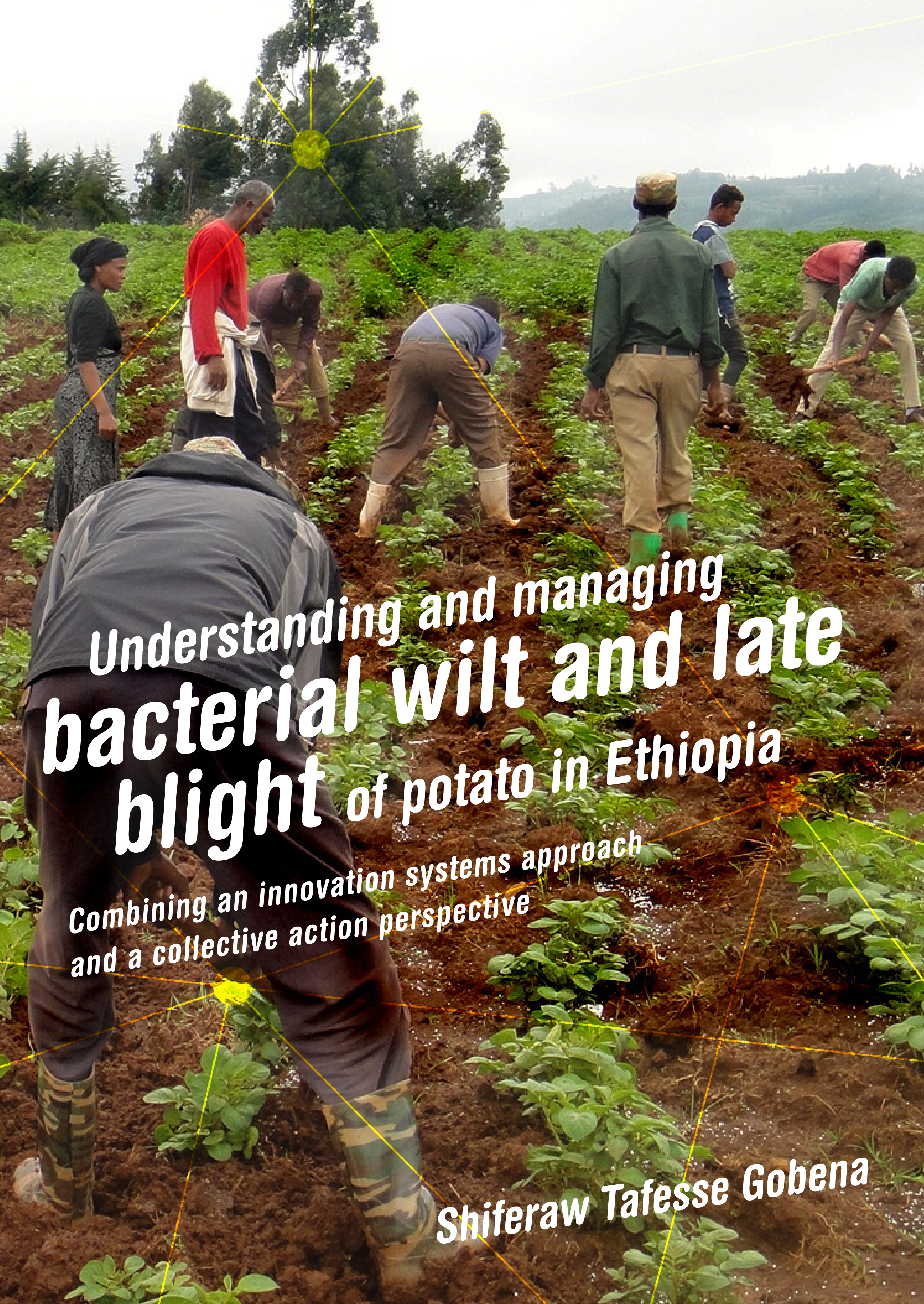

Understanding and managing bacterial wilt and late blight of potato in Ethiopia

Combining an innovation systems approach and a collective action perspective

Shiferaw Tafesse Gobena

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Chapter 1

General introduction

1.1. Background

Several studies show that global food production needs to double by 2050 to keep pace with world population growth (FAO. This is not easy to achieve as various social and biophysical factors constrain crop production. Among the biotic constraints, crop diseases and pests cause considerable economic losses and severely affect food security efforts at household, national, and global levels (Savary et al., 2019).

Potato (*Solanum tuberosum* L.) is the world's third most important food crop after rice and wheat (Devaux et al., 2020; FAO, 2013). It provides more food per unit area than any other major food crop (Devaux et al., 2014; FAO, 2008). Currently, potato is grown in developed and developing countries on about 18 million hectares of land, and around 1.3 billion people consume potato as a staple food (Devaux et al., 2020; FAOSTAT, 2017). Hence, due to its wide distribution and the role it plays in the global food system, it is considered a food security crop. Potato production is also on the rise in Africa and is considered a strategic crop in Ethiopia.

Like other food crops, potato is affected by various types of diseases such as fungal, bacterial, and viral diseases. Among the major diseases that severely affect potato, bacterial wilt caused by *Ralstonia solanacearum* is a complex disease that farmers in tropical and subtropical regions of the world have been struggling with for many years (Charkowski et al.,2020; Elphinstone, 2005). *Ralstonia solanacearum* is one of the most challenging pathogenic bacteria that devastates many plants. Aside from potato, this pathogen affects more than 250 plant species, which include food crops such as tomato, eggplant, sesame, peanut, ginger, and pepper as well as other commercial plant species such as tobacco and Eucalyptus tree species (Charkowski et al., 2020; Carstensen et al., 2017; Elphinstone, 2005; Hayward, 1991). This pathogen can survive in water, soil, and infected crops and weeds. It has diverse spreading mechanisms, including via infected seed tubers, soil, irrigation and run-off water, farm tools, farm animals, crop residues, and host weeds (Elphinstone, 2005; Hayward, 1991).

In response to the devastating impact of bacterial wilt on potato and other crops, many studies have been conducted on a range of pertinent topics worldwide. Most studies have focused on pathogen diversity and distribution, host range, detection and diagnosis, host-pathogen interactions, and disease management methods (Elphinstone, 2005; Yuliar et al., 2015).

However, despite considerable successes in understanding the molecular and ecological dimensions of the pathogen, its management has continued to be challenging both in developed and developing countries. Information is lacking on social and institutional aspects that constrain or enable effective management of the disease. Particularly in the smallholder farmers' context in sub-Saharan Africa, where the disease is rapidly expanding and the facilities to control the disease are limited, little attention has been paid to interactions among multiple actors to develop innovations to address the problem.

Management of bacterial wilt is challenging mainly because of its diverse host plant species, its transmission through latent infection of seed potatoes, the survival of the pathogen across a deep soil profile, and the multitude of sources of infection (Hayward, 1991, Janse, 2012). Recent advances in control measures include chemical, biological, physical, and agronomic mechanisms (Lemaga et al., 2001; Hong et al., 2011; Saddler, 2005; Yuliar et al., 2015). Chemical control has not been proven to be efficient in eradicating *Ralstonia solanacearum* (Saddler, 2005; Yuliar et al., 2015). Even though studies have shown the potential value of some biological control agents, their suppression capacity is usually too low to be used commercially at large scale, or they require high rates of inoculums (Whipps and Gerhardson, 2007). It can be difficult for smallholder farmers to use biological control measures given their limited technical and financial resources. Physical methods such as soil solarization have been found to suppress the pathogen in the soil effectively. But the implementation of solarization is challenging in the smallholder farmers' context (Yuliar et al., 2015). Therefore, integrating sanitation (e.g., cleaning farm tools and shoes, clean seeds and planting on clean fields) and cultural practices (e.g., crop rotation, rogueing and soil amendments) have generally been recommended as effective methods to deal with the disease in the smallholder farmers' context. These strategies have focused on how the disease could be managed at farm level with little attention to essential issues beyond the farm boundary. Consideration of social and institutional contexts in which the disease is managed is limited in the literature.

On top of its impact on one's potato fields where it occurs, bacterial wilt is a complex socio-ecological problem that poses a collective risk to other seed and ware potato farmers in the same area and beyond. Social arrangements (e.g., rules, sanctions) are required for effective management of the disease in smallholder potato production since such complex agricultural problems cannot be dealt with through technical innovations alone (Leeuwis, 2004). However, social dimensions and the interplay between social and biophysical aspects of the disease are less studied. Thus, steps towards designing an effective management strategy for bacterial wilt need to begin by understanding the social and biophysical factors that spread or aggravate the disease incidence.

1.2. Overview of the Ethiopian context

Ethiopia has the most significant potential for potato production in Africa as more than 70% of its arable land, about 10 million hectares, is suitable for potato production (FAO, 2008). The country has, therefore, an untapped potential to become the leading producer of potato in Africa, which would considerably contribute to food and nutrition security. More than 3.7 million smallholder farmers in the country now grow potatoes for food and income generation (CSA, 2016).

Over the last three decades, potato production has expanded with the collaborative efforts of the government and international development partners. For instance, more than 30 improved potato varieties have officially been released at the national level. The improved varieties are high-yielding and late blight (caused by *Phytophthora infestans)* resistant (Berihun and Woldegiorgis, 2013; Woldegiorgis et al., 2013). Governmental and non-governmental organisations have been actively promoting and distributing improved seed of potatoes (Schulz et al., 2013). As a result, high-yielding potato varieties have rapidly replaced the low-yielding local varieties in major potato growing areas (Tesfaye et al., 2013; Kolech et al., 2015). Particularly in food insecure districts, the high-yielding potato varieties have been praised by many development actors and government officials as key to improve farmers' livelihood within a short time. Due to the efforts made in promoting potato production for food security and income generation, the area of land under potato cultivation has increased nearly fivefold between 2005 (62,000 ha) and 2018 (296,000 ha) (CSA, 2018).

Despite the efforts and the potential of the country, various challenges have constrained the country's potato production and productivity, including limited access to good quality seed, poor agronomic practices, low yield, and diseases like late blight (Haverkort et al., 2012; Schulz et al., 2013; Woldegiorgis et al., 2013). Late blight has continued to cause significant damage due to increased disease pressure and expansion of potato production (Woldegiorgis, 2013; Hirut., et al., 2017). As there is no formal seed certification system in the country, most of the farmers do not renew seeds and repeatedly plant for many seasons (Gildemacher et al., 2009;

Hirpa et al., 2010). They usually use seed potatoes saved from the previous season. Such practice affects the seed health and the physiological state of the seed and significantly reduces potato yield (Struik and Wiersema, 1999). To enhance the supply of quality seed, hundreds of seed potato cooperatives have been established across different regions in the country (CIP, 2016; Sisay et al., 2017). Promoting seed potato cooperatives has been a successful initiative and their role in the country's seed potato system has been considerable. But, despite the increase in the volume of seed potato supply, poor seed quality has remained a big challenge.

Currently, the Ethiopian potato production system is facing an even more severe challenge, bacterial wilt. Historically, bacterial wilt was limited to certain areas in the country. The disease incidence level was also low. This disease has recently become the most severe threat to the country's potato production, putting its seed potato production systems at risk (Gorfu et al., 2013; Abdurahman et al., 2017). The disease is highly contagious, and it seriously damages potato production. Once introduced into a potato field, it persists in the soil for many years.

Furthermore, this pathogen may not induce symptoms and spread unnoticed through a latent infection. Considering its damaging effect, scientists have ranked this pathogen as the second most devastating bacterium worldwide (Mansfield et al., 2012). However, many actors in the Ethiopian potato innovation system were oblivious to the prevalence of the disease. The disease has now become a nationwide problem, firmly embedded in the seed potato system (CIP, 2016; Kassa, 2016; Abdurahman et al., 2017).

Despite the wide prevalence of bacterial wilt, studies in the Ethiopian potato production system are few. These studies focused primarily on characterisation and isolation of *Ralstonia solanacearum* strains and its genetic diversity in a few potato growing districts, and disease incidence in ware and seed potato fields. They have shed light on the occurrence of bacterial wilt in the country. They have also alerted the actors in the potato production system to the dangers of the disease. But previous studies are not sufficient to help design an effective management strategy to deal with the disease. Very little information is available on the conditions that have spread the disease and how various actors in the country's potato innovation system strive to address it. Therefore, understanding what biophysical and social factors contribute to the spread of bacterial wilt, and what technical and social innovations may enhance the management of the disease is imperative as there is a sense of urgency to safeguard the country's potato production.

This thesis was conducted in the above-mentioned context. It contributes to understanding what social and biophysical conditions spread the disease and aggravate its incidence, and how it can be controlled through social, technical and institutional innovations in smallholder potato production.

1.3. Theoretical perspectives

In this section, the concepts that shape the framework of the thesis are briefly described. Overall, the thesis is positioned in the literature of crop disease management, agricultural innovation systems approach and collective action (Figure 1.1).

1.3.1. Crop disease management

Plant diseases result from interactions among a susceptible host plant, a pathogen, and environmental conditions that favour disease development (Vanderplank, 2012). Plant diseases cause severe damages to crop production and aesthetic values of landscape plants. The goal of crop disease management is to reduce the damage that a plant disease causes (Vanderplank, 2012; Chaube, 2018). In the field of crop protection, an integrated disease management (IDM) approach is widely prompted to deal with plant diseases. The concept of IDM implies a combination of different methods such as chemical, cultural, biological methods, host resistance, and physical methods to manage the plant disease. Furthermore, crop disease management is regarded to require understanding of the causative agent of the disease, correct diagnosis to identify the pathogen, knowledge on disease symptoms at various stages of development, knowledge on spreading mechanisms and on environmental conditions that favour disease development, as well as monitoring of the occurrence and distribution of the disease (Chaube, 2018).

1.3.2. Agricultural innovation systems

Theoretical perspectives on agricultural innovation have changed over the years. One of the prominent perspectives in the field of agricultural innovation studies is the agricultural innovation systems approach. Other approaches to innovations in agriculture include diffusion of innovations/transfer of technology (Rogers, 1995), farming systems approach (Collinson and Lightfoot, 2000), and agricultural knowledge and information systems (AKIS) (Röling, 1990).

The transfer of technology approach considers farmers as adopters of technologies, while researchers are perceived as the sources of knowledge and technologies. Furthermore, the process of technology generation is assumed to be relatively independent of political, social, and institutional factors (Rogers, 1995). But researchers cannot be the only sources, and that social and institutional factors matter.

Due to the limitations of the technology transfer approach, the farming systems approach emerged in the 1980s. In the farming systems approach, farmers' biophysical and social contexts are taken into account, and farmers are consulted by researchers (Bawden, 1995; Norman, 2002). In this perspective, agro-ecological and economic contexts are integrated. Development of technologies was considered as relatively independent of political and institutional conditions, and multi-level interactions among actors were not given due attention in the farming systems approach (Leeuwis, 2004; Klerkx et al., 2012).

During the 1990s, the concept of AKIS emerged in response to the critique of linear models of innovation (Röling, 1990; Leeuwis, 2004). According to this perspective, farmers are experimenters, whereas researchers are farmers' capacity builders. The AKIS approach integrates different types of knowledge (e.g., scientific knowledge, farmers' local knowledge) to empower farmers. But this approach emphasizes farm-based livelihoods with a limited focus to value chain and political dimensions (Leeuwis et al., 1990).

Since the 2000s, the agricultural innovation systems (AIS) approach has emerged and became a dominant approach to innovations in the agricultural domain (Leeuwis, 2004). According to the AIS approach, farmers are considered as partners in the process of developing agricultural innovations, whereas the role of research and researchers is to enhance the capacity of the innovation system (Leeuwis, 2004; Klerkx et al., 2012; Schut et al., 2014). Furthermore, AIS has a multi-level focus, including multiple actors, the interactions between them, the infrastructure that supports the system, and the institutional and political dimensions of the innovation. Biophysical processes are also considered in the agricultural innovation systems approach as one of the contexts in which science and technology are embedded and develop. According to this perspective, agricultural innovation is defined as a process that involves technological, economic, social, and institutional change. Various forms of communicative intervention (e.g., learning, information provision, mediation) may support the process of innovation (Klerkx et al., 2012; Leeuwis, 2004; Van Mierlo et al., 2010). Since the AIS perspective is driven by responsiveness to the changing conditions in a holistic manner, it is considered as a fundamental approach to understand and develop solutions to complex socio-ecological problems.

In the field of crop disease management, the AIS perspective is highly relevant. However, crop protection literature is still primarily dominated by technology-oriented approaches despite a significant shift from a linear thinking perspective to an agricultural innovation systems approach in the broader agricultural domain. According to a systematic literature review on approaches to innovation in crop protection, previous studies have not applied an agricultural innovation systems approach to analyse and understand complex crop protection problems (Schut et al., 2014). But, a technology-focused approach alone cannot bring sustainable crop protection. Effective and sustainable crop disease management does not happen in isolation from the entire production system but entails actions and interactions of many stakeholders.

Crop disease management extends beyond addressing the interactions between a crop and a pathogen. It includes the social and institutional system in which the problem is embedded. Likewise, measures to address a crop disease cannot be taken without a clear understanding and consideration of the various dimensions of the problem. Crop disease management is multi-dimensional (encompassing biophysical and social dimensions) on the one hand, and it encompasses multiple levels (farm, community/local, and national levels) on the other hand (Giller et al., 2011; Schut et al., 2014). Innovations for crop protection are shaped by interactions between actors and institutions (e.g., quarantine rules, seed laws). Thus, institutional innovations are also essential components of sustainable crop disease management.

1.3.3. Collective action

Collective action is considered an important approach when interdependent individuals need to contribute to achieving a common goal (Ostrom, 1990). The concept of collective action is widely promoted to address problems that require cooperation among many actors such as the management of natural resources (e.g., grazing lands, irrigation water, and forests) (Meinzen-Dick et al., 2004; Ostrom, 1990). Recently, the concept of collective action has also been applied to deal with complex agricultural problems such as invasive weeds (Graham et al., 2019; Marshall et al., 2016). Collective action is influenced by various factors such as social (e.g., trust, rules, sanctions, monitoring, communication) and biophysical ones (e.g., the nature of the resource) (Araral, 2009; Binder et al., 2013; Ostrom, 2007). As discussed earlier, AIS is about coordination between different types of actors. But collective action is about joint action among similar people (farmers).

In line with the agricultural innovation systems approach, this thesis adopts the perspective that an integrated disease management approach that entails combinations of methods is not sufficient to deal with bacterial wilt in potato. In addition to integrating different disease management methods, collective actions among interdependent smallholder farmers, and collaborations among multiple stakeholders are needed. A systematic analysis of biophysical and social aspects of the disease and what effective management of the disease entails in a smallholder context are addressed in this thesis.

1.4. Research objectives and questions

Two central research objectives guide this thesis. The first objective is to examine the social and biophysical factors that explain the widespread of bacterial wilt in potato in the country. The second objective is to analyse what technical and social innovations are required to deal with the disease in a smallholder farmers' context (Figure 1.1).

The overall research question is: what biophysical and social factors contribute to the spreading of bacterial wilt in potato and what technical and social innovations may enhance the management of the disease in smallholder farmer potato production in Ethiopia? In order to answer the central research question, five sub-questions are formulated to be answered in different chapters of the thesis (Figure 1.1):

1. How do different actors in the potato innovation system understand the problem of bacterial wilt and its management? (Chapter 2)
2. How do farmers' knowledge and practices affect the spreading of bacterial wilt? (Chapter 3)
3. How do seed potato cooperatives monitor the occurrence of bacterial wilt and its management, and what are the challenges associated with the monitoring activity? (Chapter 4)
4. What biophysical conditions aggravate the occurrence of bacterial wilt, and what

technical innovations can improve the biophysical conditions? (Chapter 5)

5. How does a learning intervention enhance farmers' capacity to deal with bacterial wilt through collective action? (Chapter 6)

1.5. EVOCA project

This thesis is the outcome of a PhD study within a research for development project entitled "Responsible life-sciences innovations for development in the digital age: Environmental Virtual Observatories for Connective Action (EVOCA). Potato disease management in Ethiopia is one of the EVOCA-case studies (Cieslik et al., 2018; Leeuwis et al., 2018). Generally, the two major potato diseases with which Ethiopian smallholder farmers are struggling, are addressed by this thesis but at different depths. Both bacterial wilt and late blight are considered during the diagnostic studies given similarities between the two diseases in terms of the actors in the potato innovation system. However, following the diagnostic studies (Chapters 2 and 3), the thesis focuses on bacterial wilt to answer the overarching research question of this thesis (see Section 1.4). This was a deliberate choice made considering the social and ecological differences between the two diseases and the importance of investigating technical and social innovations required to deal with bacterial wilt (see Section 7.5). Late blight is addressed by the PhD thesis of Damtew (2020), with a particular focus on social learning, information, and collective action to control the disease.

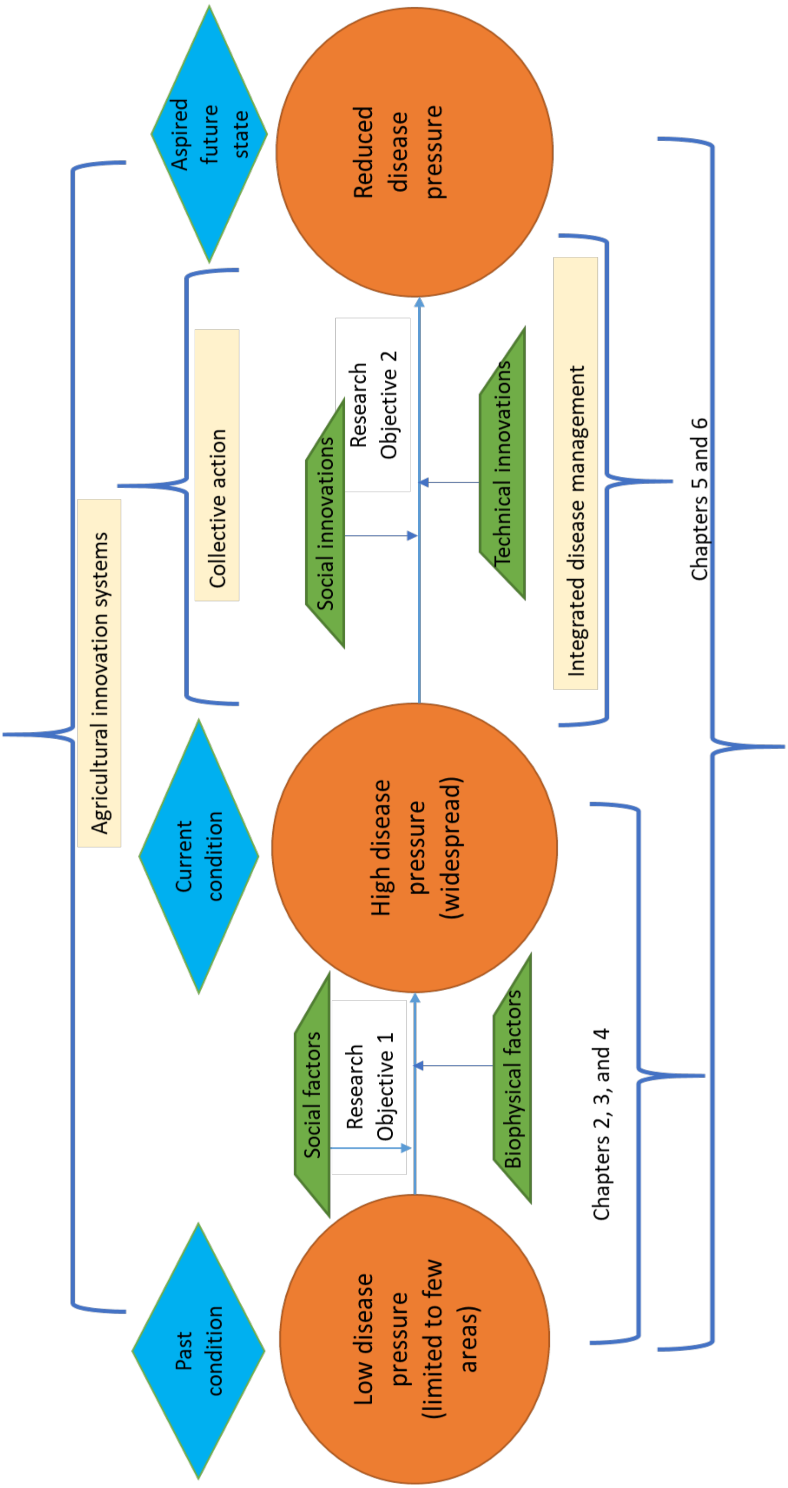

Figure 1.1. Graphical representation of the theoretical perspectives, the overarching research objectives and corresponding chapters of the thesis

1.6. Study design, data collection and analysis techniques

The research presented in this thesis is a multi-level and multi-dimensional study conducted in Ethiopia. Ethiopia was the focus of the study because of the reasons explained in Section 1.2. The study was conducted in selected districts in the central highlands of the country, which have been the hubs of the seed and ware potato production and marketing. The research is multi-level in that it consists of in-depth and systematic analyses at a system, community, household, and field levels. It is also multi-dimensional in that the relationship between biophysical processes such as soil acidification and bacterial wilt incidence was examined. The genetic diversity of the pathogen was also characterised. Moreover, investigations of how the practices and understandings of different actors contribute to the spreading of bacterial wilt, and what technical and social innovations (or learning interventions) may help address the disease in the smallholder farmers' context were carried out. The different phases and research designs of the study are briefly described below.

Diagnostic studies

The first phase of the study was a participatory systems analysis. It explored how various actors in the Ethiopian potato innovation system understand bacterial wilt and late blight and the solutions to these diseases. In addition, an investigation to understand farmers' knowledge and management practices of the two potato diseases was conducted through a cross-sectional study design (see Chapters 2 and 3). A cross-sectional study is important to investigate the prevailing conditions at a single point in time, paving the way for further studies (Kumar, 2019).

Case study

An in-depth analysis of how seed potato cooperatives monitor the occurrence of bacterial wilt and disease management practices of their members was carried out by selecting two seed potato cooperatives as a case (the details are described in Chapter 4). A novel framework, consisting of essential elements of a monitoring system, was developed to guide the analysis. Further, challenges associated with monitoring activities and future directions were also identified. A case-study design was selected because it allows in-depth investigation and exploration of phenomena, practices, organisations, context, and processes (Yin, 2009). Seed potato producers and monitoring committee members from the two cooperatives were involved in this study.

Field survey and experiments

During the fourth phase of the research, soil samples were collected from different potato fields, and soil pH was determined to examine the extent of soil acidification in the different potato growing areas and the association between soil acidity and the incidence of bacterial wilt. Furthermore, field experiments were conducted at three sites to study the effect of lime application on the occurrence of the disease. In order to detect and characterise *Ralstonia solanacearum* strains, potato samples were collected from randomly selected potato fields. Laboratory analysis was done to identify the phylotype of the strains through molecular techniques (see Chapter 5).

Action research

Action research on a learning intervention was designed and facilitated to examine how a combination of experiential and social learning approaches influence farmers' reasons for action. Action research is a process that involves planning, action, observation, and reflection (Kumar, 2019; Stringer, 2007). Action research enables an in-depth understanding of a problem in a real-life situation, and how to improve it (Kumar, 2019; Stringer, 2007). Hence, the action research method was applied in order to understand how extension can be organised to develop the capacity of smallholder farmers to deal with the complex disease problem—both seed and ware potato farmers from the same village were involved in the learning intervention. The learning intervention was evaluated at the end of the intervention to examine how the farmers learned about the disease, the importance of collective action, and feasible management methods to control the disease in their context (see Chapter 6).

An overview of the questions, research designs, data collection, and analysis methods per empirical chapter in the thesis are presented in Table 1.1. Further details are provided in each chapter (Chapters 2 to 6).

Table 1.1. Overview of the research questions, design, data collection and analysis methods used for the empirical chapters (Chapter 2-6)

Research questions	Research design	Data collection techniques	Data analysis techniques
How do different actors in the potato innovation system understand the problem of bacterial wilt and its management?	Cross-sectional	- Multi-stakeholder workshop - In-depth interviews	Content analysis
How do farmers' knowledge and practices affect the spreading of bacterial wilt?	Cross-sectional	- Questionnaire - In-depth interviews	Descriptive statistics and Chi-square test using SPSS
How do seed potato cooperatives monitor the occurrence of bacterial wilt and its management and what are the challenges associated with the monitoring activity?	Case study	- In-depth interviews - Reflective workshops - Participant observation - Document analysis	Content analysis
What biophysical conditions aggravate the occurrence of bacterial wilt and what technical innovations can improve the biophysical conditions?	Experimental	- Potato samples - Soil samples - Field experiments	- Regression and correlation analysis using R - Soil pH analysis - Multiplex-PCR
How does a learning intervention enhance farmers' capacity to deal with bacterial wilt through collective action?	Action research	- In-depth interviews - Reflective workshops - Participant observation	Content analysis

1.7. Outline of the thesis

The thesis comprises seven chapters. Chapter 2 is a diagnostic study, and it explores how various actors in the potato innovation system understand bacterial wilt and late blight and solutions to address the disease through a system thinking perspective. Chapter 3 delves into farmers' knowledge and practices for the management of the two diseases in their specific local context, thereby answering the second research question. This chapter provides a clear picture of how farmers' knowledge and practices are related to each other.

Chapter 4 goes into depth to understand how seed potato cooperatives monitor the occurrence and management of bacterial wilt through a collective effort. It shows how elements of a monitoring system are operationalised by seed potato cooperatives to monitor the occurrence of bacterial wilt and its management. It also scrutinizes the technical and socio-economic challenges that seed potato cooperatives face in the process of monitoring. This chapter also describes the importance of improving the efficacy of the monitoring system given the prevalence of bacterial wilt and the significant role that seed cooperatives can play in the country's seed potato system.

The subsequent chapters (Chapters 5 and 6) build on the findings of the diagnostic studies and investigate how the disease has become a severe threat to the country's potato production and how it can be effectively managed in smallholder farmers' context in consideration of technical and social innovations.

Chapter 5 investigates the biophysical dimensions of bacterial wilt. First, it sheds light on the association between soil acidification and bacterial wilt incidence. Secondly, the chapter demonstrates how the management of soil acidity through the application of different lime rates helps to suppress the disease in acid soils. Finally, the chapter analyses the genetic diversity of *Ralstonia solanacearum* strains that were isolated from potato and explains how the understanding of molecular aspects of the pathogen supports the management of the disease.

Chapter 6 deepens the social-scientific understanding of how a combination of experiential and social learning approaches influences farmers' reasons for action related to various aspects of bacterial wilt and its management. Combining the two learning approaches in a learning intervention for managing the disease is explained as a plausible way to help farmers learn about the technical and social aspects of disease management. Finally, Chapter 7 presents a synthesis of the findings, scientific contributions, policy implications, and recommendations for further research.

Chapter 2

Diagnosis of management of bacterial wilt and late blight in potato in Ethiopia: A systems thinking perspective

This chapter is published as:

Damtew, E., Tafesse, S., Lie, R., Van Mierlo, B., Lemaga, B., Sharma, K., Struik, P.C. and Leeuwis, C., 2018. Diagnosis of management of bacterial wilt and late blight in potato in Ethiopia: A systems thinking perspective. *NJAS-Wageningen Journal of Life Sciences*, *86*, pp. 12-24.

