional	0.13	0.6	0.11

Table B.28: Results of generalised linear mixed effect model comparing Isopoda taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Isopoda			
Fixed effects	**Estimate**	**z value**	**Pr(>Izl)**
Organic Biodynamic	0.03	0.36	0.31
Organic Bt-conventional	-0.08	-1.19	0.12
Organic Conventional	-0.03	-0.36	0.46
Bt-conventional Biodynamic	0.11	1.54	0.04
Conventional Biodynamic	0.05	0.71	0.10
Conventional Bt-conventional	-0.06	-0.83	0.31

Table B.29: Results of generalised linear mixed effect model comparing Orthoptera taxonomic group of the ground dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Orthoptera			
Fixed effects	**Estimate**	**z value**	**Pr(>Izl)**
Organic Biodynamic	0.77	0.72	0.56
Organic Bt-conventional	0.61	0.58	0.04
Organic Conventional	-0.2	-0.19	0.10
Bt-conventional Biodynamic	-0.16	-0.15	0.12
Conventional Biodynamic	-0.97	-0.91	0.23
Conventional Bt-conventional	-0.81	-0.76	0.79

Table B.30: Results of generalised linear mixed effect model comparing Zygentoma from the ground-dwelling arthropods community in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Zygentoma			
Fixed effects	**Estimate**	**z value**	**Pr(>lzl)**
Organic Biodynamic	0.03	0.38	0.46
Organic Bt-conventional	0.02	-0.25	0.73
Organic Conventional	-0.07	-1.00	0.27
Bt-conventional Biodynamic	0.04	0.63	0.39
Conventional Biodynamic	0.09	1.38	0.12
Conventional Bt-conventional	0.05	0.75	0.47

Canopy-Dwelling arthropods community for the survey 2016-2017

Table B.31: Results of generalised linear mixed effect model comparing all the taxonomic groups of the canopy-dwelling arthropods community for the survey 2016-2017

	2016-2017		
	Estimate	**Z value**	**Pr(l>zl)**
Araneae	-0.18	1.51	0.14
Blattodae	0.05	-1.09	0.23
Cicadellidae	-0.7	1.03	<0.01
Coleoptera	0.22	-1.85	0.02
Diptera	0.46	-3.12	<0.01
Hemiptera	1.06	-4.9	<0.01
Miridae	1.23	-10	<0.01
Orthoptera	0.05	-1.56	<0.01
Others	0.34	-2.85	<0.01

Canopy-Dwelling arthropods community during the survey 2018 on the farm-scale trial

Table B.33: Results of generalised linear mixed effect model comparing Aphidae from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Aphidae	Estimate	z value	Pr(>zl)
Organic Bt-conventional	-0.21	0.55	0.28

Table B.32: Results of generalised linear mixed effect model comparing Araneae from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Araneae	Estimate	z value	Pr(>zl)
Organic Bt-conventional	0.84	-2.34	0.01

Table B.35: Results of generalised linear mixed effect model comparing Chrysopidae taxonomic from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Chrysopidae	Estimate	z value	Pr(>zl)
Organic Bt-conventional	0.04	-0.37	0.36

Table B.34: Results of generalised linear mixed effect model comparing Cicadellidae from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Cicadellidae	Estimate	z value	Pr(>zl)
Organic Bt-conventional	6.11	-1.69	0.05

Table B.37: Results of generalised linear mixed effect model comparing Coleoptera from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Coleoptera	Estimate	z value	Pr(>zl)
Organic Bt-conventional	1.25	-2.43	0.01

Table B.36: Results of generalised linear mixed effect model comparing Diptera from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Diptera	Estimate	z value	Pr(>zl)
Organic Bt-conventional	0.23	-0.35	0.36

Table B.38: Results of generalised linear mixed effect model comparing Miridae taxonomic from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Miridae	Estimate	z value	Pr(>zl)
Organic Bt-conventional	1.35	-1.47	0.07

Table B.39: Results of generalised linear mixed effect model comparing Orthoptera from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Orthoptera	Estimate	z value	Pr(>zl)
Organic Bt-conventional	0.03	-0.6	0.27

Table B.40: Results of generalised linear mixed effect model comparing Others taxonomic from the canopy-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) durina the survev 2018

	Others		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	0.18	-0.77	0.22

Ground-Dwelling arthropods community during the survey 2018 on the farm-scale trial

Table B.42: Results of generalised linear mixed effect model comparing Araneae taxonomic from ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

	Araneae		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	1.13	-1.68	0.05

Table B.41: Results of generalised linear mixed effect model comparing Coleoptera from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

	Coleoptera		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	-0.06	0.16	0.38

Table B.44: Results of generalised linear mixed effect model comparing Diptera from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

	Diptera		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	-0.31	1.65	0.05

Table B.43: Results of generalised linear mixed effect model comparing Diplopoda from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

	Diplopoda		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	-0.06	0.31	0.30

Table B.46: Results of generalised linear mixed effect model comparing Isopoda taxonomic from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

	Isopoda		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	-0.17	1.27	0.10

Table B.45: Results of generalised linear mixed effect model comparing Lepidoptera from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

	Lepidoptera		
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	0.19	-0.95	0.10

Table B.48: Results of generalised linear mixed effect model comparing Orthoptera from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Orthoptera			
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	0.17	-0.46	0.32

Table B.49: Results of generalised linear mixed effect model comparing Others from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Others			
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	0.09	-0.73	0.21

Table B.47: Results of generalised linear mixed effect model comparing Zygentoma from the ground-dwelling arthropods community in two different farming systems (Organic, Bt-conventional) during the survey 2018

Zygentoma			
	Estimate	**z value**	**Pr(>zl)**
Organic Bt-conventional	-0.2	1.20	0.12

Appendices C

Earthworm density and biomass significance during the survey 2017 on the plot-scale trial