Abstract

Potato is one of the most important food crops for smallholder farmers in the Ethiopian highlands. Diseases, particularly bacterial wilt (caused by *Ralstonia solanacearum*) and late blight (caused by *Phytophthora infestans*), are among the major constraints of potato production, despite continuous efforts to control them. Bacterial wilt and late blight are complex problems with multiple technical and institutional features, involving multiple actors with different perceptions and understanding, not only of the problem but also of possible solutions. Appreciating such complexity, this study adopted a systems thinking perspective. It aimed to explore actors' understanding of the complex problem situation and its implication for the management of the diseases at a collective level. Using a multi-stakeholder workshop and in-depth interviews, a qualitative study was conducted with actors that are directly or indirectly involved in the management of the two diseases. Results showed that actors essentially overlooked key systemic problems in the management of the two diseases. This is mainly reflected in actors' tendency to give event-level responses, shift responsibilities and engage in a mutual blaming to the problem of bacterial wilt and late blight. Lack of a preventive disease management culture**,** limited recognition of interdependencies among activities of actors, power inequalities, and top-down and linear approaches in information and knowledge sharing are identified as key structural problems that are underrated by the actors. We contend that the most appropriate way forward towards the management of both diseases is designing and implementing management strategies that, on the one hand, are preventive of disease epidemics, and on the other hand, foster horizontal information sharing, learning and collective action among the local actors in the system. Digital platforms, particularly mobile-based technologies, can play a role in catalyzing new forms of information sharing, broader learning, and collaboration among farmers and local actors.

Keywords: bacterial wilt, late blight, systems thinking, complex problems, disease management

2.1. Introduction

Potato is the fastest growing food crop in Sub-Saharan Africa with a substantial increase in total production in recent years. There is a similar trend in Ethiopia: the total area of land cropped with potato has considerably expanded from about 62,000 ha to 296,000 ha resulting in an increase in total yearly production from 500,000 Mg to about 3,700,000 Mg in 10 years (CSA, 2006; CSA, 2016). As the Ethiopian population grows rapidly, potato offers opportunities as one of the main food security crops (Haverkort et al., 2012). However, despite the increasing importance of potato production in Ethiopia, its productivity remains low with an average yield around 12.3 Mg/ha, an amount very low compared to the attainable yield of up to 50 Mg/ha under improved farmer management conditions using improved varieties (Baye and Gebremedhin, 2012; CSA, 2016). A number of studies (Gorfu et al., 2012; Haverkort et al., 2012; Kassa, 2012; Tsedaley, 2014) identified disease pressure, particularly bacterial wilt and late blight[1], as the most important production constraint and the number one priority for farmers in the management of their potato crop. Bacterial wilt has spread geographically from few potato growing areas in the lowlands and medium altitudes to almost all potato growing areas since it was first reported in Ethiopia in 1956. Bacterial wilt is categorized as seed-, soil-, and waterborne. Because host resistance to bacterial wilt is limited, it is very difficult to control (Burke, 2017; Kirk and Wharton, 2014). Late blight is known to occur throughout the major potato production areas in the country (Gorfu et al., 2012; Mekonen et al., 2011; Stewart, 1956). Late blight is primarily air-borne whereby the pathogen is carried over by wind currents or rain splashes to other plants/fields, but it is also seed-borne and soil-borne. Although there are two growing seasons (*Belg and Meher*) in most potato growing areas in the country, potato is mainly grown in the short rainy season (*Belg*) that falls between February and May. A high disease pressure in the long rainy season is the main reason why *Belg* production is dominant, despite a high yield potential of the long rainy season (Bekele and Eshetu, 2008; Garuma et al., 2012; Haverkort et al., 2012).

Cognizant of the situation, a number of previous and on-going research and development efforts have been made by different governmental and non-governmental organizations to deal with the problem of late blight. The National Potato Improvement Program within the Ethiopian Institute of Agricultural Research (EIAR), together with the International Potato Center (CIP),

[1] We couldn't find studies that tried to quantify total yield loss resulting from bacterial wilt or late blight disease in Ethiopia.

several regional research Institutes and Ethiopian universities, has worked over the last three decades to develop potato varieties with resistance to late blight (Baye and Gebremedhin, 2012; Mekonen et al., 2011). On the other hand, bacterial wilt management has not received much attention (Gorfu et al., 2012), although there has been some research effort on areas of race characterization, and screening of cultural and biological control methods (Abdurahman et al., 2017; Kassa, 2016; Kuarabachew et al., 2007; Lemaga et al., 2005). As part of a wider government-led 'Quality Declared Seed' program, there are recent attempts to manage bacterial wilt through a combination of technical and institutional arrangements (MoANR, 2013; Thiele et al., 2011). Despite these efforts, the overall success to date has been limited and both diseases still continue to be major challenges in potato production in the country.

Previous research on potato disease management in general, and management of bacterial wilt and late blight in particular, is notably dominated by technical aspects of the diseases. Most technical research areas covered a range of aspects, from pathogen distribution and genetic diversity to disease management practices such as host resistance, clean seed, chemical control and agronomic practices (Bekele et al., 2012; Kassa, 2012; Kassa and Beyene, 2001; Lemessa and Zeller, 2007; Mekonen et al., 2011; Tsedaley, 2014). Only few studies tried to take a wider perspective at farmers' level (Gorfu et al., 2012; MoANR, 2013) or at system level (Gildemacher et al., 2009; Tadesse et al., 2017a,b) to assess what formal or informal institutions exist and how the institutions operate in potato disease management in general, and bacterial wilt and late blight in particular. However, there is a very little attempt made to understand structural problems that give deeper insights on *why* such institutions (both formal and informal) or actors in it are operating the way they do and what that means to the management of late blight and bacterial wilt.

Plant disease results from complex interactions among biotic and abiotic factors including hosts, pathogens and environments, and farm level human activities that intentionally or unintentionally modify these interactions (Burdon et al., 2014; Franc, 1998). A good understanding of the disease cycle, including climatic and other environmental factors that influence the cycle, and cultural requirements of the host plant, are essential to design or implement an effective disease management strategy (Trabucco et al., 2013). Likewise, successful disease diagnosis or management approaches require networks of actors from the government, scientific institutions and local organizations which help to integrate surveillance and monitoring activities on the different dynamics of the disease (Kelly et al., 2017; Mazet et al., 2014). For instance, the risk of late blight can be reduced if growers communicate with relevant parties, such as neighbors, buyers, and extension workers when late blight infects their farms. Such practice can be realized when the different actors, who are supposed to have a vested interest in the management of the bacterial wilt and late blight, find a way to network and coordinate their efforts (Liao et al., 2016). This is in line with the notion of 'connective action' which is described as a new way of organising collective action networks (Bennett and Segerberg, 2012). In this regard, various forms of ICTs (Information and Communication Technologies) may catalyze new forms of network formation, information exchange and learning that are relevant to address coordination problems (Bennett and Segerberg, 2012; Kelly et al., 2017). ICTs can play a role in facilitating real-time monitoring, cross-level and cross-scale information sharing, engagement and interaction between individuals, organizations, and agencies at multiple governance levels (Karpouzoglou et al., 2016). However, as highlighted in different strands of literature, catalyzing new forms of collective action transcends the discussion on the potential of various technology platforms and requires the articulation of the role of social, institutional or political landscapes which are crucial in formulating collective action frames (Bennett and Segerberg, 2012; Chapman and Slaymaker, 2002; Karpouzoglou et al., 2016).

In our problem context, there are different actors like farmers, researchers, government decision makers, NGOs, crop inspectors, business owners, and information providers who are expected to have different understanding or perceptions regarding the problem situation and the potential solutions to their perceived problem situation. Such different understanding and perceptions about the problem situation and the potential solutions are expected to shape the behavior of different actors towards organising their actions in the management of the two diseases (Aarts and van Woerkum, 2005; Checkland, 2000; Jørgensen et al., 2009; Leeuwis and Aarts, 2011; Maloy, 2005). As highlighted in Cieslik et al. (2018), collective action problems are further deepened by power imbalances and imperfect or asymmetric information. This warrants the need for a nuanced look at existing perceptions, views and practices that in one way or another play a role in shaping collective action in the management of the two diseases. A good understanding of this complexity is, therefore, a critical step to unravel whether and how ICT enabled collective action can play a role in the management of bacterial wilt and late blight.

In the context of disease management, traditional silo approaches (segmenting a complex whole) usually serve as barriers to understand underlying problems that emerge out of complex interactions (Mazet et al., 2014). In this regard, 'soft systems thinking', provides a framework for a holistic appreciation of complex problem situations by eluding fractionalization of problems into pieces. Moreover, the soft systems perspective provides enough emphasis to fluid and intangible social aspects that are known to slip under the radar of 'hard systems thinking' approach (Checkland, 2000; Senge, 2006). We posit that actors involved in the management of bacterial wilt and late blight need to have an understanding of systemic problems to be able to collectively design and implement effective management strategies. We define 'systems thinking' as actors' understanding of the systemic structure or underlying patterns of behavior in a complex problem situation of bacterial wilt and late blight management. Although there are technical and socio-ecological differences between the two diseases, at systemic level problems of both diseases share more or less similar organizational actors and institutional context. Owing to this, our study mainly takes into account differences that are believed to influence how the different actors understand the problem situation in the management of the two diseases. Adapting concepts from soft systems thinking, this article will answer the following three research questions: 1) To what extent and how do actors understand the systemic structure in the complex problem of management of bacterial wilt and late blight? 2) How does their understanding of the systemic structure facilitate or hinder collective action in the management of bacterial wilt and late blight? and 3) What opportunities exist for ICTs in overcoming collective action problems?

The research was conducted in Ethiopia and specifically addressed farmers in Wolmera and Gumar districts. Data were collected in a multi-stakeholder workshop and through in-depth interviews with direct and indirect actors[2]. The interviews generated qualitative information about actors' understanding of the problem situation in relation to our area of inquiry outlined in the research questions.

The article is structured as follows. The next section presents our conceptual framework by first briefly addressing 'systems' and the prominent distinctions in 'systems thinking' at a theoretical level. The subsequent section then explains the methodology that was used to collect and

[2] Those actors with first-hand involvement in the potato disease management are labeled as direct actors. Actors which do not directly work in the sector but obliquely influence the wider context are categorized as indirect actors.

analyze the data. This is followed by the results section and the discussion section. The article ends with presenting the main conclusions.

2.2. Conceptual framework

Unlike the hard tradition which presumes that the world contains 'systems' which can be engineered, the soft tradition assumes a 'system' to be a fluid social world, one which persists and changes (Checkland, 2000; Vickers, 2013). In this regard, systems or 'human activity systems' do not pretend to be models of the world with predefined elements but mainly a set of interlinked activities that embody a particular purpose or a specific stated way of viewing the world (Checkland, 2000; Mingers, 1980). Appreciating such system construct, Senge (2006) defines 'systems thinking' as a mental model for seeing the structures that underlie complex situations and for selecting high from low leverage change. Thinking in systems is about reframing how people think about what they view as a problem in the first place, and what solutions might look like (Cabrera et al., 2008). Checkland (2000) refers this framing of a complex problem situation as a perspective of a reality or 'a world-view'.

Conceptual literature in the field of plant disease management emphasizes two key elements when discussing disease management. One is the use of systematic approaches to diagnose diseases and monitor risk levels. The second one is selection and implementation of short-term or long-term disease management strategies (Apple, 1977; Pernezny et al., 2016; Van der Plank, 2013). Taking these elements as major activities in disease management, we consider bacterial wilt and late blight management as a complex 'human activity system' that involves a range of interlinked activities. However, as highlighted in the introduction, complex problem situations involving human affairs are not straightforward and cannot be fully defined in technical terms. Understanding of the wider institutional context is equally important (Checkland, 2000; Midgley, 2003). In soft systems thinking, institutions are not just simple administrative and political organizations, but also are the rules, norms or perceptions which structure and are structured by people's practices and their areas of social endeavor (Krueger and Gibbs, 2010; Röling and Leeuwis, 2001a). These institutions, therefore, can be 'formal institutions' which are consciously designed and clearly specified as in the form of written laws, rules or regulations, within which different social entities or actors operate, or, can be 'informal institutions' such as political culture, unwritten customs, norms or perception which informally shape the way 'business is done' by different actors (Krueger and Gibbs, 2010; Smith, 1997).

This perspective framed our approach to a complex problem situation whereby different thematic lines through the lenses of 'technical' and 'institutional' problem dimensions are used to analyze actors' understanding of systemic structure in the problem of bacterial wilt and late blight management. Our conceptualization of systems thinking that is employed to discuss the thematic lines is elaborated in the next paragraph.

In complex and dynamic human systems, Senge (2006) positions systems thinking as a conceptual cornerstone and a fundamental discipline that frames how actors ('learning organizations' as he calls them) understand a complex problem situation and in turn respond to it. Systems thinking is about actors' understanding of systemic structure that defines a system's pattern of behavior to create the conditions for events to become likely. It entails going beyond individual mistakes, personalities, organizations or snapshots of events to see underlying patterns in the system. Seeing major interrelationships underlying a problem situation leads to new insights into what might be done to change the pattern of behavior which in turn can change events. Based on this notion, one way of investigating if people see systemic structure or underlying patterns is to look into the way situations are explained by them. In this respect, the explanation can be a reactive one based on events which usually leads to practicing superficial or symptomatic solutions ('shifting the burden' as Senge (2006) calls it) that may only improve events temporarily but leave the underlying problem unaddressed or even worsened. The other type of explanation, not common but very powerful, is a generative one based on systemic structure or root causes to a complex problem situation which helps in identifying and applying fundamental solutions to a problem situation. Having such systemic orientation also reduces the tendency of actors to victimize or blame a particular group or organization as a cause of a problem situation (Senge, 2006). Such perspective guided our analysis of actors' understanding of systemic structure in the complex problem situation of bacterial wilt and late blight management.

To clearly discern what is and is not an evidence of "systemic structure understanding", we made an extension of the concept by defining different instances for two types of explanations and associated practices (systemic structure vs event level) discussed in the conceptual framework. This is addressed in Table 2.1.

Table 2.1. Event-level and structural explanations and actions

1. Event-level explanations and actions	2. Structural explanations and actions
a. If actors talk about personal, organizational or event related problems when explaining the different aspects of the problem situation framed as technical and institutional	a. If actors talk about long-term patterns and interactions among different activities when explaining different aspects of the problem situation framed as technical and institutional
b. If actors explain or practice solutions that are targeted at fixing personal, organizational, event-level problems	b. If actors see interdependency between their activities or engage in concerted action to deal with perceived problems
c. If actors take assumption of an 'external cause' to a problem or blame others for a problem situation	c. If actors see their actions affect the behavior of other actors to create the problem situation they discuss
d. If actors mainly focus on their own decisions or dwell on their own judgment about 'actions to improve' a problem situation	d. If actors talk about the need for accommodations of different perspectives and interest of actors

2.3. Materials and methods

2.3.1. Study context and actors involved

The study was conducted based on data generated from different actors that are involved in the management of potato bacterial wilt and late blight in Ethiopia. CIP (International Potato Center) researchers and secondary literature were consulted to decide on participating actors, both in a workshop and in in-depth interviews that were employed to collect our data (Gildemacher et al., 2009; Haverkort et al., 2012; Hirpa et al., 2010). Based on this, seven categories of actors were included in the study: Government actors, Non-government actors, FBOs (Farmer-based organizations), Research and Training Institutes, Farmers, ICT-based agricultural information providers and Private sector actors. Based on the information from the workshop, the government (Ministry, Regional, Zonal, District and Kebele agriculture offices) plays an important role in agricultural policy and strategy formulation, public extension service provision. They also work, almost single-handedly, in agricultural inputs and outputs quality control and certification, and in input and output market through farmer cooperatives and unions. Research and training institutes are mainly involved in the development, adaptation, demonstration, and popularization of agricultural technologies and in training of subject matter specialists. They also have a role in pest/disease inspection of imported potato germplasms or samples collected from potato fields and in providing technical advice in the development of strategies in input use, disease diagnosis, and management. Actors that are involved in the provision of agricultural information use different platforms (mobile-based interactive voice response; community radio and videos) to reach out to their target communities. Only ATA (Agricultural Transformation Agency) provides information on potato agronomy and disease management through its mobile-based interactive voice response (IVR) system in pilot districts, not including our study districts. NGOs are involved in training and capacity development, agricultural inputs service, market linkages and extension services. FBOs, with strong monitoring from the government, principally work in seed potato production and agricultural input-output markets. The cooperatives have management committees, which are usually composed of model farmers, to monitor potato disease problems among others. Due to the active involvement of the government in input and output markets mainly through farmer cooperatives, the private sector was found to have quite limited engagement, at least in relation to activities relevant to the management of the two diseases. This is evident in Table 2.2 where it shows that it was only possible to include a single private sector actor both in the workshop and interviews. Administratively, the actors are distributed from the national (federal) level to ‘Kebele’ level, the smallest formal administrative unit, and are situated in the capital and regional cities and in zonal and district towns in different parts of the country.

As one actor category, individual farmers were included from Wolmera and Gumer districts which are among the major potato growing districts in the country. Wolmera is located in the Oromia region, at about 40 km west of Addis Ababa while Gumer is in the Gurage zone of the SNNP region at 220 km southwest of the capital city. Both districts are in the cool highlands with potato being one of the most important crops grown in a predominantly smallholder farming system.

2.3.2. Data generation methods

Multi-stakeholder workshop

In early November 2016, a one-day multi-stakeholder workshop was organized with 21 participants representing the above-stated actor categories. The workshop was organized with the objective of joint identification of systemic constraints and entry points for intervention in the management of late blight and bacterial wilt. A methodology from the Rapid Appraisal of

Agricultural Innovation System (RAAIS) was adopted to systematically engage participants in a series of sessions to generate preliminary information on perceived constraints and opportunities in the management of the two diseases. Based on experience from RAAIS studies in different African countries the workshops provided a fast-track approach to have a generic understanding of the system that was subsequently validated and explored in more detail using the in-depth interviews (Schut et al., 2015). More generic but key findings emerged from the workshop session (e.g. *linear thinking, limited recognition of interdependency and shifting responsibilities*). Findings of the workshop were also instrumental in shaping the conceptual and methodological direction of the research. The workshop sessions were facilitated by the researchers and all workshop session presentations were audio-taped and transcribed.

In-depth interviews

Informed by the operational definitions outlined in the conceptual framework, a set of discussion points were developed. Between April and June 2017, in-depth interviews were conducted in a dialogue-based style with 30 individuals from the different actor categories out of whom 27 interviewees consented and were audio recorded. The decision on the optimal number of interviews was based on the concept of 'saturation' or the point at which no new information or themes were observed in the interview data (Guest et al., 2006).

All the interviews were conducted by the researchers with each interview taking one and half hours on average. During farmer interviews, district experts and extension workers were used as facilitators and, in some cases, as translators. As much as the formal interviews, informal conversations were instrumental in capturing information on issues that are perceived as socially or politically sensitive by the informants. Transect walks in farmers' potato fields and visits to agricultural offices, cooperative unions, input market dealers, seed quality inspection laboratories and research facilities of research centers were helpful in getting a picture of the situation on the ground. Field notes and photographs were also taken during the visits. Secondary literature was reviewed to identify some relevant teams under formal and informal institutions (Seed quality control, Research and extension, and Information sharing culture) that were found to be relevant in our problem context (Gildemacher et al., 2009; Guest et al., 2006; Haverkort et al., 2012; Liao et al., 2016; Trabucco et al., 2013). Table 2.2 presents an overview of the data generation methods used with the various actors at the different administrative levels.

Table 2.2. Summary of data generation method

Data generation method	**Objective**	**Administrative level**	**Actor categories and number of participants**							
			Farmers	Govt. actors	Research and Training Institutes	NGOs	Agricultural Information providers	Private sector	FBOs	**Total**
Multi-stakeholder workshop	Participatory analysis of systemic constraints in potato bacterial wilt and late blight management	National	-	1	2	2	3	-	-	**21**
		Regional	-	1	1	-	-	1	0	
		District	-	1	-	-	-	-	2	
		Kebele	4	-	-	-	-	-	3	
In-depth interview	Generate information on actors' views of bacterial wilt and late blight problem situation	National	-	2	3	2	3	-	-	**30**
		Regional	-	2	3	-	-	1	-	
		District	-	4	-	-	-	-	2	
		Kebele	6	2	-	-	-	-	-	

2.3.3. Data analysis

The discussion points used for the interviews were loosely organized to allow actors to share their views and practices on a range of technical and institutional thematic lines that emanated from our conceptual framework (Disease monitoring and risk assessment, Disease management strategy and Politics and power relations) and that were identified from secondary literature (Seed quality control, Research and extension, and Information sharing culture). Discussion topics mainly focused on:

- Actors' perception of their roles in relation to potato disease management; their views about major problems in potato disease management; the solution they propose or the actions they take to deal with the perceived problems; the challenges they face in the process of implementing the solutions
- Actors' views about the roles of other actors, the nature of their interactions and the challenges they encounter when working with other actors; their views on how to deal with such challenges
- Actors' planning and implementation processes of different activities they execute; if and how they involve other actors in this process; their views and encounters on conflicting interests and the way they are handled

Based on our conceptualization of actors' understanding of a complex problem situations (second element of conceptual framework), views and practices of actors that were captured in the discussion were coded and categorized into the different technical and institutional thematic lines. Inferences were then taken from their utterances in light of the operational definitions given on what constitutes and does not constitute a systemic understanding. Secondary data analysis was used to support our expert interpretation of the results and to put it in the context of current knowledge.

2.4. Results

The Results section is presented along the following three problem dimensions: Technical issues, Formal institutions and Informal institutions. As indicated in the Conceptual framework and Methodology sections, different themes are used to discuss the findings under each problem dimension. Themes discussed under the technical dimension are 'Disease diagnosis and risk monitoring' and 'Disease management strategies'. Under formal institutions 'Seed quality control' and 'Research and extension' are two thematic lines discussed. 'Political culture and power relations' and 'Information sharing culture' are themes discussed under informal institutions. Each section specifically addresses actors' understanding of the dimensions.

2.4.1. Actors' understanding of the technical problem aspects of management of bacterial wilt and late blight

Disease diagnosis and risk monitoring

High-level experts in the government, research centers and NGOs felt that disease diagnosis or risk assessment on the incidence or epidemics of bacterial wilt or late blight should be principally done by government extension workers and farmers themselves. In this regard, most informant actors, particularly government experts and researchers, strongly believed that apart from resource constraints to effectively respond to the diseases, limited knowledge of extension workers and farmers on the symptoms, favoring conditions and dispersion mechanisms of the two diseases is the key problem for existing gaps in diagnosis and monitoring of the two diseases. When it comes to technical advice on late blight and bacterial wilt management farmers seem to prefer to rely on their own judgment. Although extension workers thought that farmers have limited knowledge on detecting the diseases, most interviewed farmers believed that it is not necessary to seek advice on detecting the two diseases. Detecting late blight was perceived as an easier task for the farmers that can be done without help from the extension workers. A farmer said: *"When you see a disease symptom on your field, you just buy chemical and apply"*. Farmers also seemed to be reluctant to seek advice on bacterial wilt[3] monitoring. A farmer stated: "*There is not much the extension workers could do for you, there is no remedy for the disease*".

At the Ministry, and regional levels, crop protection experts understood their mandate as strategic planners and resource mobilizers in the management of different migratory and regular crop insects and diseases. There are other more economically important crop diseases that are given more attention than potato diseases. Experts gave a strong emphasis on insects and diseases of crops that are designated as strategic by the government. These are crops such as wheat, teff, maize, barley, oilseed and pulses that are produced in a larger amount, cover a wider geographic area or are essentially export commodities. Among the insects and diseases that are given high emphasis, Desert locust, Armyworm, rust, and maize lethal necrosis disease are the

[3] Almost all extension workers and farmers find it difficult to mention symptoms or spread mechanisms for bacterial wilt.

major ones. Owing to the focus on other crops, crop protection experts at the Ministry and regional offices said that they had little information on potato diseases in general and late blight and bacterial wilt in particular. In this regard, some opinions of district experts and extension workers at the study sites supported what is observed at the Ministry and regional levels. A district expert in Wolmera stated: *"Being one of the most important crops in our district, potato production is highly constrained by late blight and bacterial wilt but as the crop is given little attention at the regional level, it is affecting our district."*

Ministry and regional experts stressed the importance of getting their personnel and logistics ready before seasonal insect and disease outbreak comes. Once they have the resources at their disposal they can coordinate their efforts with all crop protection experts working at different levels and go out for a campaign until the disease or pest is under control. Time-bound responses are given when there is a high incidence or outbreak of diseases. But, the main challenge for the high-level experts is their limited capacity to timely respond to disease outbreaks. Experts complained: "*we usually try to control outbreaks after disease or pest has already inflicted too much damage*". Farmers also seemed to follow the same routine whereby they responded after the incidence of diseases. This was highlighted by a farmer in Gumer who said: "*to reduce damage, many farmers apply chemicals when late blight is observed."* The monitoring and gathering of information on disease incidence or severity levels are mainly done by the government, an activity that is perceived as poorly organized by experts in the Ministry and regional agricultural offices. Only farmers or field level government experts do the diagnosis and share the information with high-level experts at the Ministry and regional agricultural offices. Information on high incidence of late blight is shared with regional agricultural offices who are supposed to coordinate management responses but there is no similar practice for bacterial wilt so far. The contribution of the national research institute through its crop protection research unit is marginal due to researchers' perceived logistical and human resource problems. It is worthwhile to mention that neither the extension workers nor an informant seed quality inspector operating in Gumer district were aware that the cooperative union has experts working on disease inspection, and similarly a district crop protection expert had no information on the existence of the seed quality inspection office.

Disease management strategies

Most farmers believed that the only available management option for late blight is fungicide application, which they usually apply after disease occurrence. Few farmers mentioned that resistant potato varieties such as Gudene and Belete are better resistant to late blight compared to their local varieties. But they tended to relate the importance of the resistant varieties rather to their contribution to increased productivity than to their ability to resist late blight, which was contrary to researchers' view that the primary objective of releasing the varieties is for late blight resistance. Farmers seemed to be convinced that bacterial wilt management is beyond their capacity and that the local experts have failed to 'bring them solutions'. Similarly, there was a shared view among government experts that management of late blight can be done with existing fungicides, for which they facilitate access through farmer cooperatives. Shifting potato production to the short rain season was also mentioned by workshop participants as another key strategy to deal with late blight. Interviews revealed that in Gumer about 90% of the total yearly potato production is produced in the short rain season where late blight stress is mild. Bacterial wilt management is something that is difficult for the district experts to explain. Wolmera district expert articulated: *"late blight can be controlled with fungicide but bacterial wilt is a complicated disease and is beyond our capacity, I am personally tired of being unresponsive to farmers' consistent complaint"*. The only 'curative' management option that extension agents advise farmers for bacterial wilt is 'roguing' of wilted plants, which farmers label as hardly effective.

Researchers tended to associate the problem of late blight with farmers' limited access to late blight resistant varieties that have been released by the research centers. They also listed bacterial wilt management recommendations[4] that are barely known to potato growers and extension workers participating in the study. A researcher shared his view: *"our many experimental studies have proved that using resistant varieties is key to deal with late blight"*. Researchers mentioned resistant cultivar selection process as the most important technical aspect of late blight management arguing that releasing a disease resistant variety is a lengthy and demanding process that takes as long as twelve years from acquiring germplasm[5] to screening and performance evaluation which they thought is an overwhelming task.

[4] Keeping farm equipment clean, roguing out and burying of infected plants, sorting infected tubers, eliminating host weeds, crop rotation, using clean irrigation water are among the practices.
[5] CIP is a key partner in germplasm importation from countries like Peru, Kenya and Uganda.

2.4.2. Actors' understanding of the institutional problem aspect of management of bacterial wilt and late blight

The existence of laws, operational guidelines and procedures in 'Seed quality control' and clearly specified approaches in 'Research and extension' services (e.g. Participatory Research and Extension, non-pluralistic extension approach etc.) form the basis for their categorization as formal institutions. However, such formal institutions were not in isolation and interplay with existing informal institutions and the different technical problem aspects of the diseases discussed in the previous section.

Seed quality control

For workshop participants, marginal implementation of different seed quality-related laws and regulations[6] due to government's limited enforcement capacity was taken as a major challenge in potato disease management. Seed proclamation and legal framework on variety release, registration and internal quality control (Seed Proclamation No. 782/2013), the Seed System Development Strategy (UNDP, 2011), and the Quality Declared Seed program (ESA, 2015) were considered as the major ones. As can be seen from the documents and based on the opinion of government representatives from the workshop, MoANR (Ministry of Agriculture and Natural resources) consulted and worked with different partner organizations in developing the strategies. But there seemed to be a shared view among many of the workshop participants that its implementation should have been realized by the government seed quality control and regulatory offices at regional levels. In this regard, interviewed experts at the government regulatory offices also strongly felt that such regulations or procedures have not been effectively applied. A serious shortage of inspectors and logistical constraints to cover a wide geographic area under their mandate are among the main problems mentioned affecting their inspection capacity. In the QDS (Quality Declared Seed) scheme there is, at least in principle, 'zero tolerance' for bacterial wilt for seed potato growers. The inspectors assert that when a breach of the laws and procedures is observed, they try to take timely corrective measures as stipulated in the laws. The penalty ranges from giving written warnings and banning the sale of the seed potato to revocation of licenses. Apart from the inspection that the experts do, seed-producing cooperatives have farmer committees that inspect and supervise seed potato fields of members for disease problems. In this regard, government inspectors constantly blame the

[6] Although there is no specific organization responsible for quality control of seed potato, in the last few years different seed quality related laws, strategies and guidelines that apply to potato and other crops have been developed.

committees for their poor capacity, which according to them, has pushed all the inspection burden on them. Farmers and committee members criticize back inspectors for not doing a timely inspection as it is impossible for them to sell their seed without getting the approval of the inspectors.

NGOs that have active involvement in seed potato exchange are well aware of existing gaps in seed quality control. They explain that such problem is out of their mandate and that the government should have dealt with. When there is an appeal from the government during times of crisis, the NGOs involve in emergency seed provision programs whereby they buy seed potatoes from different seed potato producing cooperatives in the country including farmer cooperatives in the study districts. They contend that their practice is 'safe' as they are buying seed from cooperatives that are government-certified, and further argue that the government's priority in times of crisis is to curb emergency situations.

Research and extension

Researchers in the workshop claimed that since the introduction of a participatory research approach in the national research system, their success in transferring knowledge and promoting agricultural technologies has relatively improved. Although in principle the participatory approach is meant to be implemented in close collaboration with the public-funded extension service and other relevant actors[7], interviewed researchers felt that joint engagement is still poor mainly due to the limited support they get from the public extension system. A researcher explained: *"Extension workers are supposed to closely follow up the research activities especially in our absence but as the local administration hardly see the activities as their own, extension workers have limited awareness and show little interest in the research activities. In many cases, we are obliged to pay per-diems to bring the extension workers on board and hire guards to avoid theft from farmers in the experimental fields".* Another researcher added: "*all the delicate research processes done on experimental fields is considered as a waste of time by many of the low-level experts*". District experts and extension workers acknowledged the weak collaboration with the research but held researchers' approach responsible for the situation. According to them, they usually have little information on the objectives of the research activities as the researchers do not fully involve them in the process. A district expert contended:

[7] The Research, Extension and Farmer Linkage Advisory Council (REFLAC), group of stakeholders beyond research, extension and farmers, is meant to lead the linkage between research and extension but with marginal success so far [18].

"It is common to see research experiments in our area that we have no knowledge of how it is initiated".

Limited knowledge of lower level experts on crop-specific problems like bacterial wilt and late blight was among the pressing problems mentioned by the researchers that are hampering technology adoption. Another critical challenge for researchers was a scarcity of pathologists in the research system, a similar concern that was also raised by regional seed quality inspection offices. For them, universities are not giving enough attention to the problem. Interestingly, an interviewed plant pathology professor in a university, who had no knowledge of the researchers' and the inspectors' claim, shared a different view: "*No university in the country trains students in pathology at the bachelor level, I see no need! We used to train pathologists at master's degree level but as there is no job for them, we decided to shift the program to a more generic discipline in crop protection*".

Researchers largely see their roles as technology or knowledge generators. A researcher affirmed: "*we have a clear mandate in the system which is generating appropriate technology*". Informant researchers considered the public extension[8] as the weak link between their technologies and farmers. There are research departments with names like "Technology Transfer and Commercialization Directorate", "Technology Transfer Coordination Unit", and have research positions as "Technology transfer research officer". For the researchers 'the extension research' wing in the national research system has been playing an important role in facilitating conditions for technology adoption by demonstrating, promoting and popularizing different technologies generated in the research centers. However, to their dismay, a recent BPR (Business Process Reengineering) reform[9] in SARI (South Agricultural Research Institute) disbanded the extension research department with a narrative that existing role of the department is something that can be covered by the technology developers themselves.

[8] Researchers claim that apart from knowledge gaps of extension workers in crop protection, spending their time in other activities, such as distribution of agricultural inputs, and collection of input credits and taxes from farmers, is negatively affecting their role as technology promotors.

[9] After recognizing the gap in 'bridging' research and extension, the extension research department is now back in the structure again.

2.4.3. Actors' understanding of informal institutional problem aspect of management of bacterial wilt and late blight

Political culture and power relations

The government actors, particularly at the Ministry and regional level, expressed the belief that they played a key role and had a wide range of activities from policy and strategy formulation to resource mobilization and implementation of strategic plans. The Ministry of Agriculture and Natural Resources was considered by many of the actors as a focal office at the top of the structure with the highest authorized decision-making body. Country-wide strategic and annual plans have been developed by different departments at the Ministry and regional levels to go down until it reaches the lowest administrative unit (Kebele)[10]. Decision makers and experts at the Ministry and regional levels argued that doing strategic planning and monitoring at the high level is instrumental to coordinate countrywide agricultural development activities. Some district experts also claimed that the centralized planning process facilitates effective communication with farmers. Experts at the study districts mainly talked about the benefit potato farmers would get if they strictly follow experts' advice whether in the management of bacterial wilt or late blight or in other agricultural activities. Although many of the lower level experts reflected this view when it came to their downward relationship with farmers, they were also found to have reservations on their upward relationship with high-level experts and decision makers at the regional and ministry level. A seed quality inspector uttered: "*the regional office sends us the number of hectares of seed potato field that we are supposed to inspect in a year. We can only send feedback if it is not workable. Sometimes they send us numbers that are much higher or lower than what is planted in a season*".

Researchers distinguished the Ministry as a powerhouse that decides on the fate of agriculture in which researchers have little voice. A metaphoric description of the situation by a researcher was: "*Our research institute is a teeth-less lion, there is not much we can do about the problem of bacterial wilt and late blight*". The NGOs and the agricultural information providers also stressed the importance of having development projects that are in line, or at least not in contradiction, with government interests to be able to sustain in the system. An NGO expert illustrated a situation: "*Our new project approach on organic potato farming and biological*

[10] The plan can cascade down to the level of individual farm households as is the case in one of the study districts, Gumer. The 'politics and power relation' section provides a more detailed illustration of the planning process.

disease control has been an issue for the government. If we implement our project, it means that about five hundred seed potato producing farmers that will participate in our project are not going to use inorganic fertilizers, chemicals or other inputs that are government recommendations. This became a huge concern for the government people. You know, one has to be cautious in matters like this as the government views us (NGOs) only as 'gap-fillers' and can tell us to go away at any time".

Almost all actors from the workshop or the interviews acknowledged that farmers are their key partners. However, many experts from the different actor categories, particularly government experts at the lower level, held the view that despite their efforts, farmers' 'lack of knowledge' was a major challenge for the sustained problem of bacterial wilt and late blight. Likewise, NGO experts and agro-input suppliers also complained how 'limited awareness of farmers' and 'resistance to change' have compromised the success of their interventions or services. Although many of the interviewed experts believed that trainings can eventually change farmers' situation, they also mentioned that farmers usually show little interest to 'attend' or 'learn' from the trainings they organize. Among all the actors, the potato farmers are the most reluctant to share their views and mostly shy away from discussing matters that they perceive as political or will offend other actors. Very common utterances from farmers when they talked about their engagement with other actors included: "*…the district and CIP works for us….*"; "*based on the directive given to us….*"; *"…just like they told us…."*; "*if they bring us a solution…*"

The case box portrays a picture of the government power structure through which different agriculture-related plans are channeled. In such arrangement, farmers are expected, at least in principle, to comply with a plan that emanates from the government's strategic development agenda.

Case Box: *Based on countrywide strategic plans such as GTP (Growth and Transformation Plan), AGP (Agricultural Growth Program), SLM (Sustainable Land Management), short-term plans are developed by high-level experts in the different departments of the Federal Ministry or regional agricultural offices. Plans developed at this level will be shared with each zonal agricultural office within the regions. Based on those figures, the zonal offices disaggregate the information to each district under the zone and the district follows the same procedure to distribute it to the 'Kebeles' which are the lowest formal government administrative levels in the country. In such a cascade of plans, the role of the offices at immediate lower level is more of providing feedback on invalid assumptions. Although it is not formally part of the government administrative structure, a 'Kebele' also called 'Peasant Association' in rural Ethiopia, is divided into clusters that contain quite a few groups of farmers that are labeled as 'Farmer Development Groups'; the number of farmers in each group ranges from twenty-five to forty. In an ideal situation, three extension workers are distributed to closely work with such groups. Each development group has leaders appointed as chairman, vice chairman and secretary who, in most cases, are 'model farmers' and have a strong link with the local administration. To be able to get to individual farmers, 'Farmer Development Groups' are divided into a group of five farmers which is locally known as 'and le asmest', meaning 'One-to-Five'. In this final social grouping, as its name indicates, one (Model) farmer leads a team of five farmers. Using this structure, which has been in place for a decade or so, the government tries to structure its power and communicates its development agenda until it gets to a farm household level. The 'Kebeles' have a standardized form that will be filled by each household which in aggregate will fit into its Kebele-wide plan.*

Information sharing culture

Lower level government experts at the districts mainly use the social organization, discussed in the 'Politics and Power relations' section, to share different types of information with farmers. They said that through the structure, they can easily share information with farmers on different development agendas including agriculture. In such communication, mobile phone plays an important role according to a district agriculture office head in Gumer. He illustrated: *"These days, communicating farmers has become easy. All we have to do is call leaders of each 'Farmer Development Groups' and pass our message and the leaders will then call and tell each 'one-to-five' leader under them. The 'one-to-five' leaders can easily reach out the rest of the four farmers in their group who usually are their neighbors*". In such a way model farmers (group leaders), assisted by the extension workers, are expected to play a key role in facilitating information sharing with farmers. The experts labeled the model farmers as fast adopters and innovators who can play an important role in influencing other farmers that are perceived to be slow in taking up technologies. A district expert explained: *"We have model, middle and laggard farmers. We focus on model farmers who are only about ten percent of the farmers*". Government initiated trainings are organized separately to the model farmers and then together with the rest of the farmers to help the models play their catalyst role effectively. However, some of the informant farmers seemed to have their reservations on the approach stating that model farmers are usually reluctant to share the information they access and are only benefiting themselves.

Organizations that are engaged in providing agriculture-related information to farmers and other actors through the use of different ICT platforms mainly see the problem of bacterial wilt and late blight and other crop diseases in relation to having access to reliable or timely information on existing scientific management techniques. It is a widely held view that limited awareness among governmental and non-governmental actors on the role ICT can play in crop disease management and in the wider agriculture sector is a challenge. There are different perceptions on best-bet information delivery tools ranging from 'mobile-based voice response' to 'participatory radio programs' and 'educational videos'. Providing scientific and evidence-based information is a critical factor for the interviewed experts. They argued that if scientifically proven technologies and practices are shared with farmers through available ICTs, farmers are more likely to adopt it as they will see the benefit. For this reason, information contents are mainly developed by subject matter experts within or outside the organizations. They stressed the need for developing a content that is not in contradiction with the government's extension advisory service. The information content in the ATA IVR (Interactive Voice Response) system, the first of its kind in the country, mainly adapted 'improved technology packages' used by the government extension service whereby government experts from ATA, Ministry, and national research centers participated in repackaging the content to fit to the IVR system. An expert in the organization explained if there is a need to update the content by ATA, it has to be approved by the Ministry of Agriculture and Natural Resources for its conformity with governments' recommended practices.

2.5. Discussion: a systems thinking perspective

2.5.1. Diagnosis and risk monitoring

The problems mentioned in relation to the limited capacity of extension workers and farmers on diagnosing and monitoring bacterial wilt and late blight, or the resource constraints are more likely manifestations of a more structural problem that appears to be overlooked by many of the actors. Failure to adequately manage a disease can often be traced back to a failure to correctly diagnose or monitor risk levels of the problem (Palmateer et al., 2016). In the management of bacterial wilt and late blight, a preventative attitude is very important as attempting to rescue a field after disease infestation does not give satisfactory results, especially with bacterial wilt. In this regard, disease management practices of the government and those of farmers are by and large campaign-based and reactive rather than being preventive. Practically, preventive approaches for bacterial wilt can range from a containment strategy and strict quarantine measures to practices that are targeted on the reduction of inoculum sources (Miller et al., 2006; Yuliar and Toyota, 2015). In this regard, existing response-based conception and practice of disease management has intrinsically made timely or accurate bacterial wilt or late blight diagnosis and monitoring 'less relevant' in the eyes of decision makers leading to limited effort or investment to improve the technical skills of farmers and extension workers or to allocate the resources required for the work. A recent government strategy document on 'Pest and Disease management' also proclaimed the government's growing recognition that the provision of crop disease management support service has been done only whenever there is an infestation of outbreak proportions reported by farmers (MoANR, 2016). Similarly, the focus on other more important crop insects and diseases by high-level experts and decision makers could be strategically right, but this would also mean that existing reactive disease management culture would even be more pronounced and less organised for bacterial wilt and late blight problems. The absence of accredited national plant protection laboratories along the ministry structure for diagnosing crop diseases, including potato diseases, and lack of monitoring or forecast systems for late blight and quarantine measures for bacterial wilt (Gorfu et al., 2012; Haverkort et al., 2012; MoANR, 2016) are other manifestations of the structural problems that are considerably affecting proper late blight and bacterial wilt diagnosis and monitoring.

The perception by many of the actors, including the government, that disease diagnosis or risk assessment is an activity of the government has important implications from a systems perspective. Successful disease diagnosis or risk assessment approaches require networks of actors from the government, research institutions and local organizations which help to integrate risk assessment and monitoring activities on diseases (Kelly et al., 2017; Mazet et al., 2014). There seems to be a high tendency, both by the government and other actors, to see disease monitoring and risk assessment as the government's task. The tendency to underemphasize the role of other actors, which we consider as a structural problem, is limiting actors' capacity to collectively act in diagnosis and monitoring of the disease.

2.5.2. Management strategies

Disease diagnosis and monitoring and implementing management options are related activities. As highlighted before, most disease control measures should aim at preventing or protecting crops from the disease rather than 'curing' the crop after it is diseased (Miller et al., 2006; Yuliar and Toyota, 2015;). In systems thinking terms, the underemphasis in bacterial wilt and late blight diagnosis and monitoring, which is argued to come as a result of the reactive disease management culture, will have a negative feedback in pushing actors to stick to the existing dominant reactive management approach (Kim and Anderson, 1998; Senge, 2006). Owing to this, the predominant management practices, roguing for bacterial wilt and fungicide application for late blight are done after the incidence of the diseases. Such reactive responses might seem logical at the time of bacterial wilt or late blight prevalence and can indeed suppress the problem at that particular point in time but it has little long-term effect in curbing the recurrence or the fast spread of the diseases. The government has just recently acknowledged that bacterial wilt of potato which used to be a problem in few places has now turned into a national problem due to the existing management responses that are tactical rather than strategic (MoANR, 2016). A recent study by a national research center associated the problem with existing neglect for bacterial wilt suggesting the need for recognising the potential danger of the disease to the potato growers in the country (Gorfu et al., 2012).

An interesting reactive response mentioned by workshop participants that is also criticized by a previous study is the shift in potato production in many parts of the country from the long rain season (*Meher*) to the short rain (*Belg*) production, despite the high yield potential in the long rain season (Bekele and Eshetu, 2008). Promoting preventive late blight management options without sacrificing yield as a result of shifting to the short rain season could have been a more systemic response. This is with the rationale that the overall objective of late blight disease management is taken to be improving potato productivity or reducing the associated yield loss (Burke, 2017; Kirk and Wharton, 2014). Application of fungicide is the most widely used late blight management practice by potato farmers in the country (Kassa and Beyene, 2001; Mekonen et al., 2011). However, uncontrolled application of fungicide is recognized for its contribution to the development of chemical resistance in the country (MoANR, 2016). The same practice, if supported with a monitoring and information sharing mechanism on when and how to apply chemicals before late blight incidence could have been a preventive option for the disease (Pernezny et al., 2016). Such 'event' level responses could not fundamentally prevent the disease epidemics from recurring season after season or could not significantly reduce initial sources of infections.

Another notable finding from actors' views in relation to the management of the two diseases is the tendency to look at the problem situation from one's own organizational mandate or area of involvement. This is evident from the diverging views of actors on the appropriate management options for the diseases. Successful implementation of preventive management options is affected by existing perceptions towards the need for coordinating efforts. Addressing complex challenges like bacterial wilt and late blight requires that interdependent actors navigate the complexity with the help of continuous monitoring and learning, and translate progressive insight into effective coordinative capacity and collective action (Maloy, 2005). Actors' behavior to collaborate or collectively engage is highly influenced by how the different actors see their roles and scope of influence in the disease management system (Kim and Anderson, 1998; Senge, 2006). However, due to a strong emphasis on one's own organizational mandate or limited recognition of interdependencies of activities, which the different aspects of it will be discussed in the subsequent sections of this paper, successful joint engagement could not be materialized. The existing firefighting mode does not particularly work for the management of bacterial wilt, which usually demands combinations of management options that can best be implemented collectively by farmers in a village or a district (Bekele and Eshetu, 2008).

2.5.3. Seed quality control

Through a systems thinking lens, one can clearly observe a fixation on responding to a short-term situation in relation to the different problem aspects of seed quality control. Apparently, emergency seed potato provision, in a poor disease management culture, will not only advance the spread of the diseases, it can also contribute to other emergency situations when one takes into account the economic importance of the two diseases for potato growers (Gorfu et al., 2012; Kassa, 2012). As can be witnessed from the utterances of the inspectors, whenever potato seed quality control issues were raised, the inspectors mainly talked about event-level interventions like doing a timely inspection, giving instructions, warnings or revocation of license. The 'quick fix' solutions and a focus on their own activities have gravitated the actors to blame others for the problem without acknowledging that their own action is affecting the behavior of other actors thus creating the very problem that they blame others for (Senge, 2006).

Similarly, the seed potato producing farmers in the cooperatives or the NGOs could have a chance to proactively work to change their own practices in the production or distribution of disease-free seeds but instead, they are more inclined to superficially react to the regulatory and procedural demands of the inspectors who primarily see strict enforcement as their main course of action. There is no doubt that enforcement of the regulations is necessary. However, a more systemic response could have been facilitating conditions for joint learning to improve the knowledge and technical capacities of potato growers and experts on the diagnosis, monitoring, and management of the two diseases (Maloy, 2005). This does not only help growers to produce disease-free potato seeds that different actors buy and distribute to different areas, it can also lessen the burden on the inspectors who are stretching their limited capacity to casually address bacterial wilt and late blight problems through enforcement of laws and procedures.

2.5.4. Research and extension

As stated by the researchers, over the years, limited adoption of agricultural technologies by farmers through the conventional research and extension approach has indeed brought a shift of emphasis towards participatory research and extension approach in the country (Bedane and Kuma, 2002). It was envisaged that the new approach will bring together the knowledge capacities of local communities with that of scientific institutions and other stakeholders in processes of technology development and use (Bedane and Kuma, 2002; Tesfaye et al., 2002). However, despite the claim to this shift, it is observable that the traditional technology transfer model is still dominant thinking. Researchers' statements seem to implicitly authorize scientists or research institutes as the only or major suppliers of knowledge products. Existing names of the different research departments are also good imprints of a linear thinking mode. Without working towards a shift from this thinking, the 'participatory approach' cannot facilitate interactive learning processes in the direction of joint creation of knowledge and collective action (Röling and Leeuwis, 2001b). Contrary to this, a striking event-level response or a simple-fix from the researchers to the problem of not getting the required support from extension workers or farmers is paying per-diems or hiring guards. Such responses would likely have a negative long-term effect on the very participatory approach by reinforcing existing attitudes of the extension workers and probably farmers[11] in seeing the research experiments as solely researchers' business.

[11] We could not capture farmers' opinion as none of the farmers approached for the study said they had experience in participatory research.

Moreover, the extension research wing in the national research system is preoccupied with 'technology demonstration' and 'popularization' activities. This limits its research engagement on wider systemic issues or in knowledge brokering which could have contributed to institutional innovation and transformation of the enabling environment for technology development and use (Turner et al., 2016; Turnhout et al., 2013). However, as to what seems to be a total disregard for this structural problem, the decision made by SARI is to dissolve the 'Extension Research' department. A shift from a linear knowledge/technology transfer culture could have been a generative response to improve the effectiveness of the participatory research and extension approach and its contribution to co-creation of knowledge and technologies that are more relevant to the management of bacterial wilt and late blight.

From the utterances of the different actors, one can observe similar defensive routines by the different actors while explaining the different aspects of the problem situation. Such propensity of shifting responsibilities is also reflected in the Ministry's strategy document whereby its linkage with the national crop protection research has remained a very loose owing to the research institute's low focus on plant protection technology generation (MoANR, 2016). From a systems thinking perspective, the tendency to engage in a blame-game or to see themselves in isolation has led them to look for an external cause to the problem situation (Senge, 2006).

2.5.5. Politics and power relations

As people have a particular way of viewing the world, judgments to be made or 'actions to improve' a problem situation should seek accommodation or deliberation among different views and interests of actors. So politics is taken to be a power-related activity concerned with managing relations between different views and interests (Checkland, 2000). Bearing the mantle of leadership in 'smallholder-based sustainable agricultural growth and development' (Chanyalew et al., 2010), the government is playing a very dominant role in planning and agenda setting in a hierarchical and top-down fashion. By the virtue of emphasizing on the expediency of this approach, some of the decision makers and experts in the government showed little regard for any power asymmetry that could arise from the top-down decision-making process. Even though the government's approach might have emanated from pure ambition and an assumed leadership role, a vision that does not appreciate the interests and aspirations of the farmers or other actors can fail to inspire genuine enthusiasm. Decision-making processes can be transformed if all concerned actors become more able to surface and discuss productively their different interests and aspirations (Senge, 2006).

Strong dominance of the government ministry and its downward structure also seems to affect perceived capacity of other actors to instigate change in the system. This is clearly visible in the opinions of researchers and NGO experts on their perceived limited ability to change the problem situation and on the importance of aligning their activities with the agenda set by the government. In system thinking terms, such attitude and associated behavior create a difficult condition for all the actors to fully realize or unleash their potential for coordinated action (Senge, 2006). Although meaningful change can best be realized when powerful actors like the government see the importance of accommodating different interests, the belief of the other actors that change has to come from outside (the government) is characteristic of non-system thinking. It is when actors see themselves as part of the systemic structure that they realize they have the power to alter the structure of the system (Kim and Anderson, 1998; Mazet et al., 2014).

Farmers, who usually are claimed to be ‘key partners’ by the different actors, find themselves even in a more difficult situation to express their interests. Some of the common utterances from farmers clearly reveal their perceived position in existing power relations. A previous study on participatory natural resource management intervention in the country also supports our assessment that a restrictive political context and widely held negative attitudes towards farmers have undermined self-confidence among farmers, many of whom seem to have internalized the perception that experts and decision makers have towards them (Cullen et al., 2014). The perception that lack of knowledge of farmers is a key problem has shifted the focus of actors towards training and capacity building activities. However, different literature on power relations has already underscored that such interventions can potentially mask or exacerbate the more structural problem of power inequalities if existing power dynamics and the need for accommodation of different interests are not taken into account (Aarts and Leeuwis, 2011; Cullen et al., 2014).

2.5.6. Information sharing culture

As interactions are quite centralized and hierarchical, information sharing is practiced in the same mode. As part of an attempt to come up with a different approach, there have been some experiments on participatory information sharing and learning platforms by different international research-for-development organizations, particularly CGIAR institutes working in the country (Abate et al., 2011; Lema et al., 2015; Swaans et al., 2013). Although so far there is very limited local scientific evidence on the impact of such platforms in fostering interactive information and knowledge sharing or learning, a key insight from one empirical study in the country is of particular importance to our research topic. The study amplified that a failure to take into account power imbalances and political realities in and around learning platforms did not only gave the illusion of increased participation and learning but it also compromised the capacity of the platforms in catalyzing social change (Cullen et al., 2014).

Organizations that are engaged in the delivery of agricultural information through different ICT tools appear to have a shared 'technology-oriented' approach to information sharing which assumes that farmers will act in accordance with the implemented technology (Pilerot and Limberg, 2011). The experts mainly talk about how the information delivery tools can facilitate or improve farmers' or other actors' access to information, giving little emphasis to the existing top-down culture and power relations which are indicated to influence how actors access, interpret, share or use information (Banjade et al., 2006; Leeuwis, 2004). Due to existing perception of information sharing as a technical rather than a social phenomenon (Checkland, 2000), the development of the information content that is delivered through the different ICT technologies is essentially expert-driven. The ATA approach can be a case in point whereby without changing the logic of content development or information sharing culture, their practice might have even increased the power of the ministry through its control on the information. Using ICTs to enable participatory and interactive information sharing is in stark contrast with classical, expert-centered approaches where ICTs are used primarily to support the dissemination of research-based information and advice (Cieslik et al., 2018; Leeuwis, 2004). On the other hand, if ICT-based interventions are context-specific and build on local needs and capacities, it may enable the generation of new forms of locally relevant information and can catalyze new forms of network formation, information sharing and learning (Chapman and Slaymaker, 2002; Cieslik et al., 2018).

2.5.7. Opportunities for ICTs in overcoming collective action problems

Finally, our systemic analysis envisages to look for opportunities for leverage or small, well-focused interventions that have the potential of producing significant and enduring improvements to the problem situation (Senge, 2006). As it is discussed under the technical aspect of the problem situation, actors' limited recognition of interdependency and existing marginal collaboration poses a challenge to effectively monitor and manage the problem of bacterial wilt and late blight. The collective engagement problem becomes even more pronounced when the aim of disease management is geared towards disease prevention rather than disease control (Mazet et al., 2014). This is with the rationale that timely monitoring and risk information sharing, which are vital elements of preventive disease management strategy, require a network of actors that should work towards reducing reoccurring risks of the diseases at the collective level (Liao et al., 2016). In this regard, different ICT platforms have been implicated to play a meaningful role in overcoming connectivity problems or in complementing traditional collective action networks that aim to address complex challenges such as potato disease management (Chapman and Slaymaker, 2002; Cieslik et al., 2018; Karpouzoglou et al., 2016).

However, as highlighted in the introduction, the potential of ICTs to address coordination problems should be seen within the wider social, political and cultural context in which they are supposed to be used (Bennett and Segerberg, 2012; Chapman and Slaymaker, 2002). The amplifying function of digital technologies can, in fact, serve to perpetuate existing inequalities instead of eradicating them (Cieslik et al., 2018). If ICTs have to realize their full potential in contexts with limited horizontal and democratic information flow, active participation of actors at the periphery in the design, experimentation, and use of the digital platforms is crucial (Chapman and Slaymaker, 2002). In our problem context, farmers and lower level (district) actors, which seems to be prime victims of existing power asymmetries and top-down information sharing, could be potential target groups for any ICT-supported collective disease management intervention. In doing so, the platforms will have the possibility to structurally alter the existing top-down flow of information and power inequalities by decentralizing information flow, devolving ownership over information and knowledge, decreasing dependency and providing a framework for shared learning (Chapman and Slaymaker, 2002; Karpouzoglou et al., 2016). Moreover, designing ICT supported collective disease management interventions that target high-level actors at national or regional levels can potentially fail to bring genuine enthusiasm due to the prevailing focus on the management of other insects and diseases of strategic crops. Although bacterial wilt and late blight management are still weak at the district level owing to the overall reactive disease management culture, the disease problem appears to be more recognized or felt by actors operating at the local level.

As noted by Cieslik et al. (2018), different forms of participatory digital platforms in combination with more conventional forms of interpersonal communication and mass media can foster new kinds of connectivity, and enable the collection, processing and exchange of information among different actors or members of a community. Mobile phone technology has rapidly been accepted in rural communities and is playing an important role in fostering interaction between farmers, extension bodies and institutions (Chapman and Slaymaker, 2002; Chou and Min, 2009). Given the absence of potato disease forecast or early warning system in the country, ICT supported decision support tools can have a potential contribution in the generation and exchange of information that serves to initiate collective risk monitoring of late blight and in curbing existing practices of fungicide spray that is being done after late blight occurrence. Sharing information on the likelihood of late blight occurrence and on preventive spray regimes that help growers and other local actors for individual or collective decision is now becoming easier through mobile phone networks in places with low internet penetration like Ethiopia (Nakato et al., 2016). Likewise, digital platforms can play a role in the exchange of information on the different disease dynamics of bacterial wilt (e.g. prevalence, diagnosis, monitoring and control options). This can help the actors to better recognize the risks of bacterial wilt which seems to get limited attention so far. Most importantly, information sharing and learning on the risks and management of bacterial wilt can assist potato growers to advance their unsuccessful practice (roguing) in the management of the disease. With the help of mobile phones, participatory monitoring can be performed by groups of community members which can foster joint learning on the disease dynamics and enhance awareness on the need for cooperation to effectively deal with it (Trabucco et al., 2013). By designing a more bottom-up and participatory approach to content development and technology modification to better fit into local needs, existing infrastructure such as the ATA AVR system can be leveraged to better ensure institutional embeddedness. To this end, further investigation on existing information and knowledge needs in relation to the diagnosis and management of each disease would help to arrive at specific recommendations on best-bet technology options and the content of information that can be used to catalyze disease monitoring, broader learning, and collective action.

2.6. Conclusion

This study attempted to assess actors' understanding of the problem situation in the management of bacterial wilt and late blight along multiple and interacting technical and institutional problem dimensions (Figure 2.1). In so doing, it further explored its implication for management of the two diseases and the role ICT can play in overriding collective action problems. As it is demonstrated in our analysis in Section 2.5, actors essentially overlooked key systemic problems that are contributing to the continuation or even worsening of the disease problems. Lack of preventive management culture**,** limited recognition of interdependencies among activities of actors, power inequalities, top-down and linear approaches in information and knowledge sharing are among the key structural problems identified. Consequently, management responses are mainly geared towards uncoordinated short-term reactions that were found to have limited effect in catalyzing fundamental change to the systemic problems of bacterial wilt and late blight management. Figure 1 depicts actors' key reactive responses (ERs) and the systemic structure at play (ST) across various technical and institutional aspect of the problem situation represented by the four circles with smaller arrows. It is further summarized

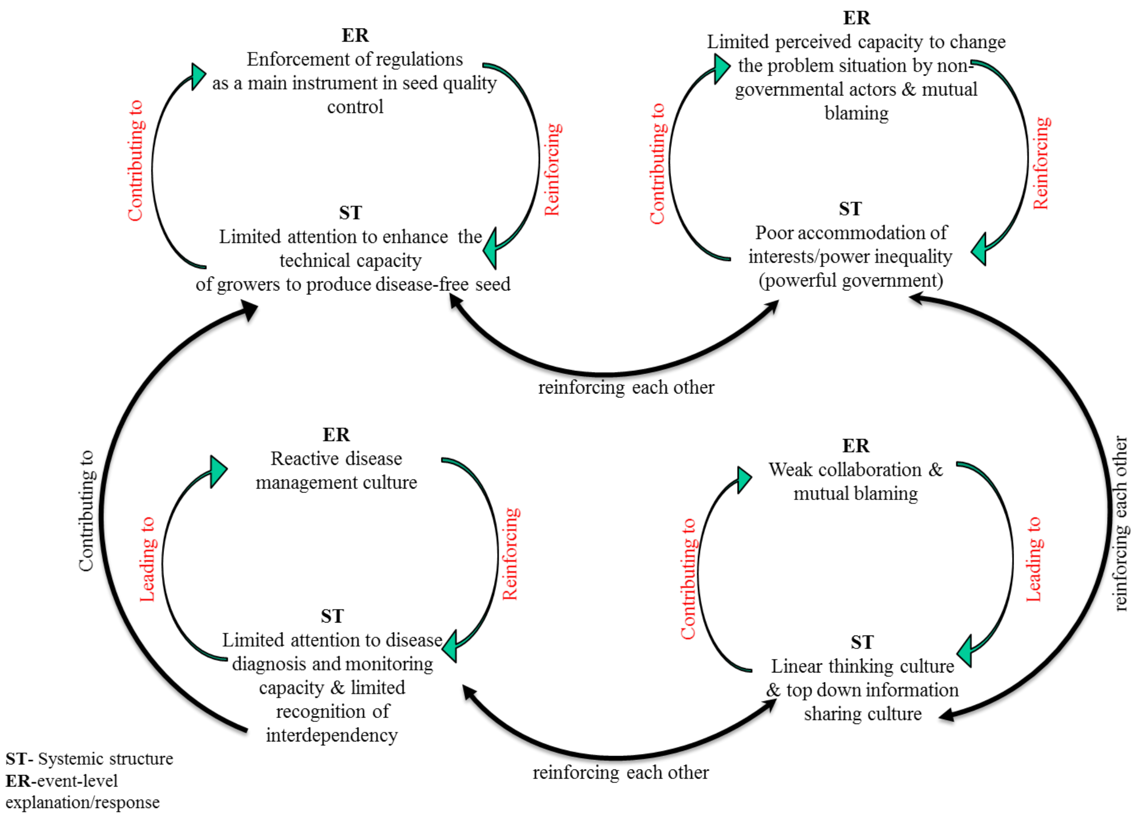

Figure 2.1. Systemic structure at play in complex problem of management of bacterial wilt and late blight

in the figure that the systemic problems within the different problem aspects interact with one another to bring about a complex problem situation in the management of bacterial wilt and late blight.

Likewise, the existing appreciation of the problem situation has pushed many of the actors to mainly focus on their own activities and decisions with little recognition that the structural problems are results of multiple interacting factors to which they themselves, knowingly or unknowingly, have contributed their share. This is evident in actors' tendencies to shift responsibilities and engage in a blame-game when discussing the different problem aspects of the diseases. In light of our research questions, we can conclude that existing understanding of actors of the systemic structure has limited their capacity to effectively and jointly respond to the complex problem of late blight and bacterial wilt management.

As problems of bacterial wilt and late blight management have multiple technical and institutional aspects, new management interventions should also be designed in such a way that the interventions can instigate technical (preventive disease management) as well as institutional (power asymmetries and top-down information sharing) change. A bottom-up and participatory disease management approach can serve as a 'local' solution to a wider systemic problem whereby farmers, together with local level actors, can drive a positive change in the bacterial wilt and late blight management system. Local level actors such as extension workers, seed quality inspectors, researchers, and NGOs can be strategized to foster institutional embedding and broader learning.

As it is highlighted in the discussion section, a shift to a more preventive management culture warrants networking of local level actors who can collectively engage in disease monitoring and information sharing on different aspects of bacterial wilt and late blight management. Designing such interactive processes will not only help local level actors to better realize their interdependency and to have a shared understanding of the systemic structure at play, more importantly, it can facilitate collaboration and collective action to deal with their shared problem. In this respect, different forms of digital technologies or information sharing platforms can play a role in facilitating actor networking, information exchange, learning and collective action in the management of the two diseases. A promising intervention for late blight could be a mobile-based decision support tool that can be used for information sharing on disease monitoring and preventive fungicide use. Similar mobile-based digital platforms can be leveraged to enhance awareness and facilitate learning on bacterial wilt disease dynamics and management. To be able to come up with a more specific recommendation, more insight on existing ICT infrastructure, and information and knowledge needs in relation to the diagnosis and management of each disease is of paramount importance.