Table C.51: Results of generalised linear mixed effect model comparing earthworm biomass in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Biomass 2017			
	Estimate	**z value**	**Pr(>zl)**
Biodynamic Bt-conventional	9.77	2.45	<0.01
Biodynamic Conventional	-10.09	-2.53	<0.01
Biodynamic Organic	1.61	-0.40	0.77
Conventional Bt-conventional	0.32	-0.08	-0.58
Organic Bt-onventional	8.17	2.05	<0.01
Organic Conventional	8.48	2.13	<0.01

Table C.50: Results of generalised linear mixed effect model comparing earthworm density in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2017

Density 2017			
	Estimate	**z value**	**Pr(>zl)**
Biodynamic Bt-conventional	105.50	-3.20	<0.01
Biodynamic Conventional	109.00	-3.30	<0.01
Biodynamic Organic	-5.50	-0.17	0.90
Conventional Bt-conventional	-3.50	-0.11	0.68
Organic Bt-onventional	100.00	3.03	<0.01
Organic Conventional	103.50	3.14	<0.01

Earthworm density and biomass significance during the survey 2018 on the plot-scale trial

Table C.52: Results of generalised linear mixed effect model comparing earthworm biomass in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2018

Biomass 2018	Estimate	z value	Pr(>zl)
Biodynamic Bt-conventional	6.22	-2.61	<0.01
Biodynamic Conventional	-6.52	-2.73	<0.01
Biodynamic Organic	-1.07	0.35	0.41
Conventional Bt-conventional	-0.30	-0.13	0.45
Organic Bt-onventional	5.15	2.16	<0.01
Organic Conventional	5.45	2.29	<0.01

Table C.53: Results of generalised linear mixed effect model comparing earthworm density in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2018

Density 2018	Estimate	z value	Pr(>zl)
Biodynamic Bt-conventional	-154.00	-3.85	<0.01
Biodynamic Conventional	-141.71	-3.45	<0.01
Biodynamic Organic	19.14	0.48	0.61
Conventional Bt-conventional	12.29	0.31	0.12
Organic Bt-onventional	173.14	4.33	<0.01
Organic Conventional	160.86	4.02	<0.01

Earthworm density and biomass significance during the survey 2018 on the farm-scale trial

Table C.55: Results of generalised linear mixed effect model comparing earthworm biomass in two different farming systems (Organic, Bt-conventional) during the survey 2018

Biomass 2018	Estimate	z value	Pr(>zl)
Organic Bt-onventional	12.84	2.37	0.02

Table C.54: Results of generalised linear mixed effect model comparing earthworm density in four different farming systems (Organic, Bt-conventional) during the survey 2018

Density 2018	Estimate	z value	Pr(>zl)
Organic Bt-onventional	87.11	2.49	0.02

Abiotic factors significance during the survey 2018 on the plot-scale trial

Table C.57: Results of generalised linear mixed effect model comparing Organic Carbon (OC) in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2018

	OC (kg/ha)		
	Estimate	z value	Pr(>zl)
Biodynamic Bt-conventional	-1053.90	-1.41	0.49
Biodynamic Conventional	-2662.70	-3.57	<0.01
Biodynamic Organic	-582.10	-0.78	0.86
Conventional Bt-conventional	-1608.80	-2.16	0.14
Organic Bt-onventional	471.10	0.63	0.92
Organic Conventional	2080.50	2.79	0.03

Table C56: Results of generalised linear mixed effect model comparing Electric Conductivity in four different farming systems (Biodynamic, organic, Bt-conventional, conventional) during the survey 2018

	EC		
	Estimate	z value	Pr(>zl)
Biodynamic Bt-conventional	70.50	3.41	<0.01
Biodynamic Conventional	-3.75	-0.18	0.99
Biodynamic Organic	8.00	0.39	0.98
Conventional Bt-conventional	-74.25	-3.59	<0.01
Organic Bt-onventional	-62.50	-3.02	0.01
Organic Conventional	11.75	0.57	0.94

Abiotic factors significance during the survey 2018 on the farm-scale trial

Table C.59: Results of generalised linear mixed effect model comparing Electric Conductivity in two different farming systems (Organic, Bt-conventional) during the survey 2018

	EC		
	Estimate	z value	Pr(>zl)
Organic Bt-onventional	-154	8.23	<0.01

Table C.58: Results of generalised linear mixed effect model comparing Electric Conductivity in two different farming systems (Organic, Bt-conventional) during the survey 2018

	pH		
	Estimate	z value	Pr(>zl)
Organic Bt-onventional	-0.37	7.85	<0.01

Primer for the fungi community for the 2016 and 2017 surveys on the plot-scale trial

Table C.60: results for the Analysis of similarities with 999 number of permutations comparing four cotton farming systems (Biodynamic, organic, conventional and Bt-conventional) for the 2016 and 2017

Systems	R statistic	Significance level	Number >= Observed
Biodynamic Organic	0.03	0.03	33
Biodynamic Conventional	0.34	<0.01	0
Biodynamic Bt-conventional	0.32	<0.01	0
Organic Conventional	0.19	<0.01	0
Organic Bt-conventional	0.15	<0.01	0
Conventional Bt-conventional	0.02	0.11	104

Fungi species richness significance for the 2016 and 2017 surveys on the plot-scale trial

Table C.61: Results of generalised linear mixed effect model comparing fungi species richness in four different farming systems (Organic, biodynamic, conventional, Bt-conventional) during the survey 2016 and 2017

	Species Richness		
	Estimate	**z value**	**Pr(>Izl)**
Organic Biodynamic	-2.32	-3.22	0.85
Organic Bt-conventional	0.14	0.20	0.99
Organic Conventional	1.75	2.41	0.07
Biodynamic Bt-conventional	-0.71	-1.00	0.75
Biodynamic Conventional	-2.32	-3.23	<0.01
Bt-conventional Conventional	-1.61	-2.20	0.12

Table C.62: Results of generalised linear mixed effect model comparing Trichoderma presence in four different farming systems (Organic, biodynamic, conventional, Bt-conventional) during the survey 2016 and 2017