Chapter 3

Farmers' knowledge and practices of potato disease management in Ethiopia

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Abstract

Effective management of potato diseases such as bacterial wilt and late blight depends to a large extent on farmers' knowledge of the diseases as well as on the integration of recommended management methods in their daily practices. Late blight has continued to be a dominant potato disease for many decades in Ethiopia, whereas bacterial wilt has emerged more recently with a devastating impact on the country's potato production systems. A survey of 261 randomly selected farmers was carried out in three major potato growing districts in the central highlands of Ethiopia to examine farmers' knowledge and management practices of the two diseases, and to analyse the role of relevant knowledge in their practices. Considering their different characteristics, three groups of farmers were distinguished: producers of quality declared seed, producers of regular seed and producers of ware. The study shed light on the vital role the lack of knowledge about the diseases plays in shaping farmers' daily potato production practices. Most farmers could recognize symptoms of the diseases on infected leaves and stems. However, they had very limited knowledge of the diseases including their causal agents, spreading mechanisms, and effective management methods, although they knew a little bit more about late blight than about bacterial wilt. Therefore, to effectively manage the diseases, farmers need to learn about the diseases and how to manage them in their local context applying a feasible combination of management options through a community-based approach. The effectivity of such approach could be enhanced by stipulating operational standards in bylaws and through continuous monitoring of changes in farmers' practices and environmental monitoring for disease occurrence by leveraging interactive mobile-based platform.

Keywords: Farmers' knowledge, potato diseases, disease management, farmers' practices, bacterial wilt, late blight, *Ralstonia solanacearum, Phytophthora infestans*

3.1. Introduction

Potato (*Solanum tuberosum* L.) is the third most important food crop in the world after maize, rice, and wheat. It provides more food per unit area than any other major food crop (Devaux et al., 2014; FAO, 2008). In Ethiopia, on top of being a key crop for food and nutrition security, potato is a vital source of income for many smallholder farmers in the Ethiopian highlands due to its high yield, combined with its early maturity and high nutritional value (Gildemacher et al., 2009a; Haverkort et al., 2012). Currently, potato is cultivated on more than 296,000 ha of land in the country, engaging more than 3.7 million smallholder farmers and with an annual production of about 3.6 million tonnes (CSA, 2016).

Despite its importance, the production of potato has been challenged by several biotic and abiotic constraints prevailing in the country. Potato yield per unit area has remained low with a national average of approximately 12.3 Mg/ha (CSA, 2016), which is low compared to the achieved yield of up to 65 Mg/ha on research station and about 50 Mg/ha on farmers' field, under good management practices and using improved varieties (Berihun and Woldegiorgis, 2013).

Among the major biotic constraints that have severely affected potato production in Ethiopia, late blight has been identified as the most important (Kassa and Eshetu, 2008; Woldegiorgis et al., 2008). The pathogen develops and spreads rapidly under high relative humidity, moderate temperature, and substantial rainfall. It infects potato leaves, stems, and tubers at any stage of development and has a potential to destroy the whole potato field within a few days.

Considering the importance of the late blight problem, several potato research and development projects have been implemented in the country. Late blight management approaches which include the use of resistant varieties, fungicide application, and cultural practices such as early planting, hilling and mechanical haulm killing before harvesting have been tested and recommended by the national agricultural research institute (Woldegiorgis et al., 2008). Studies show that management practices such as fungicide application and use of resistant varieties have been adopted by some potato farmers in different parts of the country (Tesfaye et al., 2013). However, late blight has continued to be a serious problem contributing to a significant yield reduction in the Ethiopian potato production system.

More recently, another potato disease, bacterial wilt, has become the most serious threat to the country's potato production (Gorfu and Woldegiorgis, 2013). The prevalence of bacterial wilt has been historically limited to few parts of potato-growing areas in Ethiopia until recent years (Henok et al., 2007; Lemessa and Zeller, 2007). With the rapid expansion of potato production in the country, the distribution of the disease has been increasing. And currently, the disease has spread nationwide. According to recent studies, the disease has affected the seed potato production system and it has reached an epidemic level in some districts (Abdurahman et al., 2017; CIP, 2016; Gorfu et al., 2013). Overall, given the drastic prevalence of both bacterial wilt and late blight in the country, controlling the spread of the diseases is currently a big concern of potato farmers and other actors in the potato innovation system.

In the literature, much is known about the nature of the pathogens that cause the two diseases and effective measures for prevention and control of their spreading (Arora et al., 2014; Hayward, 1991; Yuliar et al., 2015). This does however not imply that smallholder potato farmers in developing countries like Ethiopia have adequate knowledge of the diseases given the complex socio-ecological nature of these problems. A recent diagnostic study conducted in the Ethiopian potato innovation system and published in this special issue has pointed out that the design and implementation of effective management interventions for the two diseases requires an understanding of the systemic, multiple and interacting technical and institutional aspects (Damtew et al., 2018). The study recommends a community-based approach (mobilizing farming community and strategizing other local actors) to effectively manage the diseases in the context of smallholder farmers in Ethiopia (Damtew et al., 2018). Similarly, previous studies in many countries have recommended an integrated approach using a combination of disease management options as a plausible strategy to effectively manage bacterial wilt (Elphinstone and Aley, 1993; French, 1994; Lemaga et al., 2005; Priou et al., 1999) and late blight (Cooke et al., 2011; Garrett et al., 2001; Lal et al., 2017). Furthermore, addressing such complex socio-ecological challenges requires continuous monitoring and learning, and translating new scientific knowledge to foster the capacity of farmers to act collectively (Brown et al., 2010; Cieslik et al., 2018).

In the current digital era, the increasing availability of Information Communication Technologies (ICTs) has enabled management and monitoring of complex ecological challenges by generating timely and context-specific information (Cieslik et al., 2018). Likewise, in relation to complex potato diseases like bacterial wilt and late blight, mobile-based technologies have been suggested as potential ICTs to stimulate collective and connective action among farmers by generating locally relevant information (Cieslik et al., 2018; Damtew et al., 2018). However, the extent to which farmers in Ethiopia have access to mobile phones and how mobile-based platforms can be leveraged for disease monitoring and information sharing among smallholder farmers are not clear. Furthermore, for developing an effective community-based approach, good insight into farmers' knowledge and information need in relation to the different aspects of the diseases is required. Understanding the role of knowledge in farmers' practices is also an important starting point for developing a community-based management strategy that fits the context of the country's potato production systems.

This diagnostic study was designed to investigate farmers' knowledge of various aspects of bacterial wilt and late blight and to examine how the knowledge on these diseases contributes to or hinders good farmers' practices of preventing and controlling the diseases. It is recognized that relevant knowledge may consist of both scientific knowledge and local knowledge and abilities to deal with the diseases in the local context. Hence, the study focuses on farmers' understanding of scientific knowledge on the diseases and recommended management methods as well as their local knowledge on how to deal with the diseases. The findings of this study are relevant for the design of a community-based potato disease management in the context of smallholder farmers in Ethiopia. Moreover, the study offers an important scientific contribution to our theoretical understanding of how farmers' practices are related to knowledge in relation to the management of plant diseases and how mobile-based technologies can foster disease monitoring and collective action. The main objective of the study is to identify basic requirements for a community-based management strategy that induces a learning process among farmers for effective management of bacterial wilt and late blight in the central highlands of Ethiopia. The implications of the study were identified by exploring what types of learning approaches would fit the current situation of farmers' knowledge and practices. To achieve the overall objective, four related research questions were formulated:

1. What would be an effective disease management strategy for smallholder potato farmers?
2. What knowledge do farmers have about bacterial wilt and late blight and their management methods?
3. How are farmers' practices related to this knowledge?
4. What are the implications for a community-based intervention and monitoring approach by leveraging a mobile-based platform?

This paper is organized as follows. Section 3.2 develops a conceptual framework for the study. This is followed by Section 3.3 with a brief description of the methodology including study design and sample selection, description of study sites, data collection and analysis, and profile of sample farmers. In Section 3.4, the results are presented, and in Section 3.5 the findings are discussed. Section 3.6 draws conclusions.

3.2. Conceptual framework

The purpose of this section is to present a conceptual framework employed in this study. Three concepts relevant to crop disease management are key in this study. These are potato diseases, knowledge and practices.

3.2.1. Potato diseases

Plant diseases result from complex interactions among a susceptible host plant, a pathogen, and the environment (Scholthof, 2007; Vanderplank, 2012). Several human activities like cultural practices including application of chemicals modify this interaction (Burdon et al., 2014). Environmental factors such as temperature, moisture, soil pH, wind, light, and soil type play a huge role in disease development and severity (Scholthof, 2007; Schumann, 1991). Plants are considered to be diseased when they are infected by a pathogen and their normal development and functioning are disrupted. Hence, plant diseases significantly diminish growth and yield or reduce the usefulness of a plant or a plant product (Beresford, 2007; Van der Plank, 2013). Plant diseases may also lead to complete destruction of the entire plant under conditions favorable for the disease. Plant diseases can be grouped by the causal agent involved such as fungal diseases, bacterial diseases, and viral diseases (Schumann and D'Arcy, 2006; Van der Plank, 2012). Good understanding of the pathogen that causes a disease, its characteristics and life cycle, and its effective management options are critical to control or suppress the adverse effects of a plant disease (Van der Plank, 2013). This study focuses on the two major potato diseases in Ethiopian potato production systems, bacterial wilt and late blight, which are complex ecological problems. These diseases are caused by pathogens that have intricate life cycles and diverse spreading mechanisms.

3.2.2. Knowledge

For effective management, farmers need to have good knowledge of different aspects of the diseases, such as causal agents of the diseases, their life cycle, their visible symptoms on infected potato plants and tubers, how they spread from one area to another or from one plant to another, and effective management options. Without knowledge of these features of the diseases, it is difficult to effectively deal with them.

Knowledge is a generic concept that needs to be specified to be a useful analytical tool. Scholars from many fields have developed different perspectives and attach different meanings to the concept of knowledge. For Churchman (1971), knowledge is a collection of information, as an activity or as a potential residing in the user to help him adjust behavior to changing conditions. Taking an interpretive view, Davenport and Prusak (1998) define knowledge as "a fluid mix of framed experience, values and contextual information and expert insight that provides a framework for evaluating and incorporating new experiences and information." According to this perspective, knowledge originates from and is applied by humans.

Different taxonomies of knowledge have been proposed by different scholars that got prominence in different scientific or practice domains. Lundvall and Johnson (1994) consider knowledge as a key resource for economic growth. They categorize relevant knowledge into four broad categories: know-why (scientific knowledge of principles or interpretative frameworks based on experience and intuition), know-what (knowledge about facts), know-how (skills of doing different kinds of things practically) and know-who (who knows what and can do what). Know-what and know-why are usually referred to as explicit knowledge since they are easy to codify and communicate whereas know-how and know-who are tacit knowledge, which is invisible and difficult to share (Nonaka, 1991; Polanyi, 1967). This perspective on knowledge has gained prominence among innovation scholars who study learning economies. Learning mechanisms are also related to the type of knowledge to be generated, exchanged or transferred. Know-what and know-why are primarily learned by reading books and other materials and attending lectures or trainings while learning know-how and know-who is primarily rooted in experiential learning and in social interaction (Lundvall, 1992).

As disease management entails implementing a range of activities that require different types of knowledge, our study borrowed this perspective to examine the different knowledge aspects of farmers in the management of bacterial wilt and late blight. In the context of this study, know-why refers to knowledge on the causal agents and spreading mechanisms of the two diseases as farmers are not necessarily expected to understand the delicate and complex life cycles of the pathogens in order to properly manage the diseases. Know-what includes farmers' recognition of the diseases, symptoms on infected potato plants and tubers, diagnosis methods, and management methods, whereas know-who refers to farmers' knowledge of who can provide relevant information or their sources of information in their respective areas in relation to effective management of the two diseases, including fellow farmers, extension workers, NGO staffs and researchers, among others. Finally, know-how refers to farmers' skills to implement effective disease management practices.

3.2.3. Practices

Relevant knowledge shapes disease management only if it is integrated into farmers' daily practices. The concept of social practices has been used by many scholars (Leeuwis, 2004; Shove et al., 2012). Practices are patterns of human action that are common in different contexts due to social influences. Peoples' practices are shaped by a number of factors including what they believe to be true (beliefs about consequences of actions/practices, perceptions of likelihood and risk), what they aspire to achieve, what they think they are able to do (which includes availability of skills and competence), and what they think they are allowed and/or expected to do (Leeuwis, 2004). Likewise, according to Shove et al. (2012), a social practice is defined by available materials (things, technologies, and physical entities), competences (skills, know-how, and techniques) and the meaning attributed to it (symbolic meanings, ideas and aspirations). This perspective contends that while people may know why, in order to integrate relevant knowledge into their practices, it must be meaningful in their local context, they need to possess or have access to appropriate technologies and develop appropriate skills and local knowledge of how to apply scientific knowledge in a specific context. This concept of practices thus allowed us to give special emphasis to the role of knowledge in farmers' practices of bacterial wilt and late blight management.

3.3. Materials and methods

3.3.1. Study design and sample selection

A survey aimed at understanding farmers' disease management practices and their knowledge of bacterial wilt and late blight was conducted. To select sample farmers, a multistage sampling technique was used.

In the first stage of selection, three sample districts (Gumer, Doyogena and Wolmera) were chosen purposefully from two major potato growing regions of the country, Southern Nations, Nationalities, and Peoples' (SNNP) region, and Oromia region. These districts are among the major potato growing districts located in the central highlands of Ethiopia. Due to variations in terms of local conditions such as agricultural production systems and access to potato technologies, the districts were selected purposefully for the study expecting variations in farmers' practices in relation to potato disease management.

Gumer is located in the Gurage zone of SNNP region at 220 km from Addis Ababa. The agroecology of the Gumer district is moist cool highlands with bimodal rainfall and with annual rainfall of about 1600 mm. Its altitude ranges from 2800-3000 m. Doyogena district is also located in the SNNP region of Kampata Tembaro zone, at about 260 km south west of Addis Ababa, with an altitude ranging from 1900 up to 2800 m. The district also has a bimodal distribution of rainfall with an annual rainfall of around 1400 mm. Wolmera district is located in the Oromia region, about 40 km west of Addis Ababa, with a bimodal rainfall distribution. This district receives an average annual rainfall of around 1100 mm and its altitude ranges between 2060 to 3380 m. Wolmera district has been one of the hubs of the seed potato market over the last 15 years since the Holeta Agricultural Research Center (HARC) of the Ethiopian Institute Agricultural Research (EIAR) and the International Potato Center (CIP) have been operating in the area. HARC and CIP have started operating in Gumer and Doyogena districts in recent years. This may probably lead to different disease management practices among the districts since the farmers in Wolmera district have had relatively better access to information on potato production and disease management practices.

In the second selection stage, three broad categories of potato farmers were discerned, because their knowledge was expected to differ (although the categories were not mutually exclusive): producers of quality declared seed (QDS), producers of regular seed and producers of ware potatoes. QDS producers are farmers who are registered to produce seed that conforms to the minimum standards for seed potato production and undergoes some certification process (CIP, 2016; ESA, 2015) that is legislated in the seed production law. Since they are required to understand and adhere to quality seed production procedures stipulated in the QDS regulation they must have good knowledge of potato diseases and potato production practices and inform themselves. Regular seed producers are those farmers who are usually organized in groups or cooperatives to produce seed potatoes. Their seed does not pass a certification process but is expected to meet minimum requirements and therefore these farmers should have better knowledge than ware producers. Ware producers produce table potatoes either for home consumption or for marketing. There are no quality standards for ware potatoes. The knowledge of ware growers about diseases is expected to be least because they primarily get information from fellow farmers and extension workers unlike producers of QDS and producers of regular seed who get substantial support from agricultural research centers, universities and non-governmental organizations.

Lists of potato growers (population) in the study sites were obtained from the respective district offices of agriculture and natural resources and sample farmers were randomly selected from these lists. The sample size was determined with the proportional stratified sampling method, with 95% confidence interval and 5% margin of error. Overall, a total of 261 farmers were selected and interviewed in the field. Detailed numbers of interviewed sample farmers are indicated in Table 3.1.

Table 3.1. Numbers of interviewed farmers

Sample districts	Number of sample farmers			
	QDS producers	Regular seed producers	Ware potato producers	Total
Gumer	23	27	32	82
Doyogena	17	18	41	76
Wolmera	-	40	63	103
Total	40	85	136	261

3.3.2. Data collection and analysis

A questionnaire developed by the researchers was used to collect data from the sample farmers. The questionnaire was aimed at getting a clear picture of farmers' knowledge of bacterial wilt and late blight. Both structured and semi-structured questions were used.

Farmers’ know-why and know-what were investigated by comparing the current knowledge of scientists with farmers’ knowledge of the generic issues of the nature of the disease, causes of the spreading of the disease and disease management. The review of the state-of-the-art of scientific knowledge of bacterial wilt and late blight was carried out on the basis of a literature study (the know-why among scientists; see Sections 3.4.1 and 3.4.2).

The tacit knowledge forms of know-who and know-how are ideally investigated with participant observation and long, in-depth interviews. The know-who was investigated by asking about the farmers' knowledge not only about the sources of information, but also about the type of knowledge obtained from different sources and whether mobile phones were sufficiently used by farmers to be future source of information were explored. To tackle the potential drawbacks of asking about know-how in a survey, the farmers were questioned about their actual disease management practices. Hence, practices such as crop rotation, seed renewal, use of late blight resistant potato varieties, and sorting infected/damaged seed and ware potatoes at harvest were given due attention in the questionnaire about how to address the diseases. Moreover, to triangulate and complement the findings of the survey, additionally in-depth interviews were conducted with six purposely selected farmers to generate qualitative information about their know-how and know-who.

The questionnaire was pre-tested with three farmers in each sample district. Few revisions on the content and the ordering of questions were made based on observations and reflections from the pre-test. The survey was conducted in a face-to-face interview style during November and December 2016. In addition to the questionnaire, farmers were asked to differentiate the symptoms of bacterial wilt and late blight that they knew during the interview. The questions were supported by providing colored photographs, which showed infected symptoms of bacterial wilt and late blight on potato leaves, stems and tubers.

The survey data were analyzed using descriptive statistics (percentage, frequency and mean) to present findings in summaries and tables. Pearson Chi-square test was used to determine whether there was a significant difference in potato production practices and farmers' knowledge of bacterial wilt and late blight management among farmers of different categories, and study districts. All the quantitative analyses were done using SPSS (Version 22) software.

3.3.3. Profile of sample farmers

Of the 261 respondent farmers for the study, 87% were male and 13% were female. The average age was 42.7 ± 13.1 years, with many farmers (46%) between 36 and 55 years old. The majority of the respondents (67%) had formal education, either primary school (grade 1-8) or secondary school (grade 9-12). Only 18% of the farmers were illiterate. All sample farmers were smallholders, with an average potato farm size of 0.56 ± 0.57 ha; the majority of them (53%) had less than 0.5 ha. Farmers in Wolmera district owned relatively larger potato fields than the farmers in Gumer and Doyogena districts. The average potato field size ranged from 0.37 ha in Gumer to 0.83 ha in Wolmera district, and from 0.50 ha for ware potato producers to 0.64 ha for regular seed producers.

3.4. Results

3.4.1. Know-why of bacterial wilt of scientists

Bacterial wilt is a damaging potato disease, caused by *Ralstonia solanacearum* (Yabuuchi, 1995). The pathogen is categorized as seed-, soil- and water-borne since it spreads through the use of infected seed as planting material, infected soil, surface run-off and contaminated irrigation water (Elphinstone et al., 2005; Hayward, 1991; Janse, 1996). The pathogen can also be introduced to a crop field through contaminated farm tools when used for cultivation and weeding. Once the pathogen is established in a potato field, it can survive in the soil for many years and thus prohibits subsequent production of potato in that field (Denny et al., 1994; Hayward, 1991).

Ralstonia solanacearum is a widespread pathogenic bacterium that causes a wilt disease with severe effects on more than 200 host plant species which include many economically important solanaceous crops such as potato, tomato, eggplant, tobacco and chili (Elphinstone, 2005; Hayward, 1991). This bacterium enters the host plant roots, colonizes the xylem and makes the host plant collapse (Genin, 2010; Vasse et al., 2005). It has effective pathogenicity determinants to invade and colonize and destroy host plants. Visible symptoms of the infected plants are wilting, stunting and yellowing of the foliage. When the seed potato tuber is infected by this bacterium, the vascular ring decays and slime oozes are released from it until the tuber is completely destroyed (Vasse et al., 2005). After destroying the host plant, the bacterium is released to the environment and survives in soil, water or other host plants including weeds. It exhibits successful strategies for survival in harsh conditions through diverse survival forms until it contacts with a new host plant (Hayward, 1991; Vasse et al., 2005). The pathogen can also form latent infections, where host plants contain a bacterial population but without visible symptoms of infection (Aliye et al., 2015; Priou et al., 2001; Swanson et al., 2007). In Ethiopia, wide spreading of the disease has been found to be associated with latently infected seed distribution across the country (Abdurahman et al., 2017). The disease is also indigenous in many areas of the country.

Bacterial wilt is difficult to control essentially because of its diverse host plant species, its transmission through latent infection, the multitude of sources of infection, and long survival of the pathogen in the soil. Recent advances in control measures include chemical, biological, physical, phytosanitation and cultural practices (Yuliar et al., 2015). But chemical control has not been proven to be efficient to control bacterial wilt since the pathogen survives in deeper soil layers (Hayward, 1991; Huet, 2014). Also, chemicals have damaging effects on the environment. Likewise, even though studies have shown the potential value of some biological control agents, their suppression capacity is usually too low to be commercially used at large scale or requires high rates of inocula (Champoiseau et al., 2010; Whipps and Gerhardson, 2007). Physical methods like soil solarization using transparent plastic mulches have been proven to be effective against the pathogen although they are also difficult to be implemented by smallholder farmers (Yuliar et al., 2015). Thus, phytosanitation and cultural practices are the recommended and most widely used methods to eradicate or reduce bacterial wilt (Champoiseau et al., 2010; Yuliar et al., 2015). Phytosanitations include planting disease-free tuber seed on disease-free field, decontamination of farm tools, decontamination of irrigation water, diversion of surface run-off, and quarantine measures. Cultural practices include crop rotation of 5-7 years of excluding host plants, soil amendment, roguing of plants with symptoms of bacterial wilt and burning them, destruction of host weeds, and removing and destroying rotten tubers and potato haulms by burning (Lemaga et al., 2001a; Li and Dong, 2013). Overall, several studies have proven that an integrated management strategy using a combination of phytosanitation and cultural practices is the most feasible approach to control bacterial wilt (Champoiseau et al., 2010; Lemaga et al., 2005; Yuliar et al., 2015). In addition, in order to effectively control the disease and prevent it from further spreading, a community-based approach is important through cooperation among farmers. The farmers need to make a concerted effort by practicing the cultural and phytosanitation measures to significantly control the disease in their community (Pradhanang et al., 1993; Van de Fliert et al., 1998).

3.4.2. Know-why of late blight of scientists

Late blight of potatoes is also a devastating disease and it is caused by a fungus-like, microscopic oomycete pathogen *Phytophthora infestans* (Mont.) de Bary (Erwin and Ribeiro, 1996). This pathogen is predominantly dispersed aerially from one place to another and disseminates to healthy plant tissues via rain splash or on wind currents. *Phytophthora infestans* can infect and destroy all plant parts, including leaves, stems and tubers of potato plants (Cooke et al., 2011; Erwin and Ribeiro, 1996; Garrett et al., 2001). It grows and reproduces rapidly on the host plant and results in severe epidemics during conditions of high moisture and moderate temperatures (Coffey and Gees, 1991; Harrison, 1995).

Symptoms of late blight infection on potato leaves include blackish water-soaked lesions, and whitish sporulation of the pathogen around the margin of the lesions (Arora et al., 2014; Erwin and Ribeiro, 1996). The symptoms usually begin near the edges or leaf tips and lesions expand quickly, turn dark brown, and damage the plant. Symptoms of late blight on potato stems are elongated and dark brown lesions while the disease results in irregular reddish brown colored lesions on the surface of the tubers. At advanced stages of the disease, brown rot can be found on the tuber (Arora et al., 2014; Ingram and Williams, 1991).

Management methods for late blight include genetic, chemical, biological and cultural methods (Bouws and Finckh, 2008; Ke-qiang and Forrer, 2001; Struik et al., 1997). Genetic control method refers to the use of potato varieties having resistance to the pathogen that causes the disease. Resistance varieties stop or slow down the development of the disease (Kirk et al., 2005). A number of potato varieties that are resistant to late blight are being produced in many countries including Ethiopia. Chemical control using fungicides that are capable of preventing infection or of slowing down the disease are also effective and constitute predominant late blight management methods. Broadly there are two kinds of fungicides, contact and systemic. Contact fungicides only protect plant area where fungicides are applied and plant leaves developed after application of the chemicals are not protected against the pathogen. But systemic fungicides are absorbed through the plant foliage or roots and they are capable to protect leaves formed after the application (Cohen and Coffey, 1986). Biological methods consist of reducing late blight infection by using live microorganisms that have antagonistic effects against *Phytophthora infestans* (Ke-qiang and Forrer, 2001; Struik et al., 1997). Practicality and effectiveness of biological methods are, however, uncertain in the context of smallholder farmers (Ke-qiang and Forrer, 2001). Cultural practices include scheduling planting time, use of early maturing cultivars, use of pre-sprouted seed tubers, destruction of volunteer potato plants, making high hills to avoid or reduce contact of tubers with sporangia coming from infected foliage, foliage cutting two to three weeks before harvesting, timely harvesting, and destruction of discarded tubers by safely burying or burning, among others (Cooke et al., 2011; Garrett et al., 2001).

With an integrated disease management approach of a combination of resistant varieties, fungicides and cultural practices late blight could be controlled with low dose and frequency of fungicides (Kirk et al., 2005). Furthermore, an integrated approach is more economical for smallholder farmers besides reducing environmental pollution (Kirk et al., 2005; Namanda et al., 2004). Moreover, cooperation among farmers is important for effective control of the disease by avoiding infection from sources of inoculum in the environment (Ortiz et al., 2009). Hence, similar to that of bacterial wilt, a community-based approach seems to be a promising strategy to reduce late blight severity. In the Ethiopian context, an integrated disease management approach has been adopted by the national research system as a strategy to control late blight. In this regard, about 30 late blight resistant potato varieties have been released over the last three decades and are now in production in different parts of the country (Berihun and Woldegiorgis, 2013). Nonetheless, the pathogen has developed new races and most of the varieties have become susceptible to late blight and the farmers are largely relying on application of fungicides (Shimelash, 2015). This makes the use of a combination of methods more compelling to effectively control the disease.

3.4.3. Know-why of bacterial wilt of farmers

The farmers in the study areas were unaware of the causal agent of bacterial wilt and gave different assumptions based on their personal opinions and/or from what they heard other farmers say. None of the farmers mentioned the cause of this disease to be a pathogen. The farmers provided different explanations and confused a causal agent of the disease with various environmental factors, ranging from water shortage, insects, and earthworms to planting high moisture content seed potato, and waterlogging (saturation of soil with water). Farmers who claimed that water shortage is the cause of bacterial wilt seemed to perceive it as a normal plant wilting from moisture stress. Waterlogging as a cause for bacterial wilt was particularly mentioned by farmers who were producing potato using irrigation.

The majority of the farmers (60%) did not know bacterial wilt spreading mechanisms. But 40% of the farmers reported that they knew how bacterial wilt spreads and described different methods they thought it spreads through. Among these farmers, 63% and 52% of them mentioned infected seed potato and infested soil, respectively. Only few farmers, 7%, pointed out contaminated farm tools as a means for the spread of the disease. But none of the farmers mentioned other bacterial wilt spreading mechanisms such as contaminated irrigation water, and infected alternative host plants. In addition, none of the farmers was able to recognize latent infection (symptomless transmission) of bacterial wilt.

3.4.4. Know-why of late blight of farmers

Concerning the causal agent of the late blight disease, 97% of the farmers associated it with abiotic factors like rainfall, humidity and cloud that rather are environmental conditions contributing to the development and spread of the pathogen that causes late blight. Only few farmers (3%), mentioned the cause of late blight to be microorganisms. This shows that the majority of the farmers, including producers of quality declared seed and of regular seed did not recognize the actual cause of late blight.

Almost none of the farmers recognized the methods by which late blight spreads from one area to another, even though few farmers mentioned it to be through infected seed. It is important to note that none of the farmers mentioned wind or water as a spreading mechanism for late blight. As such, the farmers did not consider neighboring potato farms as a source of infection, which can potentially influence farmers’ practice in view of the need to collectively act to effectively combat the disease.

3.4.5. Know-what of bacterial wilt and its management methods of farmers

The majority of the farmers (72%) reported to know bacterial wilt, although not necessarily by its name. When the farmers were shown photographs of bacterial wilt symptoms on potato leaves and tubers without mentioning the name of the disease, most of the farmers recognized the symptoms as a problem they had in their potato fields or observed it in their neighborhood, both during *Belg* (short rainy season) and *Meher* (long rainy season) seasons. Overall, it was much easier for farmers to identify pictures of bacterial wilt symptoms on the leaves than on tubers. The farmers did identify general wilt of the potato plant. However, they did not recognize other common symptoms such as yellowing of foliage and stunting of the potato plant that can be associated with bacterial wilt. Statistically, there was a significant association between farmers’ knowledge of the disease and their location/district (Table 3.2) with farmers in Wolmera Woreda relatively having better understanding of the disease (Pearson Chi-Square = 81.136, $p < 0.001$). But there was no statistically significant association between farmers' knowledge of the disease and the category of producers (Pearson Chi-Square = 1.309, p = 0.520).

Farmers' knowledge of different management methods for bacterial wilt was also limited. Among the farmers who reported to know bacterial wilt, most of them (84%) mentioned roguing plants with symptoms of bacterial wilt as an effective management method for the disease (Table 3.2). Cultural management methods were mentioned only by a few farmers and included planting bacterial wilt free seed (28%), crop rotation (19%), and decontamination of farm tools (3%). Furthermore, about 7% of the farmers, mostly ware potato producers, mentioned chemical application as a management method for bacterial wilt (Table 3.2).

Table 3.2. Farmers' know-what of bacterial wilt management methods

Bacterial wilt management options recognized by farmers	% within type of farmers*			% within districts*			% of total respondents (n=147)
	QDS (n=22)	Regular Seed (n=52)	Ware (n=73)	Gumer (n=11)	Doyogena (n=47)	Wolmera (n=89)	
Planting bacterial wilt free seed potato	41	40	15	9	30	29	28
Roguing plants with symptoms of bacterial wilt	86	81	85	82	72	90	84
Crop rotation	59	21	6	9	40	9	19
Chemical application	0	4	11	18	11	3	7
Decontaminating farm tools	5	8	0	0	1	3	3

* Multiple answers were possible as most farmers reported more than one practice

3.4.6. Know-what of late blight and its management methods of farmers

Similar to the case of bacterial wilt, during the survey, farmers were shown photos of late blight symptoms on potato leaves, stems, and tubers without mentioning anything about the disease. The majority of the farmers (94%) recognized the symptoms as a disease problem they had in their potato fields, mainly during the main rain season (*meher*). Again, similar to the case of bacterial wilt, the farmers more easily recognized the disease on potato leaves and stems than on potato tubers. Only few farmers, 6%, could not recognize late blight from the picture shown to them. All farmers in Wolmera district recognized the disease while 88% and 93% of the farmers in Gumer and Doyogena, respectively, identified the problem and there was a statistically significant association between farmers' understanding of the disease and their location/district (Pearson Chi-Square = 12.671, p = 0.002). But there was no statistically significant association between farmers' knowledge of the disease and the category of producers (Pearson Chi-Square = 1.596, p = 0.450).