Trichoderma			
	Estimate	**z value**	**Pr(>lzl)**
Organic Biodynamic	0.05	0.33	0.99
Organic Bt-conventional	0.68	4.53	<0.01
Organic Conventional	0.73	4.80	<0.01
Biodynamic Bt-conventional	0.64	4.24	<0.01
Biodynamic Conventional	0.68	4.51	<0.01
Bt-conventional Conventional	0.05	4.51	<0.01

Appendices D

Table D.63: List of selected Environment indicators to assess the sustainability of the farming systems with the added ecological indicators highlighted in pink-

Theme	Sub-theme		Sub-theme	S.N.	Indicators	Farmer survey	Field survey	Research
I.Environment	1.1.Pest and Pesticide managem ent	1.1.1.	Pesticide application	1.1.1.1.	Quantity of active ingredients of pesticde used (kg/ha)			
				1.1.1.2.	Quantity of active ingredients of highly hazardous pesticides used (kg/ha) pesticde used (kg/ha)			
				1.1.1.3.	Number of pesticide applications per season			
		1.1.2.	Action to minimise pesticide	1.1.2.1.	Existence of a time-bound IPM plan			
		1.1.3.	Register Pesticide	1.1.3.1	The farm uses only pesticides which are nationally registered to use on cotton			
				1.1.3.2.	The farmer uses pesticides which are labelled according to national standards, in at least one national language			
		1.1.4.	Pesticide safety	1.1.4.1.	The farmer uses proper disposal methods for pesticide containers and contaminated materials including discarded pesticide application equipment			
				1.1.4.2.	The farmer is following the national recommended practices for pesticide mixing and application and cleaning of application equipment			
				1.1.4.3.	The farmer has dedicated storage facilities that keep pesticides safely and out of reach of children			
		1.1.5.	Pesticide and health	1.1.5.1.	Total percentage of cotton area involving vulnerable persons applying pesticides			
				1.1.5.2.	(Percentage) of workers applying pesticides that have received training in handling and use			
				1.1.5.3.	The Farmer has access to and uses adequate /provides to the workers/ protective equipment (by type)			
				1.1.5.4.	Knowledge on effect on pesticide on human			

I.Environment	1.2.Soil Management	1.2.1.	Soil Analysis	1.2.1.1	Soil characteristics: organic matter content,			
				1.2.1.2.	Soil characteristics: pH			
				1.2.1.3.	Use of soil sampling for N, P, K			
		1.2.2.	Soil Fertility	1.2.2.1.	Fertilizer used by type (kg/ha) - Quantity and type of fertilizer applied can provide an indication of integrated soil fertility			
				1.2.2.2.	Soil management			
		1.2.3.	Soil Health	1.2.3.1.	Bio-indicator: Earthworm diversity			
	1.3.Biodiversity and Land use	1.3.1.	Production	1.3.1.1.	Average yield (tonne of cotton lint/ha)			
		1.3.2.	Crop diversity	1.3.2.1.	Total area (ha) and % of natural vegetation converted for cotton production (ha)			
				1.3.2.2.	Border crops			
				1.3.2.3.	crops per 3-year period -crop rotation			
		1.3.3.	Ecosystem services	1.3.3.1.	Scoring of the Ecosystem services provided by the system			

Table D.64: List of selected Economy indicators to assess the sustainability of the farming systems

Theme	Sub-theme	S.N.	Sub-theme	S.N.	Indicators	Farmer survey	Field survey	Research
2. Economy	2.1.Economic viability, Poverty reduction and Food Security	2.1.1.	Cotton economic viability	2.1.1.1.	Price received per tonne of cotton lint at farmgate (last 3 years)			
		2.1.2.	Food security	2.1.2.1.	Number of days with food deficiency per annum in cotton-producing households			
	2.2.Economic Risk management	2.2.2.	Volatility	2.2.2.1.	Cotton yield volatility			
				2.2.2.2.	Farmgate cotton price volatility			
		2.2.3.	Risk manageme nt	2.2.3.1.	Farmer has taken measures to manage price risks			
				2.2.3.2.	cotton represents the largest income of the household			
		2.2.4.	Payment and Prices fluctuation	2.2.4.1.	Average number of days after sale that farmers receive payment			
				2.2.4.2.	Farmer has access to equitable credit			
				2.2.4.3.	Farmer is showing understanding of the factors involved in price formation or with daily access to international and domestic prices			

Table D.65: List of selected Social indicators to assess the sustainability of the farming systems with the added indicators highlighter in blue and pink

Theme	Sub-theme	S.N.	Sub-theme	S.N.	Indicators	Farmer survey	Field survey	Research
3. Social	3.1.Labour Rights and gender equality	3.1.1.	Employment	3.1.1.1.	Number of child labourers (by age and gender)			
				3.1.1.2.	% of workers with an enforceable employment contract (by age and gender)			
				3.1.1.3.	% of workers who are paid a minimum or living wage and who always receive their full wage in time (by age and gender)			
		3.1.2.	Gender equality	3.1.2.1.	Gender and age wage differentials for the same quantity of produce or same type of work			
				3.1.2.2.	% of children of the farmer attending and completing appropriate level of school (by gender)			
	3.2.business resilience	3.2.1.	3.2.1.	3.2.1.1.	Quality of life			
				3.2.1.2.	Future expectation			
	3.3.economical security	3.3.1.	3.3.1.	3.3.1.1.	Farmer is contributing to a pension scheme and/or eligible to receive a pension			

3. Social	3.4.Worker health and safety	3.4.1.	Safety	3.4.1.1.	Annual non-fatal incidences on cotton farms (total, % of workforce by age, gender)			
				3.4.1.2.	Total number of fatalities on cotton farms per year			
				3.4.1.3.	Safety of the farming system			
		3.4.2.	Health	3.1.2.1.	Farmer has effective access to health care facilities			
				3.1.2.2.	Farmer has access to potable water			
				3.1.2.3.	Farmer has access to sanitation facilities			
	3.5.Farmer Organization	3.5.1.	Farmer Organisation	3.5.1.1.	Farmer has attended training (by training type, age and gender)			
				3.5.1.2.	Farmer is participating in democratic organizations (by age and gender)			
	3.6.Farmers knowledge	3.6.1.	Farmers knowledge	3.6.1.1	Ecological knowledge			
				3.6.1.2.	Farmer's education			
				3.6.1.3.	Farmer is showing understanding of the factors involved in price formation or with daily access to international and domestic prices			
				3.6.1.4.	Knowledge on effect on pesticide on human			

Pest and pesticide management

The pesticides names were extracted from the interview and researched (Table D.66). The pesticides used were classified according to their hazard by using the reference from the World Health Organization recommended classification of Pesticide by Hazard (WHO, 2008) (Table D.67).