Overall, more than 92% of the farmers reported that fungicide application was an effective method to control late blight, with 100%, 94% and 89% representing producers of quality declared seed, regular seed and ware, respectively (Table 3.3). A significantly larger proportion of farmers in Gumer district (99%) reported fungicide application as a prominent method to control late blight compared with 85% and 93% of the farmers in Doyogena and Wolmera districts, respectively. About 25% and 11% of the farmers also reported use of late blight resistant potato varieties and cultural methods like early planting and crop rotation as effective late blight management methods, respectively.

Table 3.3. Farmers' know-what of late blight management methods

Late blight management options recognized by farmers	% within type of farmers*			% within districts*			% of total respondents (n=246)
	QDS (n=39)	Regular Seed (n=81)	Ware (n=126)	Gumer (n=72)	Doyogena (n=71)	Wolmera (n=103)	
Chemical/fungicide application	100	94	89	99	85	93	92
Use of resistant varieties	46	25	20	18	28	29	26
Cultural methods (early planting and crop rotation)	5	14	10	4	11	15	11

* *Multiple answers were possible as most farmers reported more than one practice*

3.4.7. Know-who: sources of information on bacterial wilt and late blight management

The majority of the farmers (68%) mentioned that they had received some information on bacterial wilt and late blight from different sources. Among these farmers, the majority of them were QDS producers (93%), followed by regular seed producers (72%), and ware producers (58%). Statistically, there was a significant association between farmers who received some kind of information on the diseases and the type of farmers (Pearson Chi-Square = 16.670, p=<0.001). Furthermore, the majority of the farmers in Wolmera district (84%) got access to information compared to 61% and 54% of the farmers in Gumer and Doyogena districts, respectively; there was a statistically significant association between farmers who got information on the diseases and their districts (Pearson Chi-Square = 20.057, p = <0.001). This variation among the study districts may be due to the presence and operation of the Holeta

Agricultural Research Center in Wolmera district for more than three decades.

Of the farmers who got information on the two diseases, most of them (64%) mentioned extension workers as the main source of information followed by fellow farmers (42%), non-governmental organizations (NGOs) (22%), agricultural researchers (19%) and seed producer cooperatives (11%). This seems to indicate that extension workers and other fellow farmers are the most important sources of information on potato diseases for the farmers in the study districts. On the other hand, almost equal proportions of QDS producers (32%) and regular seed producers (31%) reported NGOs as important sources of information, whereas only 9% of ware producers mentioned NGOs as an information source. This is explained by the considerable support that NGOs provide to seed producers in major potato growing districts in the country. Also, about 33% and 24% of regular seed and QDS producers, respectively, reported agricultural researchers as a source of information compared with only few ware potato producers (5%). This seems to suggest that seed producers are more likely to be targeted by agricultural researchers than ware potato producers.

Among the farmers who got some kind of information on bacterial wilt and late blight, most of them (83%) got information on management methods of the diseases followed by their symptoms (41%), their causes (28%) and modes of spread (22%) (Table 3.4). Relatively, more QDS farmers (54%) and regular seed producers (33%) got information on the causal agents of the diseases compared with only 11% of ware potato producers (Table 3.4). Thus, the farmers got much less information about know-why of the diseases. This seems to be the reason why sometimes most farmers did important things like crop rotation but not for disease management purpose. Likewise, more producers of QDS (46%) and regular seed (25%) acquired information

Table 3.4. Kind of information that farmers received on bacterial wilt and late blight

Kind of information	% within type of farmers			% within districts			% of total respondents (n=179)
	QDS (n=37)	Regular Seed (n=61)	Ware (n=81)	Gumer (n=50)	Doyogena (n=43)	Wolmera (n=86)	
Management methods	86	82	78	68	91	88	83
Spreading mechanisms	46	25	9	22	40	13	22
Mode of diagnosis	60	46	28	40	44	40	41
Causes	54	33	11	36	42	15	27

on modes of spread of the diseases while only 9% of the ware producers reported acquiring information on the same topic. Overall, the reason why most farmers reported getting more information on management methods than other generic aspects of the diseases seems to suggest that the information sources usually give more focus to management methods of the diseases than their causal agents and spreading mechanisms.

3.4.8. Know-how: farmers' management practices of bacterial wilt and late blight

In this section, a variety of farmers' practices of bacterial wilt and late blight management are presented considering the role of knowledge in these practices. Some practices are specific to each kind of disease while others are common to both diseases as described in the following section.

Practice of crop rotation

Most of the farmers (95%) reported growing potato in rotation with cereals, pulses or other vegetables, with all QDS producers and regular seed producers practicing it. The few farmers (5%), who reported not practicing crop rotation, were all ware potato producers. Statistically, farmers' practice of crop rotation was significantly associated with the category of the farmers (Pearson Chi-Square = 12.575, p=<0.002) but not with location/district of the farmers (Pearson Chi-Square = 5.647, p=<0.059).

In relation to the length of crop rotation, nearly half of the farmers (48%) commonly practiced a one-season interval, with only 13% of the farmers practicing a three-season interval (Table 3.5). But the number of seasons of crop rotation was significantly associated with the type of farmers (Pearson Chi-Square = 12.575, p = 0.002), with quality declared seed farmers relatively practicing more seasons of crop rotation than regular seed producers and ware producers. Twenty-eight percent of QDS producers, 38% of regular seed producers and 61% of QDS producers practiced only a one-season interval of crop rotation (Table 3.5). About 26% of QDS producers practiced a three-season interval of crop rotation compared to 15% and 8% of regular seed and ware producers, respectively.

Generally, most farmers considered benefits of crop rotation in view of improving soil fertility to avoid yield reduction due to plant nutrient depletion from the soil. They did not fully recognize the role of crop rotation for controlling soil-borne diseases such as bacterial wilt. As a result, many farmers practiced a one-season interval of crop rotation, which is an ineffective practice for disease management. This is further evidenced by only 19% and 11% of the farmers who reported crop rotation as a management practice for bacterial wilt and late blight, respectively, as pointed out in Sections 3.4.4 and 3.4.5. Furthermore, the survey revealed that none of the regular seed and ware potato producers practiced crop rotation for more than a three-season interval while only 5% of the QDS farmers applied the practice for more than three seasons (Table 3.5).

Table 3.5. Interval of crop rotation

Number of seasons	% within type of farmers			% within districts			% of total respondents (n=248)
	QDS (n=39)	Regular Seed (n=85)	Ware (n=124)	Gumer (n=75)	Doyogena (n=76)	Wolmera (n=97)	
One season	28	38	62	57	32	55	48
Two seasons	41	47	30	31	53	31	38
Three seasons	26	15	8	12	13	15	13
More than three seasons	5	0	0	0	3	0	1

Practice of seed potato renewal

Renewal of seed potato is not a common practice among the majority of all type of farmers in the study areas. Only 13% of the farmers, the majority of whom were quality declared seed producers or regular seed producers, renewed seed potato during the last five years. Other farmers had been planting potato for an unspecified number of generations without changing it. Particularly, ware potato producers seemed to be less experienced in seed potato renewal. They did not know the generation of their seed potato as they had been using the same seed for over many generations. They usually retained seed for the next planting season from their previous harvest or bought it from the local market. Many farmers had a general understanding that productivity declines if the same seed is used over and over without being renewed. However, they did not associate it with management of seed-borne diseases like bacterial wilt and late blight. It was not common to hear farmers associating the benefit of seed renewal with disease management. This is also evident from the low percentage of farmers (Tables 3.2 and 3.3) who mentioned seed related attributes ('planting clean seed' for bacterial wilt and 'resistant varieties' for late blight) as management options. On the other hand, those few farmers who knew the contribution of seed renewal to disease management, did not necessarily renew their seed due to very limited supply of basic seed and high price which hindered the farmers from practicing seed renewal.

Overall, only 13%, 9% and 15% of producers of QDS, regular seed, and ware, respectively, used new seed potatoes within the last five years. Producers of QDS and regular seed who reported to renew their seed had purchased basic seed from agricultural research centers. However, ware potato producers just bought seed potato of unknown origin from local market or neighbor farmers, which had been recycled for a number of generations. It is important to note that this practice of renewal of ware producers is not effective to prevent diseases from spreading, even though a considerable number of them claimed to renew their seed potatoes. Statistically, there was not a significant association between the practice of renewing seed potatoes and the farmers' category (Pearson Chi-Square = 1.328, p=<0.515), or their district (Pearson Chi-Square = 3.307, p=<0.191).

Practice of handling infected/damaged seed and ware potatoes at harvest

Nearly all farmers (97%) reported sorting as a practice to separate infected/damaged potato from healthy looking ones at harvest. Usually, the farmers tried to sort both infected/damaged seed potato tubers and ware potato from healthy looking ones through visual observation. When asked what they did with infected/damaged potato tubers, about 42% of the farmers reported that they would leave them on the field, of whom 8%, 39% and 54% were QDS producers, regular seed producers, and ware producers, respectively. On the other hand, nearly 30% of the farmers reported that they would collect and bury infected/damaged potato tubers sorted during harvesting, whereas about 19% of the farmers would throw infected/damaged potato tubers away at the farm side (Table 3. 6). Only 3% of the farmers reported collecting and burning of the infected/damaged potato tubers. Thus, only few farmers properly disposed diseased/damaged seed potato and some farmers even thought that leaving infected/damaged potato tubers on the field would improve soil fertility with little regard for possible contamination of the soil by potato diseases like bacterial wilt. Their current practice of handling infected/damaged potato tubers contributed more to the spread of the diseases rather than controlling them. Most farmers did not know the importance of sorting infected/damaged potatoes at harvest from the perspective of controlling bacterial wilt and late blight. They did sorting mainly to separate and dump rotten or damaged potato tubers from healthy looking ones before home consumption, marketing or storing for seed. Furthermore, referring back to farmers' knowledge of effective management methods of the two diseases (Tables 3.2 and 3.3),

Table 3.6. Farmers' practice of sorting out infected/damaged seed and ware potato at harvest

What farmers do with infected/ damaged seed and ware potatoes	% within type of farmers*			% within districts*			% of total respondents (n=147)
	QDS (n=22)	Regular Seed (n=52)	Ware (n=73)	Gumer (n=11)	Doyogena (n=47)	Wolmera (n=89)	
Leave on the field	8	39	54	33	24	63	42
Collect and burn	0	4	4	5	0	4	3
Collect and burry	43	39	20	23	42	26	30
Throw away at farm side	20	13	22	14	30	14	19
Use as livestock feed	50	21	15	38	21	11	22

* *Multiple answers were possible as most farmers reported more than one practice*

sorting diseased seed potato was not among the few management options known to many farmers.

Practice of roguing and use of clean seed

The majority of the farmers (80%) mentioned that they applied the practice of roguing potato plants with symptoms of bacterial wilt infection as a management method. Among these farmers, 68%, 81% and 82% were producers of QDS, producers of regular seed and producers of ware, respectively. There was significant association between practice of roguing and study districts (Pearson Chi-Square=15.388, $p<0.001$). A significantly larger proportion of farmers in Wolmera district (90%), reported practicing roguing of potato plant with symptoms of bacterial wilt as one of the methods to manage bacterial wilt, while 73% and 62% of the farmers in Doyogena and Gumer districts, respectively, pointed out the same method. These farmers usually removed infected potato plant with visible symptoms and threw them at the farm side or in ditches. But such practice has a striking implication for spreading of the disease instead of controlling it. Thus, farmers' current practice of roguing plants with symptoms of bacterial wilt is not effective mainly due to lack of knowledge among farmers on the spreading mechanisms of the disease. Furthermore, about 26% of the farmers reported to practice planting bacterial wilt free seed potato. Farmers that reported planting seed free from bacterial wilt infection, usually tried to visually confirm whether seed potato was infected or not, without understanding and considering the possibility of latent infection of seeds. Thus, they thought that clean seed potato can be distinguished from infected seeds through visual observation. Forty-two percent of QDS producers and 39% of regular seed producers mentioned using seed free from bacterial wilt compared with only 15% of ware producers. Nonetheless, availability of bacterial wilt free seed is questionable given the current prevalence of the disease, latent infection of the pathogen that causes the disease, and lack of a standard seed certification scheme based on laboratory testing in the country. Also, some farmers reported that they applied chemicals expecting that these chemicals could suppress bacterial wilt. As there is no chemical that can help control bacterial wilt on the market, it seems that they applied chemicals like fungicides or pesticides, which further indicates the lack of know-how among these farmers.

Practice of fungicide application

More than 87% of the farmers reported practicing fungicide application to manage late blight. The majority of quality-declared seed producers (97%) reported to practice fungicide application to control late blight as was the case for regular seed producers (91%) and ware potato farmers (82%). Statistically, there was a significant relationship between fungicide application and the category of farmers (Pearson Chi-Square= 6.569, p = 0.015). But there was no significant relationship between farmers' practice of fungicide application and their district (Pearson Chi-Square= 3.028, p = 0.220), with 89%, 82%, and 90% of farmers in Gumer, Doyogena and Wolmera districts, respectively, practicing fungicide application to control late blight.

Most farmers reported applying fungicides they got from private vendors or cooperative unions without understanding the efficacies of the fungicides and without choosing which product to use. They also did not understand late blight pressure in the surrounding and they simply applied when they observed the symptoms of late blight infection. Further, the farmers did not understand the importance of collaboration with neighbor farmers to reduce the inoculum pressure in the area. The most commonly used fungicides in the study sites were Ridomil and Mancozeb, while many farmers were not able to differentiate between the two kinds of fungicides. Most of the farmers reported to apply three to five times per season, depending on the severity of the disease and availability of fungicides. In this regard, the dosage and frequency of applications were questionable given farmers' limited know-how of appropriate fungicides application practices.

Furthermore, during key informant interviews, all farmers mentioned that the farmers applied fungicides individually when the disease occurred without being aware of the importance of collective action to reduce the inoculum of the pathogen from their respective area. In many instances, ware potatoes and seed potatoes were planted in neighboring fields, but the farmers practice different time and frequency of fungicide applications.

3.4.9. Practice of using late blight resistant potato varieties

Potato growers in all the three districts tended to grow improved potato varieties, with the majority of the farmers (66%) producing improved varieties only. Across all the three districts, few farmers (10%) grew local varieties only, and all of them were ware potato producers, whereas nearly 25% of the farmers produced both local and improved varieties. Relatively, more farmers in Wolmera district (83%) were growing improved varieties only, compared with 50% and 61% of the farmers in Gumer and Doyogena districts, respectively, (Table 3.7).

The majority of the farmers (100% of QDS producers, 97% of regular seed producers, and 87% of ware producers) reported Gudane as the dominant potato variety they were growing. Overall, three popular potato varieties, Gudane, Belete and Jalene were grown by 92%, 45%, and 33% of the farmers that reported growing improved varieties, respectively (Table 3.8). These improved varieties were released by Holeta Agricultural Research Center (HARC) primarily as late blight resistant. But the farmers reported that particularly Jalene variety became highly susceptible to late blight, which might be due to seed degeneration as the farmers have been continuously growing this variety since it was released in 2002 and its resistance could be broken by the pathogen. On the other hand, Belete variety was grown by 87%, 45% and 29% of producers of QDS, regular seed, and ware, respectively (Table 3.8). Even though Belete variety has been the most recent of the potato varieties released by the national research system, it has also become susceptible to late blight and farmers do not grow it without repeated application of fungicides. In relation to using late blight resistant potato varieties, farmers have better understanding of the importance of resistant varieties. However, since the existing potato varieties have become susceptible to late blight, farmers did not rely on this practice alone as an effective management method.

Table 3.7. Type of potato varieties grown by farmers in the study sites

Type of potato varieties	% within types of farmers			% within districts			% of total respondents (n=261)
	QDS (n=40)	Regular Seed (n=85)	Ware (n=136)	Gumer (n=82)	Doyogena (n=76)	Wolmera (n=103)	
Local varieties only	0	0	18	4	18	8	10
Improved varieties only	90	73	54	50	61	83	66
Both improved and local varieties	10	27	27	46	21	10	25

Table 3.8. Improved potato varieties grown by farmers in the study sites

Major improved potato varieties grown	% within type of farmers*			% within districts*			% of total respondents (n=236)
	QDS (n=40)	Regular Seed (n=85)	Ware (n=111)	Gumer (n=79)	Doyogena (n=62)	Wolmera (n=95)	
Gudane	100	97	87	87	97	93	92
Jalene	33	42	26	52	16	28	33
Belete	87	45	29	46	42	45	45
Guassa	0	6	15	17	0	10	9
Other improved varieties	5	2	6	6	0	6	5

**Multiple answers were possible as most farmers reported more than one potato variety*

3.4.10. Use of mobile phone among farmers

Most of the farmers in the study sites (73%) owned a mobile phone, of whom only about 2% of the farmers had smart phones. The highest rates were reported from Wolmera district (82%), while in Doyogena and Gumer districts 72% and 62% of farmers owned mobile phones, respectively (Figure 3.1). On the other hand, among the farmers who owned mobile phones 81% of the farmers were regular seed producers, followed by 73% and 68% of the farmers who were producers of QDS and ware, respectively (Figure 3.2). Further, about 45% of the farmers who had a mobile phone were between 18 and 35 years, while only 12% of the farmers who had mobile phones were above 56 years. This signifies that younger farmers were more likely to own mobile phones. Furthermore, 82% of the farmers who owned a mobile phone attended either primary or secondary schools while only 8% of the farmers who had mobile phones were illiterate.

During key informant interviews, the farmers described as they used mobile phones to communicate various social issues with their family members, relatives, and other farmers in their community. In addition, the farmers used mobile phones to communicate with agricultural extension workers, district level agricultural experts, agricultural researchers and cooperative officers mainly to check availability of agricultural inputs, arrange meetings and/or field visits, access market information, and report agricultural problems, among others.

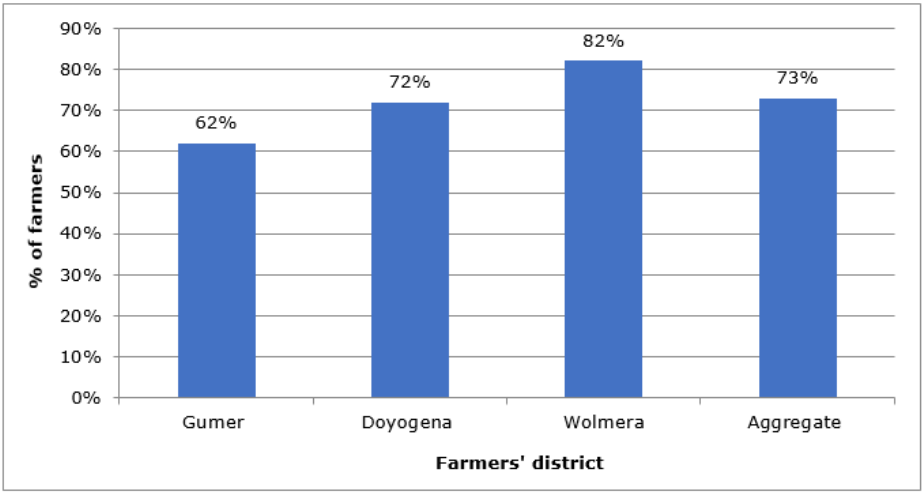

Figure 3.1. Mobile phone use by farmers' district

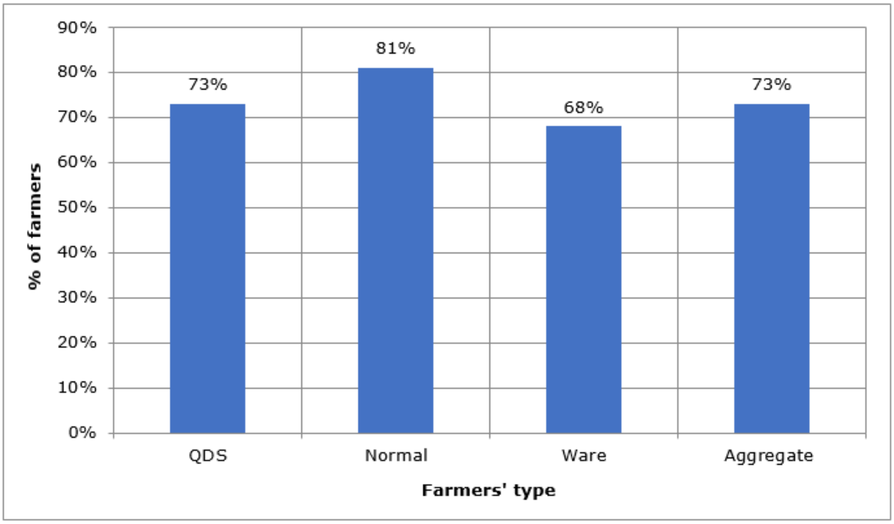

Figure 3.2. Mobile phone use by farmers' type

3.5. Discussion

This diagnostic study was designed to examine whether farmers' knowledge of the two major potato diseases, bacterial wilt and late blight, and their management methods hinders or contributes to effective disease management practices. The findings provide relevant insights regarding the requirements for developing an intervention strategy for smallholder potato farmers in Ethiopia. In order to be effective, such strategy 1) has to be community-based because of the spreading mechanisms of the diseases, and 2) needs to combine cultural practices with phytosanitary measures, according to recent insights (Champoiseau et al., 2010; Lemaga et al., 2005; Yuliar et al., 2015).

3.5.1. Knowledge of farmers about bacterial wilt and late blight

The study findings show that all the groups of farmers evidently had limited know-why, know-what, know-who, and know-how of the two diseases, when mirrored to scientists' understanding of the diseases. None of the farmers recognized the cause of bacterial wilt to be a pathogen. Rather, the farmers erroneously reported the cause to be unrelated factors such as shortage of water, insects, earthworms, and waterlogging. Likewise, most farmers did not know the cause of late blight. They associated a causal agent of late blight to be abiotic factors like rainfall, humidity and cloud. This finding is consistent with that of Nyankanga et al. (2004) who reported that most of the potato farmers in Kenyan highlands associated late blight with weather conditions. Although not fully accurate, this is relevant knowledge, because such environmental conditions favor the development of the pathogen that causes the disease (Mizubuti et al., 2000; Mizubuti and Fry, 1998).

Unlike the causal agents of the diseases, most farmers could recognize the symptoms of both bacterial wilt and late blight on leaves and stem. But the majority of the farmers could not recognize the visible symptoms of the diseases on the seed tubers. While a considerable number of farmers (40%) correctly mentioned infected seed and soil to be mechanisms through which bacterial wilt spreads, they could not act upon this knowledge. Moreover, none of the farmers knew about the latent (symptomless) infection of bacterial wilt and hardly any of them was aware of the other spreading mechanisms of bacterial wilt like infected host plants, contaminated irrigation water and contaminated farm tools (Genin, 2010; Hayward, 1991; Janse, 1996). This limited know-why has an essential implication for the prevalence and management of bacterial wilt (Genin, 2010; Hayward, 1991). Without a good understanding of its various spreading mechanisms, it is difficult to effectively control the disease.

Regarding late blight, none of the farmers were aware of the spreading mechanisms of late blight. But, since the pathogen that causes late blight is mainly airborne and largely disperses by wind (Lima et al., 2009), farmers should be aware that they can be affected by the practice of other farmers in neighboring fields. The finding signifies that farmers may think that their potato field is safe, despite the occurrence of the diseases in their neighbors' fields. Moreover, as a consequence, they seem not to recognize the importance of concerted effort to deal with the diseases.

Producers of ware potato reported agricultural extension workers and fellow farmers to be the most important sources of information on bacterial wilt and late blight management. In contrast, agricultural research centers and NGOs were reported by both QDS and regular seed producers as major sources of information on the diseases. This finding aligns with the considerable support that agricultural research centers and NGOs provide to seed producers in the country. There are however, no differences in knowledge about causes and spreading mechanisms between ware potato producers and (both kinds of) seed producers. The only significant difference between the groups concerns the know-what of crop rotation and fungicide application. There are also very few differences between the districts; in the district with an agricultural research center in the area, more farmers recognized the diseases and practiced roguing.

The overall lack of knowledge regarding causes and spreading mechanisms of bacterial wilt may be explained by the fact that it has only recently become a severe problem (Abdurahman et al., 2017; Gorfu et al., 2013) and development initiatives have not yet given due attention to the disease (Gorfu et al., 2013). The lack of knowledge regarding late blight is rather surprising because it has been the major potato disease in Ethiopian potato production systems for many years and the farmers have been receiving different forms of supports to deal with the disease. A possible explanation for this is that the efforts to increase farmers' knowledge did not include all relevant learning approaches that are related to the different forms of knowledge. Know-what and know-why are learned through reading and attending trainings while know-how and know-who can be learned mainly through experiential learning and in social interaction (Lundvall, 1992). This research, as well as other reports, indicates that many seed potato producers were trained in potato production and disease management practices in the country (CIP, 2016; CIP 2013), which emphasizes particularly the know-what. Therefore, the current limitations regarding the other categories of knowledge underlines the need for supporting the farmers to learn through a combination of appropriate approaches.

The know-why could be increased via for instance a training about the causes and spreading mechanisms of the pathogens for both bacterial wilt as well as late blight. Diagnostic tools or kits combined with tailor-made advices may help to effectively diagnose and visualize the pathogens and stimulate the farmers to take action. In addition to these well-known classic methods, the sharing of information about the prevalence of the disease may contribute to the know-what of farmers. In addition, it is crucial to provide farmers the room to generate the know-who and know-how for the management of both diseases. As these local forms of knowledge can only be generated by farmers themselves in the local context experiential learning, and social interaction should be stimulated.

The focus on seed producers in previous knowledge dissemination efforts may appear to be reasonable given the limited supply of quality seed in the country (Gildemacher et al. 2009b; Hirpa et al., 2010; Schulz et al., 2013). But in view of an effective disease management effort, QDS and regular seed producers may not succeed in controlling the diseases if ware producers' practices continue to increase disease inoculum in their surroundings. Therefore, for effective management of both diseases, this finding indicates the importance of involving ware producers in learning interventions.

3.5.2. Farmers' practices related to their knowledge

The findings of the study indicate that all three categories of farmers had better know-how of effective management methods for late blight such as use of fungicides and resistant potato varieties than for bacterial wilt.

For bacterial wilt, the dominant management practice reported by all categories of farmers was roguing of plants with symptoms of disease infection. But this practice alone is not effective in controlling the disease if it is not combined with other cultural practices like crop rotation, soil amendment, and phytosanitation. This study also found that the farmers were just uprooting and throwing the infected plants away at the farm side or in ditches which could have serious implications for spreading the disease instead of controlling it. This further confirms that the know-how of the farmers is limited. Unexpectedly, QDS producers also reported the same practice which makes the practicality of the zero-tolerance level of bacterial wilt that currently stipulated in the QDS scheme questionable (ESA, 2015) and has striking implications for the quality of seeds produced by these group of farmers. Some farmers also mentioned the use of quality seed to control bacterial wilt. However, given the current prevalence and embedding of the disease in the country's seed system (Abdurahman et al., 2017; CIP, 2016; Gorfu et al., 2013) and due to a lack of formal seed certification system in the country (Gildemacher et al., 2009b; Hirpa et al., 2010; Schulz et al., 2013), the seed potatoes that the farmers receive may be infected with bacterial wilt. In addition, farmers' practice of crop rotation was found to be ineffective from the perspective of bacterial wilt control. They mostly practice one-season interval of crop rotation while the requirement for QDS producers is at least three seasons of rotation with non-host plants (ESA, 2015) and five to seven years of crop rotation are recommended for effective elimination of the inoculum from infested soil. Also the farmers did not renew seed potatoes for many years and they continued to plant seed potatoes of unknown generations and none the farmers, not even most QDS producers, could tell the generation of seed potato they were planting. Particularly, for producers of ware potatoes who mainly use farm saved seeds as planting material, this practice coupled with short interval of crop rotation increases *Ralstonia solanacearum* build up in their potato fields.

Regarding late blight, most of the farmers (87%) practiced application of fungicides. However, the farmers did not recognize what type of fungicides (contact or systemic fungicides) to use and when to apply. Farmers did not apply fungicides before they observed the first symptoms of late blight on the potato plant, which is ineffective in controlling the disease as the pathogen spreads quickly. Despite the availability of various decision support systems (DSS) that can help farmers optimising the use and timing of fungicide applications in developed countries (Shtienberg, 2013; Wharton et al., 2008), so far none of them has been introduced to Ethiopia. The farmers still spray fungicides in a conventional way and hence often with limited success in controlling the disease.

These findings show that the farmers' practices are somewhat informed by know-what of disease management: the majority of the farmers applied some crucial management strategies such as application of fungicides for late blight control, roguing of plants with symptoms of bacterial wilt infection, and planting late blight resistant potato varieties for disease management reasons. Their knowledge is however too limited to apply these measures in an effective way. This stresses the conclusion above, that additional know-how is necessary to perform these practices effectively for disease management purpose. Moreover, some other practices that are also relevant for management of the diseases (like crop rotation, and sorting of infected potatoes) were undertaken for other than disease management reasons. This indicates that additional know-why may increase the value of these practices for farmers and stimulate them to understand their multiple functionality. It, hence, seems useful to develop a learning approach in which the know-why is locally generated and embedded and integrated with the know-what.

3.5.3. Implications for a community-based intervention and monitoring approach

The finding of this study has important implications for the development of a community-based approach to effectively deal with bacterial wilt and late blight in Ethiopian potato production systems.

Addressing the above-mentioned limitations of farmers' knowledge is imperative for effective disease management. That is, the farmers need to learn about different aspects of the diseases including, causes, diagnosis methods, spreading mechanisms, effective management methods and how to integrate these into their daily practice, and importance of concerted effort, among others. To learn to manage the diseases in an effective way the conventional methods of training and instructing farmers may not suffice. In order to stimulate the development of all relevant forms of knowledge, farmers themselves need to be stimulated to generate and revise local knowledge in an experiential and interactive learning approach.

Such learning to do things differently is a process (Beers et al., 2016) that needs to be integrated into the community-based strategy. A good start for stimulating farmers to be openly involved in such a learning process may be to raise their awareness of the interdependency among them in the local area. A relevant second step may be to define what concerted action may lead to quick improvement in this area and how monitoring would help them to recognize the effectivity of the farmers actions. What combination of measures fits in the cultural and ecological context of a specific community can be investigated in this way by farmers and experts. This exploration may stimulate the farmers to undertake these concerted actions.

Further, for the community-based intervention to be enabled, enforced and evaluated, an institutional arrangement at community level may be important (Ostrom, 1990). That is, the farmers can mutually agree on operational standards of what should be done and should not be done, from the perspective of disease management specifically and potato production more generally.

For bacterial wilt, the following phytosanitary and cultural management practices could, for instance, be integrated and stipulated in the bylaws as operational standards:

- Practicing crop rotation with non-host plants and with appropriate rotation length;
- Roguing and burning potato plants with symptoms of bacterial wilt infection;
- Eradicating host weeds from potato fields and irrigation canals;
- Decontaminating farm tools before using for potato cultivation and harvesting;
- Making diversion ditches to prevent surface run-off from infected field.

Similarly, for late blight, the following management practices could be translated into operational standards to be confirmed by the farmers.

- Applying the right dose and type of fungicides at the appropriate time;
- Cutting foliage two to three weeks before harvesting;
- Destroying volunteer potato plants that can be sources of late blight inoculum.

If the farmers have come to an agreement, it is important to track to what extent farmers are changing their practices in line with the operational standards. An ICT-based platform may support monitoring of the community-based intervention and disease occurrence. A first function of an ICT-based platform hence would be to monitor and account for their practices towards one another. Additional purposes of a platform could be 1) early warning of prevalence and spreading of the disease; 2) provision of contextualized advices; 3) provision of generic information; 4) evaluation of practices; by investigating which practices seem most effective, practical and affordable and why to be able to change direction if needed.