Pesticide application

Table D.66: Questionnaire: Table used to enter the pesticide and fertiliser used during the farmers'interviews.

Pesticide/Fertiliser Application				
		Quantity	From where	Price
Fertiliser				
1	Diammonium Phosphate			
2	NPK			
3	Farmyard Manure			
4	Single Super Phosphate			
5	Urea			
6	Muriate of Potash			
7	Neem Seed Cake			
8	Compost			
9				
10				
11				
Pesticide				
1	Acephate			
2	Comfidor			
3	Monocrotophos			
4	Trizophos			
5	Fermented Butter Milk			
6	Neem Oil			
7	Cow Urine			
8				
9				
10				

Table D.67: Pesticide used by the farmers: active ingredients and classification (extracted from(WHO, 2008)*)*

Active ingredients list	Chemical type	GHS	Class	Remarks
imidacloprid	NA	4	II	http://www.inchem.org/documents/icsc/icsc/eics1501.htm
Monocrotophos	Organophosphate	2	Ib	http://www.inchem.org/documents/icsc/icsc/eics0181.htm
Acephate	Organophosphate	4	II	http://www.inchem.org/documents/icsc/icsc/eics0748.htm

Ia: Extremely hazardous, Ib: Highly hazardous, II: Moderately hazardous, III: slightly hazardous, U: Unlikely to present acute hazard in normal use

Table D.68: Sustainability scoring card for the indicators 1.1.1.1, 1.1.1.2., 1.1.1.3.

	For each active ingredients	
1.1.1.1.	Quantity of active ingredients of pesticide used (above recommendation)	1
	Quantity of active ingredients of pesticide used (same or below recommendation)	3
	No use	5
1.1.1.2.	higly hazardous pesticide (banned in other countries)	1
	Highly hazardous pesticide (not banned in other countries)	3
	no use of hazardous pesticide	5
1.1.1.3.	Application gap recommendation respected (3 to 7 days)	5
	Application gap recommendation not respected (3 to 7 days)	1

Action to minimize pesticides

Table D.69: Questionnaire: Questions used during the farmers' interviews for the indicators 1.1.2.

1.1.2.a. Do you consider all insect pests?
1.1.2.b. Do you try to encourage beneficial insects on your farm?
1.1.2.c. How
1.1.2.d. Do you try to avoid targetting beneficial insects?
1.1.2.e. How?

Table D.70: Sustainability scoring card for the indicator 1.1.2.

1.1.2	Do you consider all insect pests?	Yes	1
		No	5
1.1.2	Do you try to encourage beneficial insects on your farm?	Yes	5
		No	1
1.1.2	How?	none	1
	P1: Border crops	at least 1P	2
	P2: Intercropping	at least 2P	3
	P3: targetted application	at least 3P	4
	P4: Other	at least 4P	5
1.1.2	Do you try to avoid targetting beneficial insects?	Yes	5
		No	1
1.1.2	How?	none	1
	P1: Border crops	at least 1P	2
	P2: Intercropping	at least 2P	3
	P3: targetted application	at least 3P	4
	P4: Other	at least 4P	5

Registered Pesticide

Table D.71: Sustainability scoring card for the indicators 1.1.3.

1.1.3.1	The farm uses pesticides which are nationally registered to use on cotton		
		registered	5
		not registered	1
1.1.3.2	The farmer uses pesticides which are labelled according to national standards,		
		yes	5
		no	1

Pesticide safety

Table D.72: Questionnaire: Questions used during the farmers' interviews for the indicators 1.1.4.

1.1.4.1.	What do you do with the application equipment once used?
1.1.4.2.	Do you get a training to know the quantity to apply?
1.1.4.2.	where is the training?
1.1.4.3.	Where do you store your pesticide ?

Table D.73: Sustainability scoring card for the indicators 1.1.4.

1.1.4.1.	What do you do with the application equipment once used?	Dedicated area	5
		Outside	3
		In the house	1
1.1.4.2.	Do you get a training to know the quantity to apply?	Yes	5
		No	1
1.1.4.2.	where is the training?	Organisation-	5
		Shopkeeper	3
		None	1
1.1.4.3.	Where do you store your pesticide ?	Dedicated area	5
		Outside	3
		In the house	1

Pesticide and health

Table D.74: Questionnaire: Questions used during the farmers' interviews for the indicators 1.1.5.

1.1.5.2.	Does the workers get training?
1.1.5.2.	Where do they get their training
1.1.5.3.	Applier uses protection
1.1.5.4.	Do you know the effect of pesticide on human being?

Table D.75: Sustainability scoring card for the indicators 1.1.5.

1.1.5.2.	Does the workers get training?	Yes	5
		No	1
1.1.5.2.	Where do they get their training	Organisation-Governement	5
		Shopkeeper	3
		Farmer	2
		None	1
1.1.5.3.	Applier uses protection	nothing	1
	(item 1: mask	1 item	2
	item 2: gloves	2 items	3
	item 3: long sleeves)	3 items	4
		special protection	5
1.1.5.4.	Do you know the effect of pesticide on human being?	Yes	5
		No	1

Soil management

During the interviews, farmers were asked the name and quantity of the fertilizers they were using in their field during the cotton season. The soil chemistry of each farm was analysed and assessed.

For the abiotic factors, soil samples were analysis in the laboratory. The methodology of the soil analysis has been detailed in the belowground biodiversity chapter. Organic matter, pH and bulk density of the soil were assessed and used as soil indicators in this assessment.

An ecological indicator was added to assess the soil health. Earthworms were used as bio-indicators. Belowground earthworm surveys have been conducted in Bt-conventional and organic farming systems to evaluate which system was the most ecologically sustainable.

Soil Analysis

Table D.76:Sustainability scoring card for the indicators 1.2.1.

1.2.1.1 Soil analysis methodology and results can be found in Chapter 4 For the performance of the abiotic factors, standards are presented below.

Bulk Density: A normal range of bulk densities for clay is 1.0 to 1.6 (Chaudhari et al., 2013). If the bulk density was below or above the normal range, the performance sustainability score of this indicator was given 1, if the bulk density was in the normal range, the performance sustainability score was given 5. For clay soil, the ideal standard electric conductivity, anon-saline clay has an electric conductivity between 0 to 1.4 EC. If the EC was between 0 and 1.4, the sustainability performance score was given 5, and if the EC was outside the range, the sustainability performance was given 1 (USDA, n.d.).

1.2.1.2.

1.2.1.3.	Do you get your soil tested (soil health scheme)?	Never	1
		more than 5 years	2
		I test a few fields "every few years"	3
		I test some fields "every two years"	4
		I test some fields "every year" to monitor long-term change	5

Soil fertility

Table D.77:Sustainability scoring card for the indicators 1.2.2.

1.2.2.1.	For each fertiliser used	
	Fertiliser used by types (Above recommendation)	1
	Fertiliser used by types (Same or below recommendation)	5
	No use of fertilisers	5

Table D.78: Questionnaire: Questions used during the farmers' interviews for the indicators 1.2.2.

1.2.2.2.	Once your cotton crop has been harvested, how to you get ride of the remaining biomass Incorporate % Burning: % Grazing: no/yes Other:

Table D.79:Sustainability scoring card for the indicators 1.2.2.

1.2.2.2.	Incorporate	100-81%	5
		80-61%	4
		60-41%	3
		40-21%	2
		20-0%	1
1.2.2.2.	Burning	0-20%	5
		21-40%	4
		41-60%	3
		61-80%	2
		81-100%	1
1.2.2.2.	Grazing	Yes	5
		No	1

Soil health

Table D.80: Sustainability scoring card for the indicators 1.2.3.

1.2.3.1. For the Soil health indicator, earthworms were used as a bio-indicator. It has been recognized as a valuable monitoring tools to understand the soil health and represent well the amount of diversity present in the soil.

The pre-surveys were done for two years in the long-term trial (refer to chapter 5 on below ground biodiversity for more details).

To assess the soil health, earthworm density and biomass were used as two indicators.

As this was a comparative study, the highest average earthworm biomass data was considered the most sustainable one, scoring a 5. The quartiles were calculated using the data from 12 surveyed farms. The average earthworm biomass data included in the first quartile was scoring 1, the average earthworm biomass data included in the second quartile was scored 2, the average earthworm biomass data included in the third quartile 3, the data included in the third 4th was scored 4. The same process was applied to the average earthworm abundance data.

Biodiversity and Land use

The farmers were asked about their farm productivity and the price they received at the farmgate for the last three years. They were also asked about the other crops they were growing apart from cotton. An ecological indicator was added to this sub-theme about ESs provided by the canopy dwelling biodiversity. The details of the methodology and results for the indicator 1.3.3. can be found in Chapter 5.

Production

Table D.81: Questionnaire: Table used during the farmers' interviews for the indicators 1.3.1.

1.3.1. Production and Market/cotton viability			
	2016-2017	2017-2018	2018-2019
kg/ha			
Rs per KG			
Total received			
Do you think to be in profit or debts			
Why your yield differ from the previous year			
Mandir			
Distance			
Mode of transport by transport			
Cost of transport			
How many time transport hire			
BioRe (house)			
Mode of Payment			

Table D.82:Sustainability scoring card for the indicators 1.3.1.

Madhya Pradesh	2016-2017	2017-2018(P)	2018-19(NA)
lakh ha	5.99	6.03	
lakh bales	20.5	20.5	
bales per ha	3.4224	3.3997	
kg/ha	581.8	577.94	

http://www.cicr.org.in/database/dbcapp5.html

1.3.1.1.	Below average	1
	Same as average (+/- 10%)	3
	Above average	5

* Data for the production benchmark for the state of Madhya Pradesh was available on the CICR website. Data were available for the year 206-2017 and 2017-2018.

When the production was below average, the score given was 1. if the average yield was +/- 10%, the score given was 3, if the yield was above average, the score given was 5.

Crop diversity

Table D.83: Questionnaire: Questions and table used during the farmers' interviews for the indicators 1.3.2.

1.3.2.2. Do you have border crops?

1.3.2.3. Crop crop rotation						
	crop1	crop2	crop3	crop4	crop5	crop6
2018						
2017						
2016						

Table D.84: Sustainability scoring card for the indicators 1.3.2.

1.3.2.2.	Do you have border crops	Yes	5
		No	1
1.3.2.3.	Total number of crops over 3 years	1-3 crop species/varieties	1
		4-6 crop species /varieties	2
		7-9 crop species /varieties	3
		10-12 crop species /varieties	4
		13-15 + crop species/varieties	5

Ecosystem services

Table D.85:Sustainability scoring card for the indicators 1.3.3.

1.3.3. Very little literature is available for pest:predators ratio. However, we follow the recommendation given by the government of India on the ratio which is below the economic threshold in cotton farming system. Araneae and C.sexmaculata have been recognised as predators and their number have been added to represent the predators. We selected these two predators as they show to be significantly different in farming system and/or has been show to be of an economical importance as bio-control against the main pest jassids. The economic threshold level was 1.5:1 specifically for jassids to predator ratio and 2:1 for general pest to predator ratio. This is how the scoring has been done, 5 if the ratio was below the jassids economic threshold level, 4 if the ratio was between the jassids ratio economic threshold level and the general economic threshold level, 2 if the ratio was above the general economic threshold level and 1 if the ratio was ten times above the economic threshold level. Thanks to this rating, the ratio pest:predators were converted to a ecological indicator that I integrated to the sustainable assessment framework.