The platform could make use of mobile phones, since the study shows that the majority of the farmers in the study sites were using these devices to communicate on various social issues and access different kinds of information. This result is consistent with the findings of Agricultural Transformation Agency (ATA) (ATA, 2013) that reported rapid expansion of mobile phone use in Ethiopia and seems to suggest that mobile phone can be tapped into for bacterial wilt and late blight diagnosis and management in the study sites. Several studies have also reported the potential role that mobile-based platforms can play for agricultural development in many developing countries (Aker, 2011; Asenso-Okyere and Mekonnen, 2012). Mobile-based technologies such as voice call, Short Message Service (SMS) and Interactive Voice Response (IVR) are commonly considered more appropriate and promoted for agricultural information sharing and enabling collective action in smallholder farmers context in many developing countries (Aker, 2011; Asenso-Okyere and Mekonnen, 2012) . Similarly, some mobile-based initiatives have been implemented in Ethiopia by the ATA and the Ethiopian Commodity Exchange (ECX) to support agricultural extension service and provide market information, respectively (ATA, 2013; Meijerink et al., 2014).

On the basis of this study, we surmise that mobile phones can have an added value in the process of information sharing in a community-based approach and potato farmers can learn about effective disease management methods through SMS, voice call or IVR. Disease occurrence can also be possibly monitored and exchanged in these ways. Specifically for late blight, mobile phone can serve as a means for timely information sharing among farmers regarding the occurrence of the disease and for receiving timely information on when to apply fungicides based on proper prediction of disease occurrence. Practices could be reported and summaries of achievements can be shared via the phones. A platform needs to be developed in order to be able to collect and interpret data regarding both diseases, for the exchange of information among the farmers, for the development of advice, et cetera. But, it is important to consider farmers' need and context as such platforms can be constrained by many factors like network interruptions in rural areas and costs of communication.

In sum, it seems that a mobile-based platform can leverage a community-based intervention for effective bacterial wilt and late blight management in the study sites. Such monitoring would serve three goals:

1. Stimulate a learning process in which know-why, know-what, know-how and know-who become closely connected and adapted to the local context, by reflecting on what

works and what does not work in the specific context and change the standards accordingly;
2. Stimulate collective action, by increasing trust among farmers and show that their efforts are worthwhile and sanction free-riders;
3. Connecting professional expertise of agricultural extensionists and researchers with farmers in need for advice in specific situations.

3.6. Conclusion

The study has provided new insight into farmers' knowledge of bacterial wilt and late blight in Ethiopian potato production systems. The study has indicated that farmers have limited know-what and know-why as well as know-who and know-how to effectively deal with the diseases in their specific local context. Regarding the first two types of knowledge, there were significant incongruences between scientific explanations and farmers' understanding of the diseases and practices to deal with them. Further, the study has shown that farmers' practices contribute to the spreading of the diseases rather than effectively manage them due to a lack of relevant and applicable knowledge among farmers. Previous extension efforts have not had the desirable effect although farmers had relatively better know-what and know-how of late blight than bacterial wilt.

Overall, given the current prevalence of the diseases and their diverse spreading mechanisms, there should be an emphasis for a community-based approach with due consideration of the social and biophysical dimensions of the diseases. The proposed community-based approach should comprise four basic elements 1) interactive learning, 2) combination of effective management practices (phytosanitation and cultural practices), 3) bylaws and 4) monitoring by leveraging mobile-based technologies on a digital platform. Farmers' knowledge of the diseases, which informs their management practices, needs to be enhanced in a learning approach that integrates generic and local knowledge. Moreover, the farmers need to act collectively and integrate several management practices in their efforts towards dealing with each disease. To enable a collective action among the farmers, community-based bylaws with mutually agreed upon operational standards can be a good institutional arrangement. Appropriate mobile-based technologies such as voice call or SMS can support the monitoring of the changes in farmers' practices and the prevalence of the disease.

Chapter 4

Analysis of a monitoring system for bacterial wilt management by seed potato cooperatives in Ethiopia: challenges and future directions

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Abstract

Collective action is required to deal with various complex agricultural problems such as invasive weeds and plant diseases that pose a collective risk to farmers. Monitoring systems could help to stimulate collective action and avoid free-riding. The paper develops a novel framework consisting of essential elements of a monitoring system for managing a complex disease like bacterial wilt in potato crops. The framework is used to explore how seed potato cooperatives in Ethiopia operationalised the essential elements of a monitoring system and identifies which challenges remain to be overcome. Data were collected through in-depth interviews, reflective workshops, participant observation, and document analysis. We found that the cooperatives had organised a self-monitoring system to monitor disease occurrence and the disease management practices of their members. Monitoring committees were in charge of the data collection and enforcement of sanctions on farmers who did not adhere to the cooperatives' bylaws. The main challenges included the dependency on visual observation, which does not disclose latent infections, limited financial incentives for the monitoring committee members, lack of trust, weak peer monitoring, and the social and ecological interdependency between producers of ware and seed potatoes. Suggestions are provided to strengthen the monitoring systems of farmers' seed potato cooperatives in Ethiopia. In addition, we discuss the broader value of our novel framework for describing and analysing monitoring systems for future research and intervention.

Keywords: collective action; monitoring system; seed cooperatives; bacterial wilt; disease management

4.1. Introduction

Potato (*Solanum tuberosum* L.) is the third most important consumed crop in the world, playing a vital role in food and nutrition security in many countries (Devaux et al., 2014). Particularly, in the face of the rising global population, the role of this crop is significant in enhancing food supply. However, due to biotic and abiotic conditions, the actual yield of potato is much lower than its potential yield. According to a recent study by Haverkort and Struik (2015), there is a gap of 10% to 75% between the actual and potential yield of potato due to various socio-ecological problems. In East Africa, where the livelihood of millions of smallholder farmers depends on potato, poor quality seed and bacterial wilt have been identified as main yield gap drivers (Harahagazwe et al., 2018). Reducing the yield gap due to complex socio-ecological problems such as bacterial wilt can therefore improve the livelihood of millions of smallholder farmers.

In cognizance of the potential of potato for food and nutrition security, Ethiopia has been expanding potato production (CSA, 2016; FAO, 2008; Haverkort et al., 2012; Woldegiorgis et al., 2013). Annual potato crop production is currently valued at more than USD 1.16 billion, and over 3.7 million smallholder farmers are growing the crop in the country (CSA, 2016; Sharma et al., 2018). To enhance quality seed potato availability in the country, hundreds of seed potato cooperatives have been established during the last decade (Ayana et al., 2013; CIP, 2016; Hirpa et al., 2010; Sisay et al., 2017). The seed potato cooperatives have been able to enhance seed availability in the country (Ayana et al., 2013; Sisay et al., 2017). For instance, according to Sisay et al. (2017), more than 20% of the national seed potato demand was supplied by seed potato cooperatives in Ethiopia. Despite the improvement in the availability of seed potato, poor seed quality has remained a major constraint (CIP, 2016; Schulz et al., 2013). The use of poor quality seed spreads various potato diseases from one area to the other. For instance, recent studies showed that bacterial wilt has spread nationwide and is embedded in the country's seed potato system due to the uncontrolled movement of latently infected seed (Abdurahman et al., 2017; CIP, 2016).

In 2015, the government of Ethiopia, in collaboration with development partners, developed a quality declared seed (QDS) production scheme with the objective of improving seed quality (CIP, 2016; ESA, 2015). This scheme was established in response to the outbreak of bacterial wilt in the country and requires cooperatives to obtain certain certificates. Furthermore, there are seed standards that QDS cooperatives need to meet (ESA, 2015). Among the standards, there is a zero-tolerance level for bacterial wilt. A considerable number of seed potato cooperatives in different parts of the country are now producing QDS. However, many seed potato cooperatives are still operating in the same way as they have been doing over the last 10 years. Therefore, both QDS and non-QDS seed potato cooperatives currently operate in the country's seed potato systems.

The Ethiopian seed potato market has been largely dominated by large organisational buyers like non-governmental organisations (NGOs), the Ministry of Agriculture, and the regional bureaus of agriculture (Hirpa et al., 2010; Schulz et al., 2013). Therefore, seed potato cooperatives did not have market problems until recently, and they were encouraged to intensify production and marketing. However, due to the rapid prevalence of bacterial wilt and the increasing awareness of the devastating nature of the disease among different actors in the country's potato production system, and in addition to the resulting zero-tolerance policy, seed potato cooperatives are now increasingly facing problems when selling seed potato tubers.

Potato farmers are interdependent, and individual efforts alone are not sufficient to combat bacterial wilt. Farmers share farm tools and exchange labour, and diseases can easily spread to neighbouring fields. Thus, ineffective practices by one farmer may result in a considerable impact on both, in the farm where these are carried out and in neighbouring farms (Tafesse et al., 2018). As a result, the cooperatives mobilise their members to implement a range of recommended methods to manage bacterial wilt and other diseases on their potato fields, to produce disease-free seed and to prevent the disease from spreading. They also make efforts to monitor disease occurrence and its management (Tadesse et al., 2019).

Considering their interdependency, several studies on the management of bacterial wilt have shown the importance of collective action among smallholder potato farmers (Campilan, 2002; Damtew et al., 2018; Lemaga et al., 2005; Tafesse et al., 2018). Furthermore, studies show that monitoring disease occurrence and management by seed potato cooperatives can play an important role in ensuring quality seed production (Ayana et al., 2013; Schulz et al., 2013; Tadesse et al., 2019). The research to date has generally pointed out the importance of monitoring for collective action but does not elaborate in detail what a monitoring system entails and what the associated challenges are (Sisay et al., 2017; Tadesse et al., 2019). This study conducts a multidimensional investigation of the various practices involved in the monitoring of bacterial wilt management by seed potato cooperatives in Ethiopia and the challenges they encounter in doing so.

In the next sections, we first present the theoretical underpinning of the study and the associated research objective and research questions. We then proceed to describe the context of the two seed potato cooperatives selected for the study and the research methodology employed. This is followed by the presentation of our findings and an analysis and discussion of the implications for intervention and future research.

4.2. Theoretical underpinning of the study

In this section, the concept of collective action and the essential elements of a monitoring system are described based on the common-pool resource literature.

Collective action is widely recognised in the literature as critical in case many individuals need to contribute to achieving a common objective. It is generally understood as the same individual action taken by a group of people with a common concern. Collective action has a wide range of applications, including the management of common-pool resources such as forests, irrigation water, fishing grounds, and grazing lands (Abdullaevet al., 2010; Meinzen-Dicket al., 2004; Ostrom, 1990). In recent years, the concept of collective action has also been applied in the context of complex agricultural issues such as invasive weeds (Marshallet al., 2016; Yung et al., 2015) and the marketing of agricultural produce (Barham and Chitemi, 2009; Fischer and Qaim, 2012; Ochieng et al., 2018). For the latter, farmer groups and cooperatives have been promoted as ways to consolidate economies of scale, particularly for smallholder farmers (Barham and Chitemi, 2009; Ochieng et al., 2018).

Similarly to common-pool resources, the management of bacterial wilt has public good features. But the disease can be considered as a “public bad”, a nondepletable negative phenomenon that does not get reduced when people are exposed to it (Leeuwis et al., 2018). For the effective management of this disease, collective action is essential. Isolated efforts of individual farmers cannot be effective since the disease spreads from field to field in a variety of ways, such as contaminated irrigation water, surface run-off, farm tools, and infected seed (Hayward, 1991; Janse, 1996). Notably, in the case of seed potato cooperatives, farmers need to cooperate and implement various disease management methods to produce and market quality seed potato. All farmers in a similar area would benefit from disease-free seed potato production.

Issues requiring collective action are often characterised by a tension between short-term individual interests and long-term collective interests, and individuals tend to free-ride (Leeuwis, 2004; Meinzen-Dick et al., 2004; Ostrom, 1990; Ostrom, 2009). For an effective and sustainable governance of common-pool resources through collective action, Ostrom (1990) proposed eight design principles. A monitoring system is one of them. An effective monitoring system is expected to help address the problem of free-riders and audit the conditions of the common-pool resource (Ostrom, 1990).

The literature on common-pool resources shows that a monitoring system can be organised in two main ways: through self-monitoring and third-party monitoring. In the case of self-monitoring, the resource users are responsible for monitoring the condition of the resources and the behaviour of the community members, while in the case of third-party monitoring an external body is entirely in charge of the monitoring activities. The scholarly debate regarding these models is about the associated effectiveness and costs. Many scholars suggest that communities should have the capacity for self-monitoring and enforcement of sanctions to manage common-pool resources through collective action (Ostrom, 2005; Pretty, 2003; Singleton, 2000; Singleton and Taylor, 1992). Agrawal and Goyal (2001) also suggest self-monitoring as a more practical approach for a small group of common-pool resource users, given the high cost of third-party monitoring. Several studies show that a self-monitoring system organised by resource users is less expensive than a centralised external system (Baland and Platteau, 1996; Davies et al., 2004; Dietz et al., 2003; Ostrom, 2005). However, self-monitoring tends to be more prone to free-riding than third-party monitoring (Ostrom, 2005). This may explain the greater effectiveness of third-party monitoring found by Baland and Platteau (1996) based on an analysis of many surveys on common-pool resources.

While there currently exists no comprehensive framework describing what precisely constitutes “a monitoring system”, the literature indicates several elements of an effective monitoring system, including data collection, institutional arrangements (rules and standards), sanctions, decision-making, and the enforcement of sanctions (Hartanto et al., 2002; Ostrom, 1990;

Ostrom, 2005). Synthesising the scattered information available in the literature, we have identified and aggregated seven essential elements of a self-monitoring system for farmer cooperatives. These are (1) organisation of the monitoring system, (2) rules, standards, and sanctions, (3) data collection for monitoring, (4) decision-making, (5) enforcement of rule compliance with sanctions, (6) efficient communication, and (7) resources for monitoring (see Figure 4.1).

Figure 4.1. Elements of a self-monitoring system.

The organisation of an effective monitoring system for community-based natural resources management needs to be simple and cost-effective. Furthermore, it should be transparent in order to be trusted by the community members (Topp-Jørgensen et al., 2005). To this end, a locally-elected committee of users is usually responsible for the monitoring activities (Danielsen et al., 2005; Topp-Jørgensen et al., 2005).

Rules and standards are needed for optimal use of the available natural resources and to shape the behaviour of the resource-users (Ostrom, 2005). The community usually sets rules and standards for monitoring by consensus with the goal of sustainable use and management of natural resources (Agrawal and Goyal, 2001; Ostrom, 2005). In self-monitoring systems rules should be set regarding how to use and manage the existing natural resources without compromising their ecological sustainability. Sanctions are used to provide incentives for obedience to the rules and standards.

Data collection is a relevant monitoring activity usually involving periodic and repeated observations of different parameters (Ostrom, 2005). For instance, for irrigation water, it is crucial to collect data on a regular basis on how much water the irrigators take at different times to ensure fair utilisation. Likewise, in the case of forest resources, data need to be collected on the status of the forest resources and the behaviour of the resource users (Ostrom, 1990). Hence, the data collection of a monitoring system for disease management should include both the occurrence and locations of the public bad and actual disease management practices.

Decision-making is an important component of a monitoring system. Based on the monitoring information gathered, conclusions are drawn regarding the status of the public good or bad, and decisions are made regarding follow-up actions (Agrawal and Goyal, 2001; Ostrom, 1990). If the agreed rules on management practices are broken by resource users, it could be decided to enforce the agreed sanctions against free-riders.

Several studies show that rule compliance is affected by many factors, including the severity of sanctions, the behaviour of other resource users, social norms, personal morals, economic reasons, and local contexts (Agrawal and Goyal, 2001; Eggert and Ellegård, 2003; Mosler and Brucks, 2003; Ostrom, 1990). Hence, in addition to the monitoring of the compliance to the rules, enforcing the compliance by implementing the collectively agreed sanctions is a vital element of an effective self-monitoring system.

Communication is also essential in an effective self-monitoring system. The availability of ample opportunities for communication has been shown to enhance the levels of cooperation (Bicchieri, 2002; Ostrom, 1998; Sally, 1995). In a community-based approach to managing common-pool resources, communication enables, among others, collecting and sharing data, exchanging mutual commitments, reaching agreements on standards, sharing information for decision-making, enforcing rules, and developing trust in the monitoring system (Bicchieri, 2002; Ostrom, 1998). While face-to-face communication is known to be of particular importance (Balliet, 2010; Ostrom, 1998) in collective action settings, the increased connectivity through mobile phones and internet (Information and Communication Technologies, or ICTs) in Ethiopia may offer new opportunities for strengthening communication in such contexts (Cieslik et al., 2018; Damtew et al., 2018).

ICTs can support the regular monitoring for the management of complex socio-ecological problems through collective action (Cieslik et al., 2018; Leeuwis et al., 2018). Among the emerging communication tools, mobile telephone has high penetration rates and a broad appeal to rural populations across developing countries. This has created new forms of communication and supported efforts to deal with various agricultural problems by enabling the farmers' access to knowledge and information (Asenso-Okyere and Mekonnen, 2012; Asongu and Roux, 2017; Furuholt and Matotay, 2011). Recent studies show that there have been successful initiatives involving the use of mobile phones for communication and information exchange to deal with complex agricultural problems. They have been used for the management of crop diseases, soil fertility management, and market issues in smallholder farmers' conditions (Asongu and Roux, 2017; Kaske et al., 2018). Effective communication would thus make use of media that are available to the members of the community.

Finally, sufficient resources are essential for a long-lasting monitoring system. Particularly, the availability of sufficient financial resources is critical for a rural community without external financial support (Topp-Jørgensen et al., 2005). In addition to finance, pathogen detection kits are crucial for rapid disease diagnosis and the effective monitoring of potato disease occurrence in the field.

Research objective and questions

The main objective of the study is to assess the features of the existing monitoring systems for the collective management of potato bacterial wilt by seed potato cooperatives in the central highlands of Ethiopia. It investigates (a) the operationalisation of elements of the existing monitoring systems, and (b) the challenges associated with monitoring. The two underlying research questions are formulated as follows:

How do seed potato cooperatives operationalise the essential elements of a monitoring system for bacterial wilt management?

What are the challenges associated with existing monitoring systems and what implications do these challenges have for future interventions?

4.3. Research methodology

4.3.1 Description of the Seed Potato Cooperatives Selected for the Study

For this study two seed potato cooperatives were selected from Wolmera and Doyogena districts. These are among the major potato-growing districts in the central highlands of Ethiopia. Wolmera district is located in the Oromia regional state, whereas Doyogena district is located in the Southern Nations, Nationalities, and People's Regional (SNNPR) state. In both districts, the rainfall pattern is bimodal, with a main rainy season (*Meher*) from June to September and a short rainy season (*Belg*) from February to May.

Since the new national policy addressing the outbreak of bacterial wilt occurrence came into existence, two kinds of potato seed cooperatives exist in Ethiopia: regular potato seed cooperatives and seed cooperatives working under the QDS system. The two key differences are: (1) cooperatives that produce regular seed potato operate using a legal certificate that they have received from a cooperative promotion office, whereas cooperatives that produce quality-declared seed potato need to get an additional competency certificate from the regulatory department of the regional bureau of agriculture and natural resources, and (2) for quality-declared seed producers there is a standard of zero-tolerance level for bacterial wilt, whereas for regular seed potato cooperatives there is no clear standard in this regard.

Taking the differences into account, two different cooperatives were selected for this study: Agota, a regular seed potato cooperative in Wolmera, and Wanjala, a QDS potato cooperative in Doyogena (see Figure 4.2 for their respective locations). The selection was made based on discussions with agricultural experts at the respective district offices of agriculture. Agota had 30 members at the time of the study, producing seed potatoes during both the *Meher* and *Belg* seasons. The farming system in Wolmera district is cereal-based, and potato is an important cash and food crop in the area. Wanjala has 18 members who collectively produce and market seed potato. The members of this cooperative produce potato during the *Meher* and *Belg* seasons, with major production during the *Belg* season. The farming system in Doyogena district is enset-based. Potato is the second most important crop after enset (*Ensete ventricosum*).

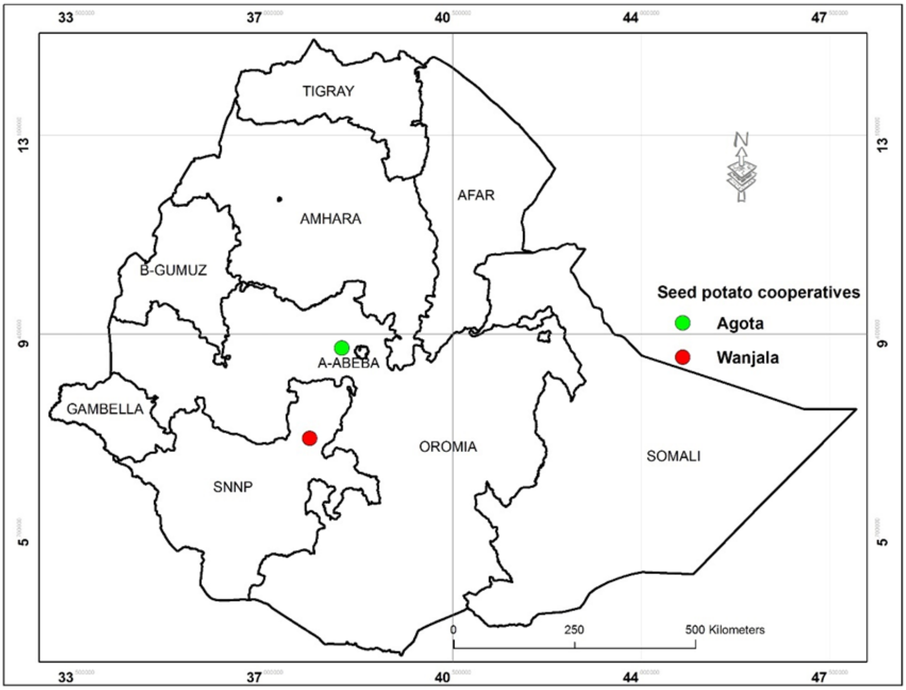

Figure 4.2. Location map of the studied seed potato cooperatives in Ethiopia.

4.3.2. Data collection and analysis

In order to gather relevant data for investigating the monitoring systems of the selected seed potato cooperatives, a multimethod approach was employed (Corbin and Strauss, 2014). Data were collected through semi-structured interviews, reflective workshops, participant observation, and documents analysis.

Two rounds of interviews were conducted; one with six monitoring committee members (three farmers from each cooperative) and another with 18 seed potato farmers (10 farmers from Agota seed potato cooperative and 8 farmers from Wanjala seed potato cooperative). Questions addressed to the monitoring committee members were related to the essential elements of the self-monitoring system of a collective bad, to the effectiveness of the system, and to challenges and suggestions for improving the system. Questions addressed to seed potato farmers focused on issues such as farmers' perception of the performance of the monitoring committee, communications and interactions, the efficacy of the monitoring system, and their trust in the decisions of the monitoring committee members.

Reflective workshops were organised to discuss the findings of the monitoring and associated challenges at the end of the production season. A total of respectively 30 and 18 seed potato farmers from Agota and Wanjala seed potato cooperatives participated in the reflective workshops conducted at the study sites. During the reflective workshops, the participants (seed potato farmers and monitoring committee members) discussed the reflection questions designed to facilitate the workshops. The reflection questions were designed to move from general questions about the importance of monitoring to control bacterial wilt to their perceptions about the key issues of monitoring disease occurrence, management, and associated challenges at their sites.

Participant observation was applied by partaking in seed potato cooperative meetings to capture the concerns and opinions of all the cooperative members. Besides, the potato fields were observed when the crop was at different growth stages, and diffused light stores owned by the seed potato cooperatives were visited. Finally, all relevant documents of the monitoring system were analysed, including cooperatives' minutes of meetings, internal bylaws, manuals and guidelines, and standards for seed potato production.

4.4. Results

In this section, the results of this study are presented as they relate to the essential monitoring system elements and associated challenges experienced by seed potato cooperatives: (1) organisation of a monitoring system, (2) rules, standards, and sanctions, (3) data collection for monitoring, (4) decision-making, (5) enforcement of sanctions, (6) communication, and (7) resources for monitoring.

4.4.1. Organisation of the monitoring systems

The study shows that both seed potato cooperatives recognised the importance of monitoring and organised a self-monitoring system. The cooperatives made efforts to perform monitoring activities to ensure the production of quality seed potato. The seed potato cooperatives have seed quality monitoring committees consisting of three members which are in charge of dealing with seed potato quality related issues. The committee members are elected by cooperative members to serve for a three-year term, and operate on a volunteer basis. They could be re-elected to serve for a second term of another three years based on their performance and the assessment of the cooperative members.

Both regular seed and QDS potato cooperatives had clearly defined roles and responsibilities for the monitoring committee members. From the interviews with the monitoring committee members and during reflective workshops, it was noted that the committee was supposed to visit each farmer's field to conduct the monitoring work. The committee mentioned that making regular field visits was essential to enhance the efficacy of the monitoring activity. But time did not allow them to do so, and the frequency of the field visits was limited to only about two to three times during different growth stages of the crop. During the field inspection, the committee members checked for the occurrence of visible potato diseases, and whether the farmers put the recommended management methods into practice or not. To ensure transparency, the committee members visited farmers' potato fields in the presence of the owner of the field.

In the QDS potato cooperative, agricultural extension officers and researchers provided some technical support to the seed quality monitoring committee. The researchers and extension officers joined the seed quality monitoring committee during a field inspection. According to the committee members, this support is crucial because they feel that the presence of the researchers can help them make a better diagnosis of disease incidence in potato fields. However, so far, the extent to which the researchers and extension officers support the monitoring work is limited, in the committee members' view. This support depends on the presence of development projects that promote the QDS scheme. During the reflective workshop, the monitoring committee members repeatedly expressed that the support from researchers and extension workers was not sufficient. Besides, the committee members stated that without the help of these actors, it would be difficult for their seed cooperative to continue producing quality-declared seed potatoes. They also expressed the importance of more training to perform the monitoring activity. It could also be expensive and challenging for the cooperatives to sustain the support from these actors due to their limited financial capacity.

The monitoring committee reported that the technical support they got from agricultural research institutes and agricultural offices was inconsistent. Furthermore, the monitoring committee members mentioned that sometimes they had to wait too long for the support from researchers, as they had to come from far away. The committee suggested that researchers and extension officers need to prioritise the support for the QDS potato cooperatives. Giving them priority is vital because the monitoring work is time-sensitive, and the disease is difficult to diagnose visually once the crop is mature.

In addition, seed potato farmers, the members of the seed potato cooperatives, have recently become vigilant about the practices of ware potato producers in their respective areas, in general, and of those with adjacent potato plots, in particular. Consequently, due to the contagious nature of the disease, seed potato cooperatives are compelled to recognise the importance of monitoring the practices of neighbouring ware potato farmers and disease incidences in their potato fields. However, the seed cooperatives do not have organisational and institutional arrangements that enable them to monitor the practices of ware potato farmers.

4.4.2. Rules, standards, and sanctions

Both QDS and regular seed potato producer cooperatives have an institutional arrangement (internal bylaws) to ensure quality seed production and enforcement of sanctions on non-adherents. The rules (bylaws) of the cooperatives encompass the details of how the cooperatives should operate as a business enterprise, requirements for membership, the role of the member farmers, and seed quality monitoring committee members, among others. The bylaws are written documents approved by the general assembly (members) of the cooperatives during their establishment. If there is a need to amend the bylaws, it happens during the annual general meeting of the cooperatives.

As specified in their bylaws, the cooperatives aggregate seed produced by their members, store them in common or individual diffused light stores (DLS), search for market opportunities, and sell collectively. In order to guarantee seed potato quality, the seed cooperatives also have rules and bylaws with regard to the management of pests and diseases. To a considerable degree, these rules and standards are linked to externally imposed standards for different types of cooperatives.

The regular seed potato cooperative (Agota) does not have a precise standard regarding the level of disease occurrence. It just mentioned that seed potato fields should be free from infection of bacterial wilt and other diseases. The committee members explained that—in connection with this—it orders the seed potato farmers to implement different methods to control bacterial wilt and maintain the hygiene of their potato fields. These methods include the roguing of potato plants with symptoms of bacterial wilt infection, crop rotation, use of healthy seed, runoff diversion, farm tools decontamination, and other sanitation measures.

QDS potato cooperatives have to meet much more rigorous standards than regular seed potato cooperatives (see Table 4.1). Among the standards, there is a zero-tolerance level for bacterial wilt, which is hard to meet given the prevalence of the disease in all major potato growing areas. Instead of enforcing zero-tolerance, the committee of the Wanjala cooperative usually advises farmers to uproot diseased plants and dispose of them safely to avoid further spreading of the disease. Another standard is that if disease infestation is observed on a potato field, potatoes should be banned from that field for five consecutive seasons. However, some QDS farmers mentioned that they were unaware of such requirements, while others stated that it is impossible to follow this standard given the shortage of land and wide prevalence of the disease.

The monitoring committee members of the Wanjala cooperative highlighted the need for revising quality-declared seed standards such as the zero-tolerance level and the minimum

Table 4.1. Standards for quality-declared seed potato production (Source: Ethiopian Standards Agency, 2015)

	Parameters		**QDS 1**	**QDS 2**	**QDS 3**	**QDS 4 –QDS 8**
1	Class of seed as a source *		Pre-basic or Basic or C1	C2 or QDS 1	C3 or QDS 2	C4 or QDS 3–7
2	Rotation (Minimum number of seasons)		3	3	3	3
3	Isolation Distance (Minimum meters)		5	5	5	5
4	Off-types and other cultivars (Maximum %)		2	3	4	5
5	Diseases	Bacterial wilt (Maximum %)	0	0	0	0
		Potato leaf roll virus (PLRV), Potato virus Y (PVY) and others (Maximum %)	5	10	12	13
		Black leg (Maximum %)	0	0	0	0

* Seed generations/categories: (C1) certified seed of the first generation, (C2) certified seed of the second generation, (C3) certified seed of the third generation, and (C4) certified seed of the fourth generation.

isolation distance (see Table 4.1). They suggested that due to the expansion of the disease and the difficulty to find disease-free fields, there should be some level of tolerance for bacterial wilt incidence. The committee suggested the increase of the minimum isolation distance at least up to 10 m instead of the current 5 m. They noted that varietal mix and disease transmission is possible with the currently practised 5 m of isolation distance.

Seed potato farmers and monitoring committee members in both cooperatives considered sanctions as an effective approach to ensure compliance with the bylaws and avoid free-riding. In response to bacterial wilt infestation and poor management practices, the main sanction that the committee members enforce is to reject selling the farmers' seed potatoes through their respective seed potato cooperatives. Farmers whose seed potato fields are infested are told to sell their produce as ware potato, and hence at lower prices. During the reflective workshops, the downside became clear: the farmers mentioned that the price of seed potato was two to three times higher than that of ware potato in both study sites. The other stiff sanction that the cooperatives are allowed to impose on members violating the rule is the cancellation of their cooperative membership. This sanction was also specified in the bylaws of the cooperatives.

4.4.3. Data collection for monitoring

During monitoring, committee members assessed disease occurrence only through visual observation of the potato fields. During field inspection, both committees collect data on different parameters, including potato variety, source of seed, size of potato field, disease occurrence, disease management practices, isolation distance between the seed potato field and other potato fields, crop rotation history, seed generation, and off-types, among others.

Most committee members mentioned that they often found it hard to properly diagnose disease incidence in the farmers' fields. The fact that the disease might not show symptoms (latent infection) further complicated the efficacy of the monitoring. They also referred to the difficulty of monitoring the implementation of disease management methods that are hard to trace, such as keeping farm hygiene and sanitation (decontamination of farming tools, washing shoes before getting into potato fields, removing and burning or burying infected plants, and use of disease-free seed). The committees have no appropriate mechanisms to figure out malpractices in these regards, apart from trusting the farmers' assertions. Finally, since the farmers know when the committee members will visit their fields, they always try to rogue all potato plants with symptoms of bacterial wilt infection, so that their potato fields look clean and healthy prior to the monitoring committees' visit.