Economy

Economy viability and food security

Cotton economic viability

Table D.86: Sustainability scoring card for the indicators 2.1.1

	2016-2017	2017-2018	2018-2019
MSP per quintal	₹4160	₹4320	₹5450
MSP per kg	₹41.6	₹43.2	₹54.4

http://agricoop.nic.in/sites/default/files/english.pdf

2.1.1.1.	Above MSP	5
	MSP (+/- 10%)	3
	Below MSP	1

* Looking at the price of the pesticide used in the 3 last year to see if there were fluctuation in the market using online resources.

Food security

Table D.87: Questionnaire: Questions used during the farmers' interviews for the indicators 2.1.2.

2.1.2.1.	Do you eat enough everyday?

2.1.2.1.	Do you eat enough everyday?	Eat enough	5
		eat but "still hungry"	3
		eat but "not every meal"	1

Economic Risk management

The percentage of volatility of the cotton yield over three consecutive years was calculated and a score was given accordingly, the same was done for the farmgate price. A series of questions was being asked to the farmers during the interview to understand the risk management.

Volatility

2.2.2.1. Yield Volatility		
	0-19.9%	5
	20-39.9%	4
	40-59.9%	3
	60-79.9%	2
	80-100%	1

2.2.2.2.	Farmgate Price Volatility		
		0-19.9%	5
		20-39.9%	4
		40-59.9%	3
		60-79.9%	2
		80-100%	1

Risk management

Table D.88: Questionnaire: Questions used during the farmers' interviews for the indicators 2.2.3.

2.2.3.1.a	Do you have a back up for low price or low
2.2.3.1.b	If your crop fail, if your crop has failed will the
2.2.3.1.c	Do you have other source of incomes?
2.2.3.2.	Is cotton your main income over the year?

Table D.89:Sustainability scoring card for the indicators 2.2.3.

2.2.3.1.	The farmer has a back up for low price or low yield?	Yes	5
		No	1
2.2.3.1.	If the farmer's crop fail the government gives indemnity?	Yes	5
		No	1
2.2.3.1.	The farmer has other sources of incomes?	No	1
		Crops	2
		Other Activity	4
		crops and activity	5
2.2.3.1.	Cotton is the main income over the year	No	5
		Yes	1

Payment and Prices fluctuation

Table D.90: Questionnaire: Questions used during the farmers' interviews for the indicators 2.2.4.

2.2.4.1.	After how many days do you receive payment?
2.2.4.2.	Have you taking loans in the past?
2.2.4.3.	Why does the price of the cotton change every year?

Table D.91: Sustainability scoring card for the indicators 2.2.4.

2.2.4.1.	Average number of days after sale that farmer received payment	less than a week	5
		more than a week	1
2.2.4.2.	Have you taking loans in the past?	No because "no access to loan"	1
		"yes" because of crop lost	3
		"No" but access to loan	5
2.2.4.3.	Why does the price of the cotton change every year?	Don't know	1
		Some idea	3
		Understand very well	5

Social

Labour rights and gender equality

Farmers were questioned about the labourers who work on their farm. Questions were asked about their salary, mode of payment, type of work the labourers were doing on the farm. The second part of this sub-theme is about gender equality.

Table D.92: Questionnaire: Questions used during the farmers' interviews for the indicators 3.1.1. and 3.1.2.

Employment									
	Number of people	Total days worked per season	Price per day	Type of work: Fertiliser application	Type of work: Weeding	Type of work: Picking	Type of work: other	Paid under 250 a day	Do you hire labour day to day or do you promise them a number of days?
Women								Yes/No	Yes/No
Men								Yes/No	Yes/No

Employment

Table D.93: Questionnaire: Questions used during the farmers' interviews for the indicators 3.1.1.

3.1.1.1.	Do you hire children for some activities (picking up cotton)?
3.1.1.2.	Do your workers have an enforceable contract?
3.1.1.3.a.	Do you pay your employee on time?
3.1.1.3.b.	How many hours do they work per day?

Table D.94: Sustainability scoring card for the indicators 3.1.1.

3.1.1.1.	Hire children for some activities (picking up cotton?)	Yes No	5 1
3.1.1.2.	Workers have a enforceable employment contract	Yes No	5 1
3.1.1.3.a	Paying employees on time	Yes No	5 1
3.1.1.3.b.	Work Hours and Overtime Pay in India. Working Hours in India: As per the Factories Act 1948, every adult (a person who has completed 18 years of age) cannot work for more than 48 hours in a week and not more than 9 hours in a day.		
		Less than 9hours in a day More than 9hours in a day	5 1

Gender equality

Table D.95: Questionnaire: Questions and table used during the farmers' interviews for the indicators 3.1.2.

Children and Education				
What s your education level?				
	age/education level	age/education level	age/education level	age/education level
Girl				
Boy				
Type of school (governmental/private)				
	yes	no		
Do you want them to farm				
Do you want them to manage the farm				

3.1.2.1.a.	How much do you pay women workers?
3.1.2.1.b.	How much do you pay men workers?
3.1.2.2.	Do your children go to school?

Table D.96: Sustainability scoring card for the indicators 3.1.2.

3.1.2.1.a	Women are paid above 250 a day	Yes	5
		No	1
3.1.2.1.b	Men are paid above 250 a day	Yes	5
		No	1
3.1.2.2.	Children going to school	No	1
		Only the boys	3
		All my children	5

Business resilience and economic security

The farmers were asked if their quality of life has been improving over the last few years and if the farmers think their farm business is struggling or booming. The farmers were asked about their expectations concerning farming in the future.

Quality of life

Table D.97: Questionnaire: Questions used during the farmers' interviews for the indicators 3.2.1.

3.2.1.1.a.	In the last five year do you think your life quality has improved, regressed or is the same?
3.2.1.1.b.	How is your farm doing?