According to farmers and monitoring committee members, another challenge that constrained sufficient data collection for the monitoring activity was the inaccessibility of some potato fields. For example, in the Wanjala seed cooperative, as a solution to land shortage, QDS producers rent land outside their village to meet the land requirement for QDS production. At the same time, this practice posed new challenges. The farmers indicated that they could not frequently visit their potato fields or take actions they would have to take because of poor access to such remotely located fields. They also mentioned that it was difficult for them to protect their potato fields from human and livestock interferences. Likewise, monitoring committee members mentioned that such practice forced them to travel long distances to do their monitoring work.

Some QDS farmers in the Wanjala seed potato cooperative mentioned that the practice of ware producers affected their success in producing disease-free seed. They mentioned that since their land was bordered by ware potato fields, they faced challenges in meeting the minimum requirement of isolation distance of five meters between QDS potatoes and other potato fields.

In the case of the Agota seed potato cooperative, the monitoring committee described that some farmers living elsewhere came to their village to grow potatoes. These farmers accessed potato fields through rental arrangements for one or more seasons. It was difficult to monitor the practices of those farmers and to oblige them to control the disease, as they do not belong to that community. In such cases, the committee mentioned that they try to put pressure on the farmers who rent their lands to external farmers so that they in turn compel those farmers to control the disease by properly implementing different disease management methods. The committee revealed that such efforts were not effective enough to control the disease. Going forward, the committee thought it might be good to convince the farmers who rent their fields to other farmers to include disease management practices in the agreement they sign for land rental.

When asked during the reflection workshop about the possibility of doing the monitoring work on a weekly basis, the farmers and the monitoring committee members indicated that this was an unrealistic and unattainable proposal. They recognised the importance of improving the frequency of monitoring, considering the complexity of the disease problem. However, the monitoring committee enunciated that they did not have time to do so, as they were volunteers and had to do their own various farming activities.

4.4.4. Decision-making

The monitoring committees make decisions based on field inspection findings and share their findings with cooperative members at regular meetings. They try to substantiate their findings with evidence and take minutes of the meetings. However, despite the visible prevalence of bacterial wilt in both study sites, the monitoring committees reported only few cases of rejection of potato fields as seed. This is also true for the QDS cooperative that officially has a zero-tolerance policy for bacterial wilt. They tend to give warnings and provide recommendations rather than to take the agreed sanctions. The committees also stated that after each season they organise meetings to discuss the challenges they faced during a particular growing season and how to avoid them in the next season.

The monitoring committee members of the QDS cooperative stated that agricultural extension officers supported them in explaining their reasons for the rejection of seed potatoes. Most farmers also mentioned the facilitation role of the extension officers as important. Some seed farmers mentioned that they trust the extension officers more than the monitoring committee members. In addition, some farmers felt that the decisions made by the committee were biased and unacceptable. These farmers were mostly those who got their seed potato field rejected at least once. These farmers made comments such as:

> "The decision of the monitoring committee is partial because all the committee members' potato fields get accepted every time. But they reject those of other farmers. How can their fields be accepted every time?"

> "The monitoring committee members sometimes undermine when they observe considerable problems on potato fields of their relatives and make a positive decision."

The monitoring committee rejects mainly the fields of the farmers who failed or refused to implement the recommendations given by the committee in a previous season. For example, during the reflective workshop, one of the farmers who was a member of the Agota seed cooperative complained about the decision made by the monitoring committee. He said that the committee rejected his field although he implemented the recommendations given by the committee. The committee mentioned that the field of this particular farmer was infested by bacterial wilt and he could not rogue all plants with symptoms of bacterial wilt infection, since they were too many.

The other constraint that the farmers mentioned about the decisions of the monitoring committee was a lack of transparency. The monitoring committee members approving potato fields that should not be accepted for seed appeared to create the farmers' distrust in the monitoring process. For instance, while stating their distrust in the monitoring committee, farmers from the Agota seed potato cooperative said the following:

> "My potato field was cleaner than that of my neighbour, but the committee rejected my field and accepted that of my neighbour. I did not know on what basis they made their decision."

> "The amount of seed that some farmers bring to the cooperatives' diffused light store (DLS) is sometimes far more than what they can actually harvest from their small plot of land. These farmers might bring their neighbours' or relatives' ware potato produce to sell through the cooperative as seed."

4.4.5. Enforcement of rule compliance with sanctions

As mentioned earlier, the monitoring committee members in both types of seed potato cooperatives—QDS and regular—rarely enforced sanctions by rejecting potato fields infected by bacterial wilt. In most instances, the committee members compromised and showed sympathy. Indeed, when the disease infestation was low, the committee typically advised the farmers to properly remove (rogue) and dispose of the plants with symptoms of bacterial wilt infection, instead of rejecting the infested field. In most cases, they opted to limit their punishment to verbal warnings in spite of the visible occurrence of bacterial wilt in the potato fields. Likewise, the two cooperatives had never imposed the sanction of banning farmers from the cooperative. Some committee members mentioned that a cancellation of seed producers' cooperative membership is not easy to impose. But other committee members and some farmers emphasised the importance of imposing this sanction on farmers who repeatedly violate cooperative rules.

The monitoring committee members from both cooperatives reported that they frequently face challenges in enforcing the sanctions. Farmers whose fields were rejected did not easily accept the decision of the committee. For instance, one of the committee members from the Wanjala seed potato cooperative said:

> "Some farmers get furious when we do not allow their potatoes to be sold as quality-declared seed due to bacterial wilt problems."

According to monitoring committee members, the generality and lack of precision in the standards for regular seed potato cooperatives tended to reinforce the emergence of complaints and tense debates whenever potato fields were rejected on the basis of disease infestation. Affected farmers tended to deny the occurrence of the disease in their fields, and some farmers struggled to manipulate their potato fields by removing infected plants to make them attractive to the committee members.

4.4.6. Efficient communication

Monitoring committee members communicate with each farmer through various mechanisms. They regularly organise meetings to discuss and communicate face-to-face with each cooperative member about their plans, the progress of different activities, agricultural inputs availability, market issues, disease problems, and other matters. The cooperatives write letters to their cooperative members, particularly when they communicate critical issues such as the rejection of their potato fields on the basis of severe disease infestation.

The comments given by the farmers and committee members stressed the prominent place that mobile phones had in communication for monitoring collective action by seed potato cooperatives. During the interviews, one of the committee members from the Agota seed cooperative said the following:

> "Before a few years, we used to visit each farmer's house and call the farmers for a meeting, as most farmers did not have mobile phones. But now almost all farmers use mobile phones and we easily communicate with each other."

Similarly, when asked how mobile phones supported the monitoring of collective action, a farmer from the Wanjala seed potato cooperative said:

> "Monitoring committee members call and ask us when they plan to do potato field

> inspection. We discuss through the mobile phone and make an appointment on a convenient date."

Although mobile phone communication appeared to have had a prominent place in supporting the logistics of the seed potato cooperatives, farmers mentioned lack of access to electricity to charge their mobile phones and network interruptions as challenges. These problems constrained the effective and regular use of mobile phones for communication. More generally, farmers reported that regular communication with the monitoring committee members helps them understand the status of disease occurrence in their community, while the committee members emphasised the importance of timely communication with farmers to give feedback and encourage them to take necessary measures to improve the quality of seed. One of the challenges that the committee mentioned in relation to communication was that some farmers did not regularly attend meetings due to various social problems.

4.4.7. Resources for monitoring

The monitoring committee serves on a volunteer basis, and seed potato cooperatives do not incur a considerable cost for the service that the committee provides, apart from a limited daily allowance which is intended to cover operational costs. Since effective monitoring entails visiting several scattered potato fields on a regular basis, monitoring committee members suggested the importance of increasing the incentives to encourage them to do the monitoring activity diligently on a regular basis. During the reflective workshop, the committee also repeatedly raised the importance of increasing the incentives allocated by the cooperatives to the monitoring activity. Seed potato farmers also reported that regular monitoring of many farmers' fields was a labour-intensive activity and that the monitoring committee members deserved additional (financial) incentives. Some farmers, however, were hesitant about the increment of allowance for the committee, stating that they did not have enough money to pay raised fees. Particularly, a considerable number of farmers from the Agota seed cooperative explained that due to the lack of a reliable market for their seed produce in recent years, they started selling seed potatoes to ware potato traders during harvesting time. As a result, these farmers were not in favour of increasing the allowance for the monitoring committee.

When asked about the possibility of using a third-party monitoring for the collective management of bacterial wilt, both farmers and monitoring committee members reported that there was no third-party that could be involved in such activities in the country. They also highlighted their concern, as this would be beyond the financial capacity of their cooperatives and individual farmers. The committee members reported that they participated in some capacity development trainings organised by the government and non-governmental organisations, but felt that the capacity development support was insufficient, and stated that they do not have access to kits to help them make proper disease diagnoses.

4.5. Analysis and discussion

Seed potato cooperatives have indeed established a working monitoring system to stimulate disease management and improve the quality of the seed production by their members. Moreover, the framework regarding the essential elements of an effective monitoring system that we compiled on the basis of literature on the collective management of common-pool resources proved useful for describing the way in which cooperatives have operationalised their monitoring system. The presence of an organised self-monitoring system among the cooperatives can—in principle—contribute to the supply of quality seed and the control of bacterial wilt (Andersson et al., 2014; Coleman and Steed, 2009; Gibson et al., 2005). However, the findings of this study indicate that monitoring disease occurrence and management is a complex and multifaceted activity that faces many challenges.

4.5.1. Challenges for effective monitoring

Despite the existence of an organised monitoring system to ensure quality seed potato production by seed potato cooperatives, it is clear that the functioning of the system faces many challenges in light of the wide spread of bacterial wilt in the country's major potato production areas. An overview of the experienced challenges is provided in Table 4.2.

Proper disease diagnosis skills are vital for the effective monitoring of the occurrence of the disease and farmers' management practices. However, the study showed that the monitoring committee members depended on visual observation to collect data on the incidence of bacterial wilt in seed potato fields. As the disease may not always show the symptoms due to latent infection (Genin, 2010; Priou et al., 2001; Swanson et al., 2007), the committee may fail to detect the disease. As a result, seed cooperatives could produce and market infected seed, which could aggravate the spread of the disease. Such circumstances could damage the reputation of

Table 4.2. Challenges reported and observed in the monitoring system.

Element of the Monitoring System	Challenges Observed
Organisation of the monitoring system	• Volunteer basis constrains regular monitoring • Members of committee are not fully independent, since they need to monitor their own fields as well • Boundary of the organisation does not coincide with boundaries relevant to the disease (in terms of members and distance) • Organisation has weak linkages with research and extension
Rules, standards, and sanctions	• For regular cooperatives the rules are formulated in general terms and therefore ambiguous • Rules only apply to fields of seed potato producers and not to ware producers
Data collection for monitoring	• Visual observation is a sub-optimal technology for data collection • Proper diagnostic tools are lacking • Frequency of data collection is generally insufficient, and even more so in rented fields outside the community
Decision-making	• Decisions related to enforcement are frequently contested • Transparency of decision-making process is regarded as sub-optimal, creating distrust
Enforcement of rule compliance with sanctions	• Fields are only occasionally rejected, even in cases where the rules would justify this • Frequent offenders are never banned from the cooperative
Efficient communication	• Boundary of communication networks does not coincide with boundaries relevant to the disease • Pre-announcement of field inspections by mobile phone enables farmers to hide disease infestation • Participation in face-to-face assembly meetings is insufficient
Resources for monitoring	• Remuneration of monitors is insufficient to guarantee regular monitoring • Limited financial resources to purchase diagnostic tools • No support for raising income of the cooperative through higher fees

all seed producers belonging to that cooperative. To reduce such risks, the committee would need to have access to kits that support a proper and regular disease diagnosis at the field level. However, the financial and human resources available to cooperatives do not allow for this.

Several studies on common-pool resource management show that sanctions enhance compliance with the rules and help avoid the free-riders problem (Ostrom, 2005; Trawick, 2001). In the case of seed potato cooperatives, we have observed that the bylaws do include stiff sanctions (i.e., withholding of access to the seed potato market) that the monitoring committees are supposed to enforce on the basis of observed disease infestation. In practice, however, the monitoring committees seemed to compromise in enforcing sanctions, as only a few cases of rejection were reported by the cooperatives. In addition to the lenient enforcement practice, compliance with the rules may have been poor due to several other factors, such as personal morals, social norms, legitimacy, and contextual factors (Colquitt et al., 2001; Gezelius, 2004).

In relation to decision-making, our findings indicate that the trust between members of seed potato cooperatives and monitoring committees was limited. The decisions of monitoring committees were frequently contested, and both parties raised questions about each other's integrity. This has important implications, since trust among key stakeholders is imperative for the effective management of common-pool resources (Davies et al., 2004; Ostrom, 2005). To develop trust, the monitoring committee members need to make their decision-making process more transparent, be consistent in their decisions, and also apply the rules to their own seed potato fields.

A complicating factor in this regard is that the monitoring system only applies to seed potato producers, while neighbouring producers of ware potatoes are also a source of disease infestation. This makes it difficult to hold members fully responsible for disease occurrence and is likely to contribute to the dilemma that monitoring committees face in enforcing bylaws and to the contestation of the decisions made. Thus, the current monitoring system of the seed cooperatives needs to go beyond the members and to find alternatives to involve ware potato producers in the monitoring. Due to the collective risk that the disease poses, seed and ware potato farmers need to make concerted efforts to deal with the disease.

Arguably, the communication element of the monitoring system poses relatively fewer challenges, not least since both farmers and monitoring committee members have benefitted from new opportunities created by the widespread availability of mobile phones. Committee members can easily communicate with each other and with seed potato growers, extension officers, and researchers. Farmers also stated that the expansion in mobile telephony facilitates easy communication with each other and with their respective cooperatives. This is in line with the report of the Ethiopian Agricultural Transformation Agency on how mobile telephony has created an opportunity to deliver agricultural information to many smallholder farmers in the country and how mobile phone communication has become a common practice among many smallholder farmers in Ethiopia (ATA, 2014; Kaske et al., 2018; Tadesse and Bahiigwa, 2015). The downside of the use of mobile phones in planning field inspections is that farmers knew when inspectors were coming and had time to conceal disease infestation. In addition, challenges were reported in relation to the participation of members in face-to-face group meetings that were relevant to the functioning of the cooperative. Moreover, it is questionable whether the current boundaries of cooperatives and their communication networks are appropriate in view of the mechanisms involved in the spreading of the disease. One may argue that more intensive communication is needed across broader geographical spaces, as well as with different types of farmers (seed potato producers and ware potato producers alike) in the same community.

From an historical perspective, the observed challenges relate to the ways in which seed potato cooperatives were established. During their establishment, the development organisations that facilitated their establishment did not consider the social and ecological interdependencies between ware potato producers and seed producers. They facilitated the establishment of many seed potato cooperatives as an innovative initiative in response to the limited seed potato supply in the country (Hirpa et al., 2010). The ecological and social context of the farmers in view of the occurrence and management of potato diseases like bacterial wilt were not well considered during this period. Consequently, even though the seed potato cooperatives have been able to enhance the seed potato supply in the country (Sisay et al., 2017; Woldegiorgis et al., 2013), nowadays almost all of them are experiencing serious problems due to their limited capacity to effectively respond to the emerging and devastating potato disease caused by bacterial wilt (CIP, 2016; Gorfu et al., 2013).

All in all, the results of this study confirmed that both regular seed and QDS potato cooperatives were not in a position to effectively monitor collective efforts to multiply seed potato by controlling bacterial wilt with a zero-tolerance level. The prevalence of bacterial wilt has complicated the management of the disease and the practice of quality seed production. Some seed producers reported selling their seed produce as ware potato due to the lack of market likely due to the problem of bacterial wilt. This has a huge implication for the already underdeveloped seed system in the country. If seed producers turn back to growing ware potato, the gap between the demand and supply of seed will be widened, resulting in the limited availability of seed potatoes. Further potato diseases like bacterial wilt will spread more, as farmers will be forced to repeatedly use infected ware potato tubers as seed. This can indeed jeopardise the food and nutrition security initiatives in different parts of the country, since potato is a strategic crop that has been promoted to address food insecurity problems. Tensions between food insecurity pressures and the attention given to seed potato quality can also have a significant negative effect on the efforts towards the effective management of the disease. Therefore, over the coming years, the problem of bacterial wilt can be aggravated unless the farmers and other actors such as research, extension offices, and non-governmental organisations make concerted efforts to deal with it.

4.5.2. Implications for future interventions

Although the seed potato cooperatives had organised systems to monitor disease occurrence and its management for quality seed production, they were underprepared to respond to the recently emerged but widely spreading potato disease, bacterial wilt. This raises the question of how the monitoring system can be made more effective.

In the literature on collective action, both self-monitoring and third-party monitoring are recommended, even though there has been a debate among several scholars in relation to the effectiveness and costs associated with the two approaches. Some researchers advocate self-monitoring (Agrawal and Goyal, 2001; Singleton and Taylor, 1992), while others suggest that third-party monitoring is more effective (Baland and Platteau, 1996; Ostrom, 2005). Even though our study points to important weaknesses in the self-monitoring system, there are also strong indications that third-party monitoring is currently not feasible for seed potato cooperatives, in view of various conditions such as the limited financial capacity of smallholder farmers and their cooperatives, and the absence of an organisation that can provide third-party monitoring services in the country. This is confirmed in many studies showing that the implementation of formal seed systems is not feasible in low-income countries due to technical and institutional constraints (Buddenhagen et al., 2017; Schulz et al., 2013; Thomas-Sharma et al., 2016). Likewise, in Ethiopia, the role of seed cooperatives has been and will continue to be significant in potato seed systems, since a formal seed certification system cannot be developed at a sufficient scale anytime soon (Schulte-Geldermann, 2013; Schulz et al., 2013; Thomas-Sharma et al., 2016). This underscores the importance of strengthening the self-monitoring capacity of the existing seed potato cooperatives for the subsistence of seed potato producers.

While the current self-monitoring system is unable to address the disease, it is important to recognise that this inability relates to the enormous prevalence of the disease in the country and to the fact that no adequate treatment exists. Hence, the cooperatives are facing a near impossible task, also because their neighbouring ware potato producers are not currently enrolled in the cooperative efforts.

While it is relevant to eventually address all reported challenges through training, resource acquisition, and measures to enforce sanctions and enhance transparency and combat distrust, the most important issue to be dealt with in the short term is the creation of better linkages between seed potato farmers and ware potato farmers. This is because any effort from the side of seed potato cooperatives is bound to fail if it is not coordinated and negotiated with ware producers. In essence, ware producers need to become an integral part of the entire monitoring system. In addition, it is important to invest in technical and agronomic research aimed at finding strategies to get rid of bacterial wilt once the disease has established itself. Moreover, it is important to identify and protect areas in communities and in Ethiopia where bacterial wilt is not yet established.

This means that on top of monitoring potato fields for disease occurrence and farmer practices, it is important to monitor seed movement within the community. Both incoming and outgoing seed potato to and from the community needs to be monitored. This could bring about the need for strong peer monitoring, which has to be well integrated to support the efforts of the monitoring committee.

4.5.3. Implications for future research on monitoring systems

As part of this study, we developed a novel framework consisting of essential elements of monitoring systems for disease management. The current study suggests that the framework is useful for describing and analysing the way in which seed potato cooperatives in Ethiopia engage with disease monitoring, and that it can serve to diagnose and categorise challenges and reflect upon solutions. Since the elements in the framework are quite general, it is likely that it can be applied to describe and evaluate monitoring systems in other contexts, including monitoring systems for other crops and diseases. Comparative analysis across multiple cases and contexts can potentially yield interesting insights, for example in how specific characteristics of diseases (e.g., spreading mechanisms) can pose specific challenges and demands on the operationalisation and design of effective monitoring systems for disease management, or in how specific social, economic, and political conditions in society may enable or constrain the emergence and implementation of such systems. Thus, the framework may orient future research and open up interesting areas of investigation, which can at the same time contribute to a further refinement of the constituting elements of the framework for different situations.

4.6. Conclusions

Our study has demonstrated that seed potato cooperatives do indeed have a reasonably well elaborated self-monitoring system, geared towards safeguarding seed quality and disease management. This reflects one of the design principles for sustainable and effective management of common-pool resources, which in our case relates to the prevention of a public bad. However, it seems that seed potato cooperatives in Ethiopia are currently underprepared to control bacterial wilt. The monitoring systems that the seed potato cooperatives put in place do not match the dynamics of the disease and its wide prevalence. Governmental and non-governmental organisations operating in the country's potato innovation system can therefore benefit from the findings of this study for a better understanding of the complexity of the monitoring activity for quality seed production and the management of the disease. In order to effectively respond to the increasing disease pressure, the existing self-monitoring activity of seed potato cooperatives needs to be improved in several respects. This includes the enhancement of disease diagnosis, the strict enforcement of sanctions, greater transparency in decision-making, and the extension of the monitoring system towards seed movement. However, the most important measure to be taken in the short term is to ensure that producers of ware potatoes are included in the self-monitoring system. Any measure taken to combat the disease on the fields of seed potato producers is bound to fail if neighbouring ware producers are not involved in collective action. Finally, further research should be done to understand risk factors for the disease and to investigate alternative management methods that are feasible in a smallholder farmers' context for an effective collective action to deal with the disease.

Chapter 5

Association between soil acidity and bacterial wilt occurrence in potato production in Ethiopia

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Abstract

Soil acidity is one of the main constraints to crop production worldwide. In Ethiopia, the problem of soil acidity has been increasing. Currently more than 40% of cultivated land in the country has pH <5.5. Recently, bacterial wilt (caused by *Ralstonia solanacearum*) has become a serious problem reaching epidemic levels in some of the major potato growing districts in the country. However, it is hitherto unknown if the current outbreak of bacterial wilt in potato production is associated with soil acidification or not. To examine the association between bacterial wilt and soil acidification, we conducted a field survey and field experiments and detected and characterised *R. solanacearum* strains. The study showed that 50% of potato fields were very strongly acidic (pH 4.5-5.0) and bacterial wilt incidence was higher in potato fields with low soil pH. The field experiments indicated that lime application significantly increased soil pH (p <0.001) and reduced bacterial wilt incidence (p<0.001). The more lime was applied, the stronger the positive effect on pH and the stronger the reduction in bacterial wilt incidence. Bacterial wilt incidence was on average 10.8% under 12 t/ha lime application while it was about 40% in control plots (without lime) after 90 days. All *R. solanacearum* strains isolated from the symptomatic potato plants were Phylotype II. Our findings show that the current outbreak of bacterial wilt in Ethiopia is associated with soil acidification. They add to the understanding of the risk factors for bacterial wilt in potato. Aside from farm hygiene, sanitation and cultural practices, addressing soil acidification using lime needs to be considered as additional component of an integrated package to deal with bacterial wilt in potato under acidic soil conditions.

Key words: bacterial wilt; genetic diversity; lime; soil acidification; soil pH

5.1. Introduction

Bacterial wilt, caused by a soil-borne pathogen (*Ralstonia solanacearum*), has become a serious constraint to potato production in Ethiopia. The disease has widely spread in the last few years. Previous studies have shown that the occurrence of bacterial wilt seemed more prominent in some potato growing districts than in other areas (Bekele et al., 2011; Gorfu et al., 2013; Lemessa and Zeller, 2007). Causes of variation in disease incidence among districts remain unclear. However, cool highlands that have historically been known to be free from bacterial wilt are currently also being affected by the disease (Abdurahman et al., 2017; CIP, 2016; Kassa, 2016).

Previous studies have shown that free movement of latently infected seed potato contributed to the spreading of the disease in Ethiopia (Abdurahman et al., 2017). Limited knowledge among farmers and lack of coordinated action among the various actors in the country's potato production system constrained effective management of the disease (Damtew et al., 2018; Tafesse et al., 2018). Furthermore, poor seed quality produced and marketed by seed potato cooperatives has contributed to the spreading of the disease (Tafesse et al., 2020). Ecological interdependency among seed and ware potato farmers coupled with infectiveness of the existing seed potato certification system in Ethiopia has also made it difficult to manage the outbreak of the disease (Schulz et al., 2013; Tafesse et al., 2020).Apart from this knowledge about the primary social conditions facilitating the spreading of the disease, there is very little knowledge on biophysical factors that could explain the outbreak of the disease.

Many studies show that about 40% of the arable land in Ethiopia is currently covered by acidic soils (pH <5.5) and the problem of soil acidity has been increasing in the country (Abebe, 2007; Agegnehu et al., 2019; ATA, 2014). The problem of soil acidity is aggravated in Ethiopia mainly because of complete removal of crop residues from crop fields, overgrazing, and high rainfall that washes basic cations and organic matter away through soil erosion and leaching (Abate et al., 2017; Abebe, 2007). Long-term application of acid-forming inorganic fertilizers like urea and diammonium phosphate (DAP) also considerably contributed to soil acidification in the country (Abate et al., 2017; Agegnehu and Amede, 2017; Barak et al., 1997; Guo et al., 2010). According to Warner et al. (2016), the problem of soil acidity is rampant in high rainfall areas of the western, north western, south western and southern parts of Ethiopia. In contrast, the northern and eastern parts of the country have alkaline soils (ATA, 2014; Kebede and

Yamoah, 2009).

Soil pH affects various chemical and biological processes in the soil. Solubility and availability of plant nutrients such as calcium, magnesium, phosphorous, potassium and trace metals depend on soil pH (Weil & Brady, 2016). Many studies show that activities of soil microorganisms are strongly influenced by soil pH (e.g., Garbeva et al., 2004; Rousk et al., 2010). Abundance and diversity of bacteria are also affected by soil pH (Bååth and Arnebrant, 1994; Hartman et al., 2008; Rousk et al., 2010). There are plant growth promoting (beneficial) and pathogenic (harmful) bacteria in the soil. Beneficial bacteria (e.g., *Pseudomonas fluorescens*, *Bacillus pumilis*, *Bacillus cereus*) supply nutrients to plants, enhance plant growth and protect plants from various pathogens (Lodewyckx et al., 2002; Strobel and Daisy, 2003; Wang et al., 2017). Plant-pathogenic bacteria (e.g., *Xanthomonas oryzae*, *Ralstonia solanacearum*) have harmful effects on plants and cause significant economic losses (Elphinstone, 2005; Hayward, 1991; Wang et al., 2017).

The knowledge about the relationship between *Ralstonia solanacearum* and soil acidity is limited. Recent research shows that *Ralstonia solanacearum*, causing bacterial wilt in tobacco, has been found to be more serious under acidic soil conditions (Li et al., 2017). Further, the same research shows that acidic conditions are conducive to the expression of virulence genes of the pathogen while the expression of a resistance gene is controlled in tobacco (Li et al., 2017). Growth and antagonistic activity of the antagonistic bacteria *Bacillus cereus* and *Pseudomonas fluorescens* were also suppressed at pH < 5.5 (Li et al., 2017; Shen et al., 2018; Wang et al., 2017).

In this paper, we describe our efforts to study the relationship between soil acidity and incidence of bacterial wilt in potato production in Ethiopia. Our study was designed with the main objective of understanding the extent of soil acidification in major potato growing districts in Ethiopia and to elucidate if there is an association between the occurrence of bacterial wilt and soil acidification. We also tested through field experiments liming as a management method to decrease soil acidity and thus suppress the pathogen in the context of smallholder potato growers in Ethiopia. Moreover, since knowledge of genetic diversity of the pathogen is important to control the disease, the study also aimed to detect and characterise *Ralstonia solanacearum* strains in seed and ware potatoes. The specific objectives of this study were:

1. To determine the extent to which soil acidification is a problem in major potato growing districts in Ethiopia.
2. To assess the extent of bacterial wilt incidence in potato fields and its relationship with soil acidity.
3. To examine the effect of different levels of lime application on soil acidity and the incidence of bacterial wilt.
4. To detect and characterise *Ralstonia solanacearum* strains in potato fields.

5.2. Materials and methods

This study employed a combination of methods to generate data including field surveys to assess soil acidity and the extent of bacterial wilt incidence in potato fields. Field experiments were conducted to examine the effect of different levels of lime application on bacterial wilt incidence under field conditions. Molecular analyses were carried out to detect *Ralstonia solanacearum* and to determine the genetic diversity of its strains isolated from potato tubers. Details of the methodologies employed in this study are described in the following sub-sections.

5.2.1. Soil sampling and bacterial wilt incidence survey in potato fields

Soil samples were collected (0-20 cm) from 147 randomly selected potato fields to determine the status of soil acidity and bacterial wilt incidence in seven potato growing districts (Wolmera, Meta Robi, Ada'a Barga, Dendi, Jeldu, Ambo and Wonchi) in the central highlands of the country. Soil pH analysis was done in a suspension of 1:2.5 soil:water at Ambo University, Chemistry Laboratory. An assessment of bacterial wilt incidence was also carried out. Three quadrants (about 5 m × 5 m each) were selected diagonally from each field to assess disease incidence as the percentage wilted plants of the total number of plants in the three quadrants.

5.2.2. Field experiments

Site description and experimental design

To examine the effect of ameliorating soil using lime on bacterial wilt incidence, field experiments were conducted at three sites in Wolmera district during the main potato growing season (June to October) of 2018. This district is in the Oromia regional state, Ethiopia. Over the last two decades, this district has been serving as a hub for seed potato production. The sites were Bakaka, Gabi Robi and Wolmera Choke. The soil type at each site is a well-drained

Nitisol. Initial soil pH was determined. Details of the experimental sites are presented in Table 5.1.

At the three sites, an experiment was conducted in a randomised complete block design with five treatments, replicated three times. The five treatments included: control (no lime); lime at 3 t/ha; lime at 6 t/ha; lime at 9 t/ha; and lime at 12 t/ha. Lime was obtained from Guder Lime Factory, Oromia, Ethiopia. Individual plot size was 3 m × 3 m. The different quantities of lime were mixed with the soil one day before planting potato. The number of plants per plot was 40 (i.e. a plant density of 44,444 plants per ha). Before treating the plots, soil samples were collected from each site and initial pH and soil texture were assessed. Changes in soil pH were monitored by collecting and analysing soil samples from each plot, on 30, 60, 90 and 120 days after treatment.

Table 5.1. Description of experimental sites

Experimental site	Location		Altitude (m)	Soil pH	Soil texture (%)		
	Latitude	Longitude			Sand	Silt	Clay
Bakaka	09°06’28.8’’N	038°28’3.1’’E	2521	5.22	50	30	20
Gaba Robi	09°07’33.8’’N	038°26’39.3’’E	2592	4.81	47.5	30	22.5
Wolmera Choke	09°06’13.2’’N	038°31’55.5’’E	2459	4.58	57.5	30	12.5

Inoculation

To examine the effect of lime on bacterial wilt incidence under different soil pH, permission was obtained from Wolmera district office of agriculture to inoculate the plots with *Ralstonia solanacearum*. Each plant in each plot was inoculated with 10 ml of a bacterial suspension (10^8 CFU/ml) of the local *Ralstonia solanacearum* strain (WA36; Phylotype II). The bacteria were cultivated on modified semi-selective media (M-SMSA) (Elphinstone et al., 1996). Isolated colony was transferred to 250 mL Erlenmeyer flasks and incubated in a rotary shaker. Dilution of bacterial suspension was performed using distilled water and the suspension was adjusted to 10^8 cfu/ml. Dilution was checked by measuring optical density (OD_{600nm}) with a spectrophotometer. The strain was sequenced in forward and reverse strands. The inoculation was carried out by drenching at the base of each potato plant (Figure 5.1). Disease development was monitored weekly and the final bacterial wilt incidence (percentage of wilted plants over

Figure 5.1. Field experiment. A) Inoculation of each plant by drenching, B) Bacterial suspension prepared for inoculation in Erlenmeyer flasks and C) Experimental plots at one of the sites (Wolmera Choke).

total number of plants per plot) was calculated 90 days after inoculation.

5.2.3. Detection and characterisation of *Ralstonia solanacearum*

Potato tuber sampling

Potato tuber samples were collected from symptomatic plants from nine major potato growing districts (the seven districts mentioned in Section 5.2.1 and two additional ones). Three tubers were taken from a selected potato plant with wilting symptoms. A total of 135 samples were collected in collaboration with an expert from Holeta Agricultural Biotechnology Research Centre and agricultural extension workers from the districts.