Table D.98: Sustainability scoring card for the indicators 3.2.1.

3.2.1.1.a	In the last five year, the quality of life	Improved	5
		Same	3
		Regressed	1
3.2.1.1.b.	Farm status	Struggling	1
		Surviving	2
		Making a living	4
		Booming	5

Future expectation

Table D.99: Questionnaire: Questions used during the farmers' interviews for the indicators 3.2.2.

3.2.2.1.a.	Do you expect to be in business next year?
3.2.2.1.b.	Do you expect to be farming in 10 years?
3.2.2.1.c.	Do you expect your children to be farming after you?

Table D.100: Sustainability scoring card for the indicators 3.2.2.

3.2.2.1.a.	Expected to be in business next year	Yes No	5 1
3.2.2.1.b.	Expected to be farming in 10 years	Yes No	5 1
3.2.2.1.c.	Expected your children to be farming after you	Yes No	5 1

Health and safety

During the interview, questions about safety of labours and health care facilities were asked to the farmers.

Safety

Table D.101: Questionnaire: Questions used during the farmers' interviews for the indicators 3.4.1.

3.4.1.1.	How many of your workers and yourself felt sick after applying pesticide/fertilisers?
3.4.1.2.	Have you had death on the cotton farm?

Table D.102: Sustainability scoring card for the indicators 3.4.1.

3.4.1.1.	Percentage of workers falling sick	100%- 67% 66%-33% 32%- 0%	1 3 5
3.4.1.2.	Death on the cotton farm	Yes No	5 1

Health

Table D.103: Questionnaire: Questions used during the farmers' interviews for the indicators 3.4.2.

3.4.2.1.	Do you have access to drinkable water?
3.4.2.2.	Do you have easy access to health care facilities?
3.4.2.3.	Do you have toilet at home? Near the field?

Table D.104: Sustainability scoring card for the indicators 3.4.2.

3.4.2.1.	Drinkable water	Yes,good water	5
		Yes, but boiled the water	4
		Yes but water is more than 1km	2
		Buy water	1
3.4.2.2.	Health care	Yes, very good health care	5
		Yes but mediocre health care	4
		No, its very far	2
		Not at all	1
3.4.2.3.	Sanitation facilities	defecate in an open area	1
		commun bathroom	3
		bathroom at home	5

Farmer's organization

Questions were asked to the farmers were related to trainings that farmers have had. During the interview they are asked if they were part of a farmers' organisation.

Table D.105: Questionnaire: Questions used during the farmers' interviews for the indicators 3.5.1.

3.5.1.1.	Have you partipating to any type of training?
3.5.1.2.a	Do you participate actively with a farmers organisation (farmer committee)
3.5.1.2.b.	Where do they get their training

Table D.106: Sustainability scoring card for the indicators 3.5.1.

3.5.1.1.	Participating to a training	At least once a year	5
		At least one	3
		Never	1
3.5.1.2.a	Actively participating to actively a farmers organisation (farmer committee)	Yes	5
		No	1
3.5.1.2.b.	Where do they get their training	Organisation	5
		Government	4
		Farmer	3
		Shopkeeper	2
		None	1

Farmer's knowledge

This sub-theme of indicators has been added to the assessment. Questions about the farmer's education, understanding of the price fluctuations and knowledge of pesticide effects on humans were gathered from other sub-themes and clustered together in this sub-theme. An ecological indicator was added about ecological knowledge of the farmers. A set of questions were asked to the farmers regarding his/her education level, and his knowledge on the fluctuation of the price of cotton as well as the effect of pesticides on the human beings. From the ecological survey, 10 of the most common surveyed arthropods were selected and a sample of each was shown to the farmer who was asked to identify the specimen and identify its ecological function.

Table D.107: Questionnaire: Table and questions used during the farmers' interviews for the indicators 3.6.1.

Most commonly surveyed arthropods in cotton farm	3.6.1.1.a Identification	3.6.1.1.b Function
Coccinellidae adult		
Coccinellidae juvenil		
Curculionidae		
Scarites		
American Bollworm		
Bee		
Araneae		
Jassid		
Chrysopodae		
Earthworm		

3.6.1.2.	Farmer's education level:
3.6.1.3.	Why does the price of the cotton change every year?
3.6.1.4.	Do you know the effect of pesticide on human being?

Table D.108:Sustainability scoring card for the indicators 3.6.1.

3.6.1.1.a.	Identified invertebrates		
		0-1	1
		2-3	2
		4-5	3
		6-7	4
		8+	5
3.6.1.1.b.	Function of the invertebrate identified		
		0-3	1
		4-5	3
		6+	5
3.6.1.2.	What is your education level?		
		illeterate	1
		Primary	2
		Secondary	4
		Post secondary	5
3.6.1.3.	Why does the price of the cotton change every year?	Don't know	1
		Some idea	3
		Understand very well	5
3.6.1.4.	Do you know the effect of pesticide on human being?	Yes	5
		No	1

Visualizing the thesis

This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the Lanchester Library, Coventry University.

Left: Accommodation from 2016 to 2019,

Bottom: BioRe employees and research team,

Top: BioRe association CEO Vivek Rawal (left) and Aashish Joshi, team leader (right)

Long term experimentation plot-scale cotton systems

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Meeting with BioRe research team leading by Dr. Gurbir Bhullar Singh

Germinated cotton seed with lint (June 2017)

Cotton plant in its vegetative stage (July 2018)

Cotton flower with a solitary bee (LTE, August 2017)

Cotton field with cotton lint ready to be harvested (farmer's field, October 2017)

Above: Canopy dwelling arthropods survey with the help of Dharmendra Patel, Lokendra Mandloi and Dinesh (Farmer's field, September 2018)

Below: Canopy dwelling arthropods survey with the help of Manish Chandi, Mahesh and Dinesh (Farmer's field, August 2018)

From left to bottom: Ladybird (Cheilomenes sexmaculata) adult and grub, jassids (Hemiptera: Cicadellidae) and Araneae

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Left: Long legged fly (Dolichopodidae) on a cotton leaf.

Right: Night survey of canopy-dwelling arthropods with Mahesh in the background (LTE, September 2016)

Top: Bulk density soil survey with Danesh
Left: Soil sampling with the help of papu and kaka
Right: Earthworm survey, hand sorting earthworms with the help of Jyothi

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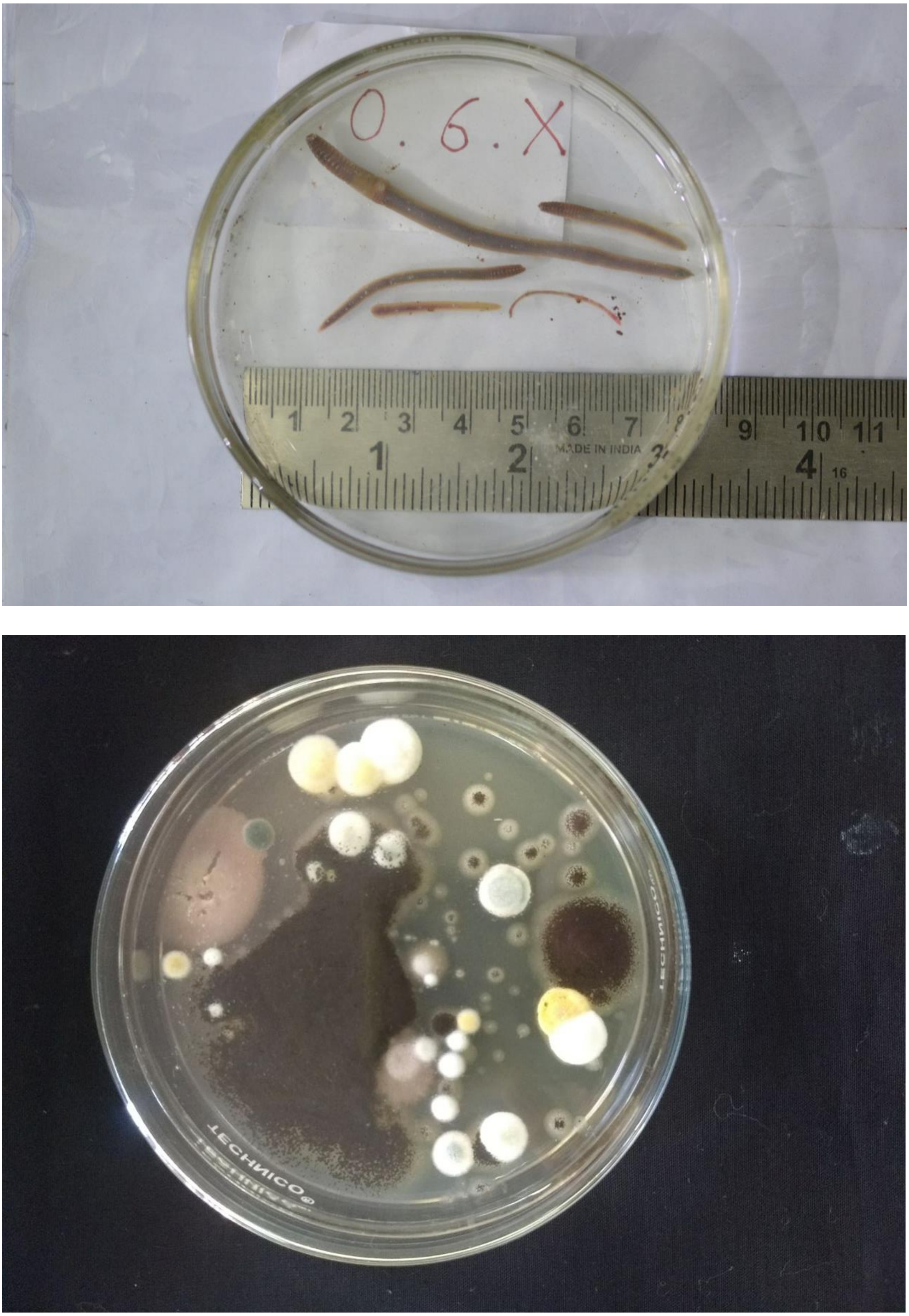
Top: Storing of the arthropod's saplings from the canopy-dwelling and ground-dwelling arthropods surveys. Bottom: Separating the arthropods and biomass of the canopy-dwelling samplings with the help of Sandhya Jiju (present in the photo) and Manish Chandi

Left: Coleoptera:Carabidae from the ground-dwelling arthropods survey on farm-scale organic system, Center: Stereoscope with camera set up in the identification laboratory Left: Picture of a Curculionidae from the stereoscope

Top Left: Soil analysis for Nitrogen with the help of Nitin Tomar, Top Right: soil analysis for carbon with the help of Nitin Tomar. Bottom: Laboratory set up for the earthworm analysis



Top: A earthworm sapling from organic farm-scale system. Bottom: fungal community from one of the soil sampling

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Top: Field visit for farmer's selection. Middle: Mode of transport to go to field visit with Lokendra Mandloi Singh. Bottom: One of the surveyed organic cotton farming system

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mer's interview with
help of Dhamendra
el and Lokendra
ndloi Singh

Top: Mahesh explaining hand pollination to Fairlie for the pollinator survey with Lokendra Mandloi Singh (LTE, August 2017). Bottom: Visit of Dr. Kranthi S. and Dr.Kranthi K. (farmer's field, September 2019).

Top: Visit of Dr.Smith B. observing cotton plants with Yogendra, Bhupendra and Lokendra (LTE,). Bottom: Visit of FiBL team from Switzerland, Kenya and Bolivia for the 4 years evaluation (LTE, September 2018)

Top: Agricultural ecology initiative conference organised by Dr.Smith B. and myself sponsored by the BES (London, UK, September 2017), Bottom left: Global Organic Convention where I have presented my research (Nagpur,India, September 2019), Bottom right: Agroecology Europe Forum where I have presented my research (Heraklion,Crete, September 2019)