Isolation of Ralstonia solanacearum strains and DNA extraction

Isolation of *Ralstonia solanacearum* strains was performed at the National Agricultural Biotechnology Research Centre, Holeta, Ethiopia. Each potato tuber sample was washed with tap water and the surface was disinfected using 70% ethanol. Then, strips along the vascular ring were removed from each potato tuber, added into an extraction buffer and placed on a shaker for 15-20 min to allow the release of bacteria. Streaking a bacterial suspension was done on modified semi-selective media (M-SMSA) (Elphinstone et al., 1996) and purification of *R. solanacearum* colonies was done on tetrazolium chloride (TZC). DNA was extracted using DNeasy Blood and Tissue kit (supplied by QIAGEN).

Detection and identification of Ralstonia solanacearum

To detect and identify the bacterial isolates, a *Ralstonia solanacearum* species-specific universal primer pair (759/760) was used for polymerase chain reaction (PCR) amplification (Opina et al., 1997) at the Laboratory of Phytopathology, Wageningen University and Research, Wageningen, the Netherlands. PCR conditions were run with initial denaturation at 95 °C for 15 min, followed by 30 cycles of 94 °C for 30 s, 59 °C for 1 min, 72 °C for 1 min, and a final extension at 72 °C for 10 min. PCR products were checked through electrophoresis using agarose gel.

Phylotype identification

Phylotype identification was done following a protocol described by Prior and Fegan (2005) and Sagar et al. (2014). Multiplex PCR amplification was done using *Ralstonia solanacearum* Species Complex (RSSC) specific universal primer and phylotype-specific primers (Table 5.2). PCR reactions cycling conditions were initial denaturation during 9 min at 96°C; 30 cycles of 1 min at 95°C, 1 min at 70°C, 2 min at 72°C, and final extension of 10 min at 72°C. Examination of PCR products was conducted by electrophoresis using 1% agarose gel, stained with ethidium bromide. A known Phylotype I strain (PD 7123), *Ralstonia pseudosolanacearum*, was used as a positive control. This representative strain was obtained from the National Plant Protection Organisation (NPPO) of the Netherlands.

Table 5.2. List of primers used for multiplex PCR

Primer	Primer Sequence (5' to 3')	Specificity	Amplicon size (bp)	Reference
759F	GTCGCCGTCAACTCACTTTCC	Universal *R. solanacearum* specific primer	280	Opina et al., 1997
760R	GTCGCCGTCAGCAATGCGGAATCG		Reverse	
Nmult21:1F	CGTTGATGAGGCGCGCAATTT	Phylotype I	144	Fegan and Prior, 2005
Nmult21:2F	AAGTTATGGACGGTGGAAGTC	Phylotype II	372	
Nmult23:AF	ATTACSAGAGCAATCGAAAGATT	Phylotype III	91	
Nmult22:InF	ATTGCCAAGACGAGAGAAGTA	Phylotype IV	213	
Nmult22:RR	TCGCTTGACCCTATAACGAGTA	All phylotypes	Reverse	

5.2.4. Data analysis

A correlation analysis was conducted to evaluate the relationship between pH and incidence of bacteria wilt in potato fields (%). A scatter plot graph was constructed using ggplot2 R package.

In order to assess how lime affected the soil pH linear regression analysis was performed using the R statistical package (version 3.6.1). Similarly, to determine the effect of lime application on bacterial wilt incidence, linear regression analysis was done. Furthermore, multiple comparisons of the means were performed using the least significant difference method (LSD) after analysis of variance (ANOVA). Graphs were drawn using ggplot2 package of R.

5.3. Results

5.3.1. Soil acidity status in potato fields

We analysed the proportion of soil pH ranges in potato fields. The pH value in the sampled potato fields ranged from 4.40 to 5.94. The highest proportion (50%) of the potato fields was very strongly acidic (pH 4.5-5.0), followed by strongly acidic (pH 5.1-5.5; 30%) as indicated in Figure 5. 2. Only 11% of the fields were moderately acidic (pH 5.6 – 6.0), 9% was extremely acidic (3.5-4.4) and none was neutral or alkaline. These findings show wide prevalence of soil acidification in potato fields.

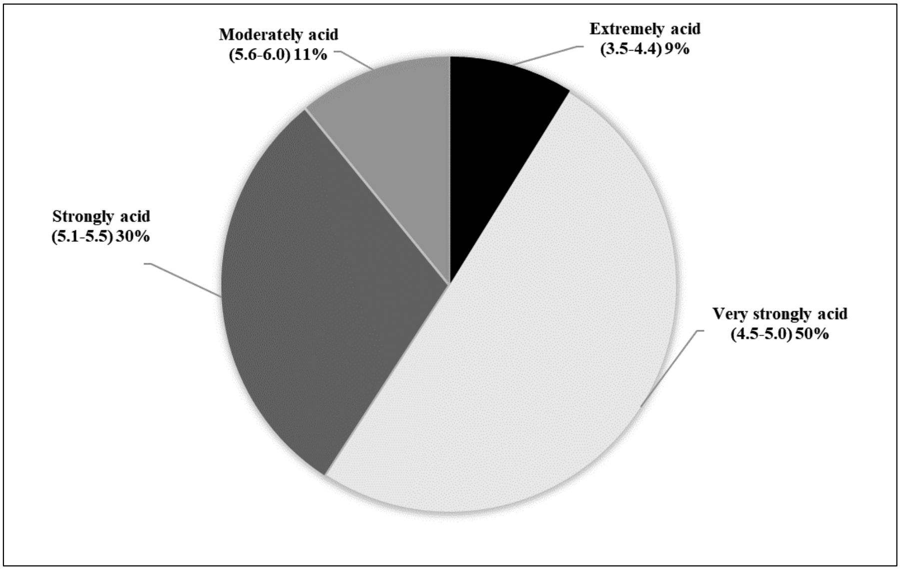

Figure 5.2. Proportion of soil pH ranges in sampled potato fields (n=147).

5.3.2. Correlation between soil acidity and bacterial wilt incidence

The incidence of bacterial wilt in seed and ware potato fields in the central highlands of the country ranged from 0.0 to 19.7%. As indicated in Figure 5.3, we found a negative correlation between soil pH and bacterial wilt incidence (R = -0.27, p = 9e-04).

5.3.3. Effect of lime on soil pH value

The application of lime significantly affected soil pH: the more lime was applied, the higher the pH value of the soil became (Figure 5.4). The regression analysis showed that the factors time and location were not significant in accounting for variation in pH (data not shown).

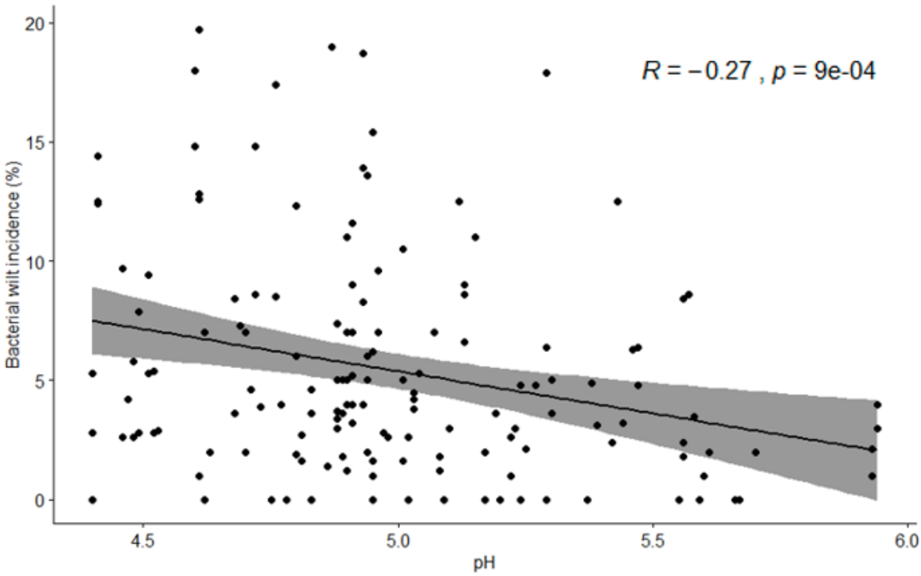

Figure 5.3. Correlation between soil acidity and bacterial wilt incidence in different potato fields. Each point indicates an observation of soil pH and bacterial wilt incidence on a different potato field.

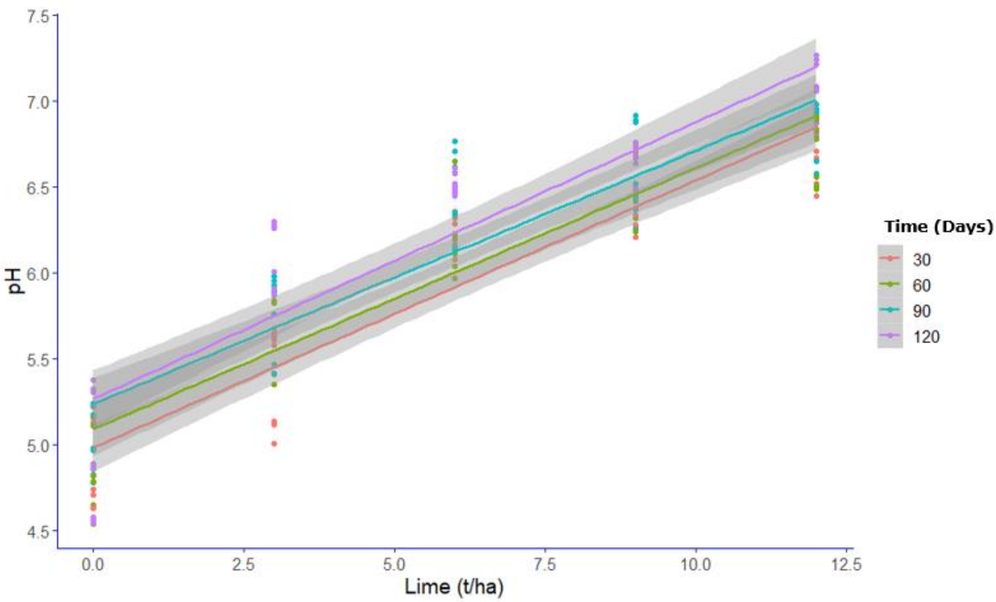

Figure 5.4. Linear regression curves showing highly significant positive relationships between soil pH and lime application for different dates of measurement (R = 0.93, p < 2.2e-16 after 30 days, R = 0.91, p < 2.2e-16 after 60, 90 and 120 days).

5.3.4. Effect of lime on bacterial wilt incidence

Bacterial wilt incidence was explained significantly by lime application rate. Separate linear regression analysis considering bacterial wilt incidence as dependent variable, and lime rate as independent variable is depicted in Figure 5.5. The bacterial wilt incidence was reduced by an increase in lime application rate. This effect was stronger when the assessment was done later, because the increase of bacterial wilt incidence over time was stronger at lower rates of lime application (data not shown). Location was not significant in explaining the variation in the incidence of bacterial wilt. Bacterial wilt incidence on average was 10.8% under 12 t/ha lime application while it was about 40% in control plots (without lime) after 90 days of inoculation. Furthermore, analysis of variance followed by mean separation indicated there was no statistically significant variation between the lime application rates of 12 t/ha and 9 t/ha. But there was significant variation between the lime application rate of 6 t/ha and 3 t/ha (Table 5.3).

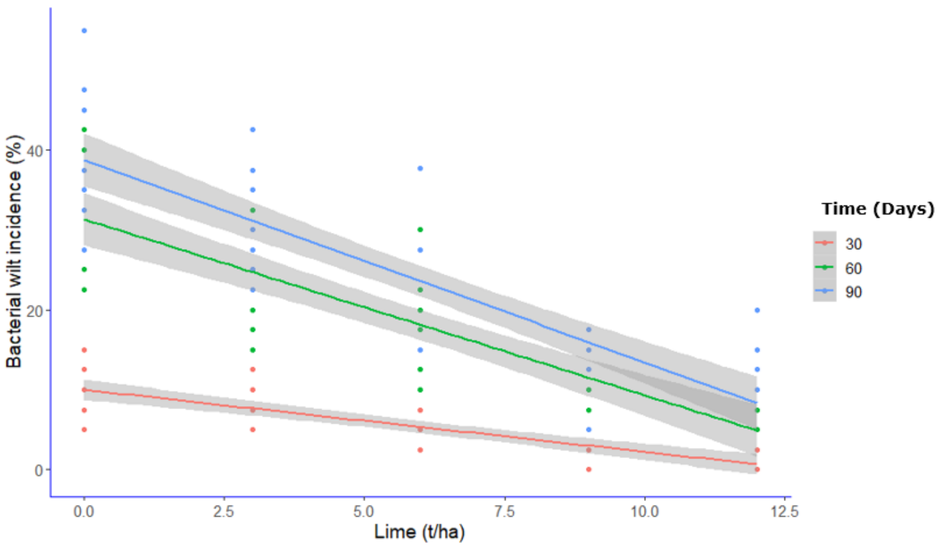

Figure 5.5. Linear regression curves showing highly significant negative relationships between bacterial wilt incidence and lime application for three dates of disease observation after inoculation (R = -0.80, p = 2.8e-11 for time after 30 days; R = -0.84, p = 8.8e-13 for time after 60 days; R = -0.87, p = 1.74e-14 for time after 90 days).

Table 5.3. Effects of different rates lime on bacterial wilt incidence

Lime treatments	Bacterial wilt incidence after 90 days
Control	39.4 ± 8.46a
3 t/ha	31.4 ± 6.26b
6 t/ha	23.6 ± 7.24c
9 t/ha	12.5 ± 3.95d
12 t/ha	10.8 ± 4.33d

Note: Value in the same column followed by the same letter do not differ significantly ($p< 0.05$). The values are averaged over the three locations.

5.3.5. Phylotype identification of *Ralstonia solanacearum* isolates

Bacterial isolates collected from the various potato fields were confirmed to be *Ralstonia solanacearum* by PCR amplification using the *Ralstonia* species complex (RSSC) universal primer pair (759/760). PCR amplification yielded a single 280-bp fragment. All *Ralstonia solanacearum* isolates that gave a positive PCR reaction using the universal primer pair (759/760) were identified as Phylotype II using multiplex PCR based the amplicon size (Figure 5.6).

5.4. Discussion

5.4.1. Extent of soil acidity in major potato growing areas

The results of this study show that the extent of soil acidity in potato fields in the central highlands of Ethiopia is worrisome (Figure 5.2). All investigated potato fields had low soil pH values. The findings observed in this study mirror those of previous assessments that have indicated the pervasiveness of soil acidity in arable lands in Ethiopia (Agegnehu et al., 2019; ATA, 2014; Haile et al., 2017). The high soil acidity could be due to improper use of acid-forming fertilisers and soil erosion or leaching that washes away the basic cations calcium, magnesium, sodium, and potassium (Abebe, 2007; Brady and Weil, 2008). When basic cations are leached or washed away by soil erosion, acidic cations (hydrogen and aluminium) replaces them, causing soil acidity (Brady and Weil, 2008; Fageria and Baligar, 2008; Fageria and Nascente, 2014).

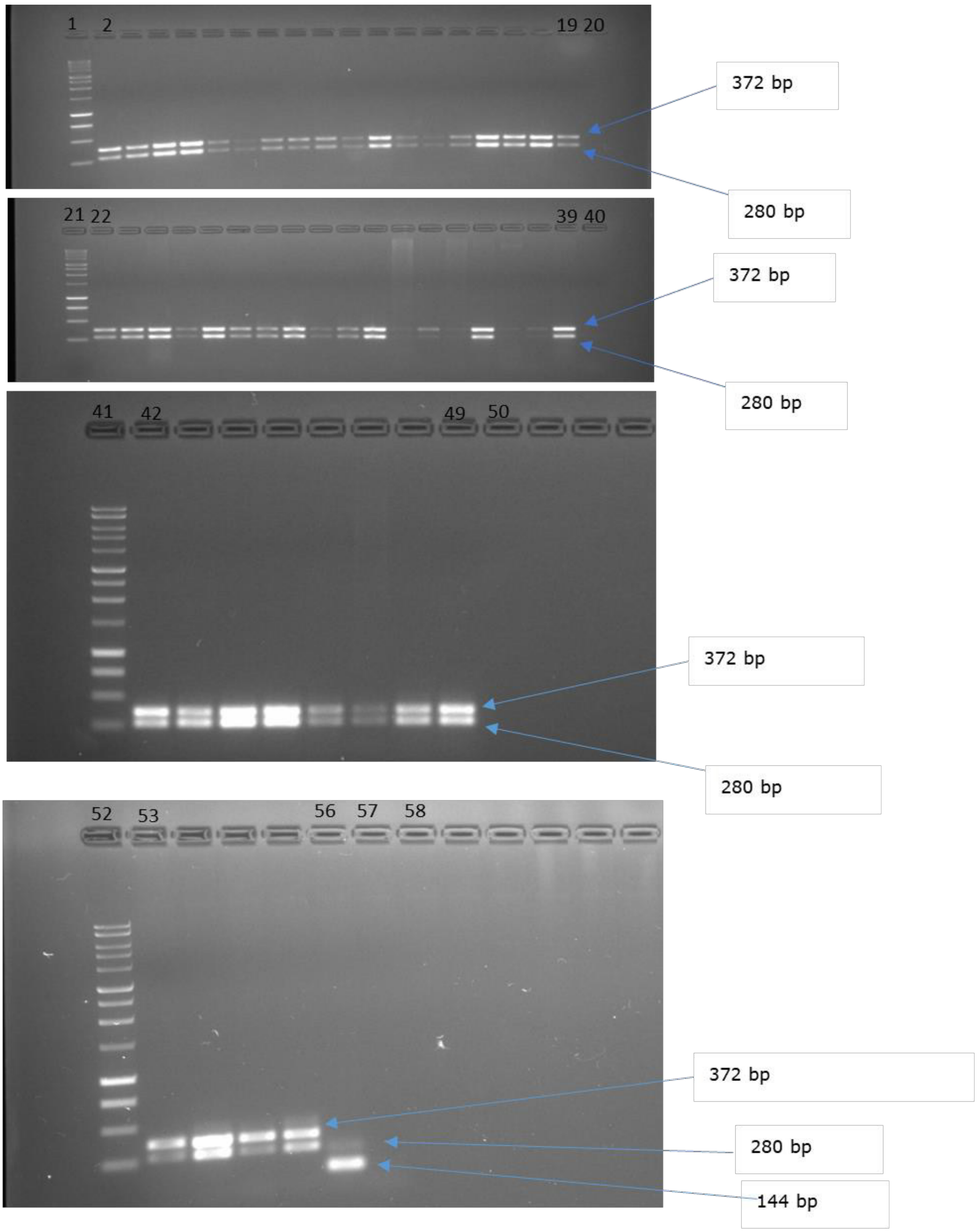

Figure 5.6. Detection and identification of *Ralstonia solanacearum* strains. Lanes 1, 21, 51, 52 molecular marker (100 bp); Lanes 20, 40, 50 and 58 negative control; Lanes 2-19, 22-39, 42-49 and 53-56 isolates of this study; Lane 57 Phylotype 1 (PD 7123) positive control).

5.4.2. Association between soil acidity and bacterial wilt incidence

This study has shown a negative correlation between bacterial wilt incidence and the level of soil pH (Figure 5.3). Highly acidic potato fields had a higher incidence of bacterial wilt in most samples. The occurrence of bacterial wilt depends on various conditions, such as whether the seed is infected or not. It can also depend on whether the pathogen previously infested the crop field or not. In addition to these and other risk factors, potato fields with lower pH values seem to have a higher incidence of the disease (higher number of wilted plants per field) than those with relatively higher soil pH values. A previous study conducted to investigate the epidemiology of the disease in the Ethiopian potato production system showed that the incidence of the disease reached an epidemic level in some districts such as Chencha (Abdurahman et al., 2017). This study indicated that bacterial wilt prevalence was about 97% whereas disease incidence reached more than 96% in some potato fields in this district. Another recent study indicates that this district receives high rainfall (Minda et al., 2018), which could be one of the leading causes of soil acidification by leaching basic cations. Furthermore, a recent soil acidity map (Figure 5.7) developed by the Ethiopian Agricultural Transformation Agency shows that the soil acidity problem is rampant in arable lands of the Chencha district (ATA, 2014).

Likewise, in the Amhara region, one of the major potato growing areas that have been severely affected by bacterial wilt, soil acidity is also a serious problem. For instance, a soil pH map indicated in Figure 5.7 for Guagusa Shikudad, one of the potato growing districts in the region, shows that most of the district is strongly acidic (ATA, 2014). Furthermore, the previous study has reported a severe incidence of bacterial wilt in this district (Bekele et al., 2015).

A key reason why bacterial wilt incidence is more severe in some potato fields than in other ones thus might be the soil acidity status of the potato fields. Moreover, across different parts of the country the current serious incidence of the disease seems to be intensified by the wide spread of soil acidification in high rainfall areas in the country. Overall, it looks like bacterial wilt problem is severe in areas affected most by soil acidity in the country.

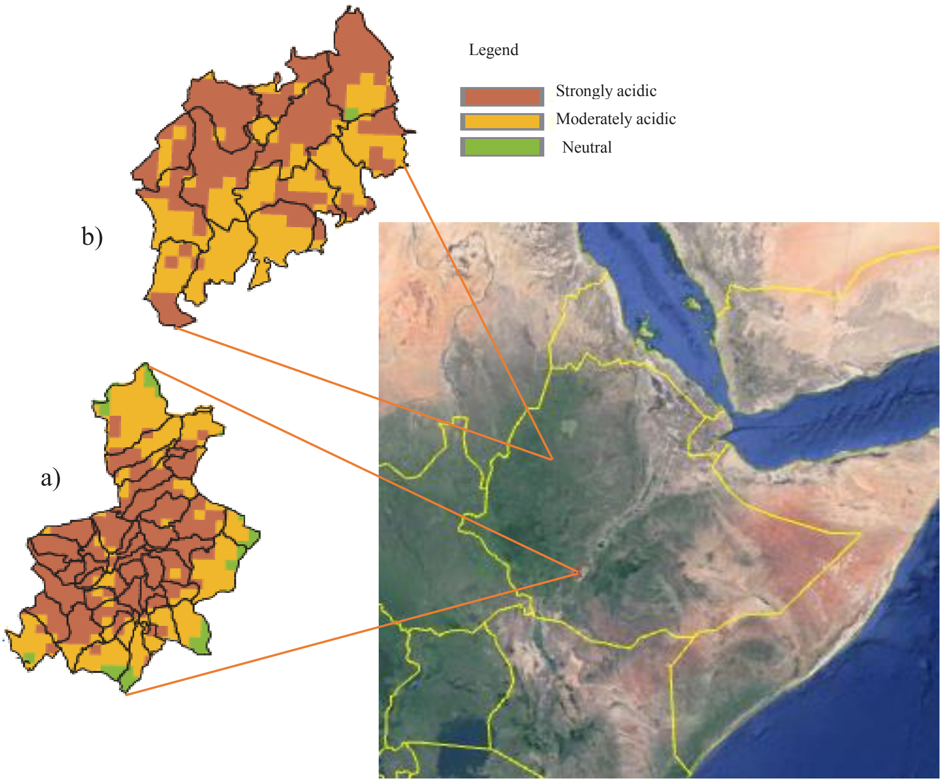

Figure 5.7. Map of soil pH for a) Chencha district (SNNP regional state, Ethiopia), and b) Guagusa Shikudad district (Amhara Regional State, Ethiopia). Reproduced with kind permission by Ethiopian Agricultural Transformation Agency (ATA, 2014).

5.4.3. Liming reduces bacterial wilt incidence

The field experiments showed that application of lime at different rates significantly increased soil pH (Figure 5.4). The highest change in soil pH was observed under 12 t/ha of lime (Figure 5.4). Our results confirm other studies showing that liming is an effective and common practice to ameliorate soil acidity (Brady and Weil, 2016; Opala et al., 2018; Rengel, 2011). Lime has immediate and residual effects on soil acidity. Due to low solubility of lime in water, its residual effects can last for years (Costa et al., 2016; Kisinyo et al., 2014; Rengel, 2011). Unlike fertilisers, lime application should not be done every year since its benefits persist for more than five years (Lukin and Epplin, 2003).

The findings of this study show that liming reduced bacterial wilt incidence under all rates of lime application (Figure 5.5 and Table 5.3). Bacterial wilt incidence was only 10% under 12 t/ha, compared to about 40% under the unlimed plot (Table 5.3). Since *Ralstonia solanacearum* is (also) a soil-borne pathogen, soil chemical and biological properties affect its growth and development. This result is in line with the findings of recent studies. Li et al. (2017) reported that *Ralstonia solanacearum* can survive well under acidic soil conditions. Furthermore, this study has shown that the growth of the antagonistic bacteria *Pseudomonas fluorescens* and *Bacillus cereus* are suppressed under acidic soil conditions. These findings align with the many studies that have shown that soil pH is one of the key factors determining the composition of the soil microbial community (Högberg et al., 2007; Rousk et al., 2010; Wange et al., 2017).

Potato is an acid tolerant crop and grows well under acidic soil conditions (pH 4.5-6.0). Hence, farmers in the highly acidic highlands of Ethiopia can expand potato production as it is a good alternative to cereals, which are sensitive to acidic soil conditions. However, if bacterial wilt is not controlled well, acidic conditions can intensify disease incidence, resulting in considerable yield loss. Therefore, dealing with soil acidity could help reduce the impact of the disease in areas affected by soil acidification and sustain potato production.

5.4.4. Detection and characterisation of *Ralstonia solanacearum* strains

The results of this study revealed low genetic diversity among *R. solanacearum* strains affecting potato in Ethiopia. All strains belonged to Phylotype II (Figure 5.6). This finding confirms previous studies that reported *Ralstonia solanacearum* strains isolated from potato as Phylotype II (Abdurahman et al., 2017; Lemessa and Zeller, 2007). Furthermore, many studies conducted in East African countries reported *Ralstonia solanacearum* isolated from potato mainly as Phylotype II (Abdurahman et al., 2019; Fouché-Weich et al., 2006). But, according to the previous classification of *R. solanacearum* species complex, Phylotype II is composed of strains mainly from America (Prior and Fegan, 2005). Phylotype II strains are maintained to be *R. solanacearum* by the recent work that has revised the taxonomy of the *R. solanacearum* species complex (Safni et al. 2014). Studies show that Phylotype II strains are cold tolerant (Cellier and Prior, 2010; Milling et al., 2009). The wide occurrence of this phylotype in a warm climate in Ethiopia and in other East African countries shows the adaptability of the pathogen to various environmental conditions and its ability to cause damage worldwide. Moreover, these findings show that similar strains of *Ralstonia solanacearum* spread in the country and the East

African region threatening the potato industry.

This finding confirms the wide spread of the disease across different regions in Ethiopia. Abdurahman et al. (2017) suggested that this spread was caused by uncontrolled movement of latently infected seed tubers. Large NGOs and government offices of agriculture usually purchase and distribute seed potato without knowing whether the seed is infected or not, because they do not have reliable means to check seed health. This calls for strengthening the capacity of seed potato cooperatives to become effectively involved in quality declared seed production through a robust monitoring system (Tafesse et al., 2020). Developing quarantine systems could also foster efforts to control the disease in the country's smallholder potato production. Particularly, regional level quarantine stations are needed to limit further spreading of the disease through the distribution of infected seed potatoes.

5.5 Conclusion

The Phylotype II of the pathogen *Ralstonia solanacearum* has widely spread throughout Ethiopia, probably because it can adopt to diverse environmental conditions. The findings of this study show the association between the occurrence of bacterial wilt across major potato growing areas in Ethiopia and soil acidification. Improvement of soil acidity by lime may significantly reduce the incidence of the disease. While soil acidity by itself is a serious constraint to potato production due to its effect on the availability of plant nutrients, although potato is relatively acid-tolerant, it also affects the productivity by enhancing the incidence of bacterial wilt. Hence, ameliorating soil acidity urgently requires attention from various actors in the country's potato production system. Because dealing with soil acidity is a prerequisite for effective management of bacterial wilt. Integrating the application of lime as part of the existing extension services to manage bacterial wilt could benefit potato farmers. Future studies need to explore further how lime application affects the population of *Ralstonia solanacearum* and the diversity of soil microbial population in acidic soils over the years.

Chapter 6

Learning to control bacterial wilt in smallholder potato production: a complex socio-ecological problem

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Abstract

Effective control of crop diseases is a key precondition for sustainable crop production and to improve food security globally. In Ethiopia, potato production has substantially expanded and benefited millions of smallholder farmers over the past three decades. However, bacterial wilt disease has recently become a devastating threat to the country's potato industry. In addition to potato, this disease affects more than 200 plant species, including many food crops. A community-based learning intervention was designed and facilitated in two villages of the central highlands of Ethiopia, involving both seed and ware potato farmers. This intervention was evaluated to understand how farmers learned about the disease and its management from experiential and social learning theories' point of view. Data were derived from face-to-face in-depth interviews, reflective workshops, and participant observations. The findings show that farmers acquired new knowledge on bacterial wilt disease dynamics and management methods. Farmers indicated that they recognised and became vigilant about disease incidence and confident about the pathogen that causes the disease, its spreading mechanisms, host plants, and disease diagnosis. Learning about the cause of the disease stimulated the identification of locally relevant spreading mechanisms and the feasibility of a range of recommended disease management methods. Moreover, farmers recognised their interdependency, their role and responsibility to cooperate to reduce the disease pressure in their community. We conclude that learning interventions aiming to improve smallholder farmers' capacity to deal with complex crop diseases need to combine experiential and social learning approaches and consider farmers' local knowledge.

Keywords: Experiential learning; Social learning; Bacterial wilt; Disease control; Complex problem, Collective action

6.1. Introduction

Crop diseases are major biotic threats to global food security, exacerbating food supply deficit by reducing the quality and yield of crop production (Savary et al., 2019; Strange and Scott, 2005). Effective management of crop diseases has, therefore, significant implications for sustainable crop production and food security. If the yield loss caused by various crop diseases could be minimized, the availability of food would be improved for millions of people who currently lack sufficient food. Notably, in sub-Saharan African countries where yield loss due to crop diseases is much higher than the rest of the world (Savary et al., 2019; Tadele, 2017), smallholder farmers would benefit most from effective disease management. Crop disease management in smallholder farmers' context has received considerable attention over the last decades, but yield loss due to the impact of various types of crop diseases has continued to be a significant hindrance to crop production (Roopa and Gadag, 2019).

Potato (*Solanum tuberosum* L.) is one of the most important food crops produced worldwide (Devaux et al., 2014; FAO, 2008). This crop is affected by various types of infectious diseases caused by bacterial, fungal, oomycete, and viral pathogens (Stevenson et al., 2001). Bacterial wilt, prevalent in potato production systems in many parts of the world, is the most difficult potato disease to manage (Elphinstone et al., 2005; Yuliar et al., 2015). Its management is difficult mainly due to the nature of the pathogen responsible for the disease, *Ralstonia solanacearum*. This pathogen has diverse spreading mechanisms and infects more than 200 plant species, including many food crops such as tomato, eggplant and pepper (Elphinstone et al., 2005; Genin, 2010; Hayward, 1991). Since there is no single effective control method for bacterial wilt, several studies have shown the importance of integrating different management methods (Allen et al., 2005; Elphinstone, 2005; Lemaga et al., 2005; Yuliar et al., 2015). The integration of farm sanitation and cultural practices such as crop rotation, roguing infected plants, use of disease-free seeds, and decontamination of farming tools have been recommended as plausible approaches to control the disease in smallholder farmers' context (Elphinstone and Aley, 1993; Lemaga et al., 2005; Lemaga et al., 2001; Yuliar et al., 2015).

In Ethiopia, potato production has been widely promoted as a strategic crop for food security. Currently, more than 3.7 million smallholder farmers grow potato for food and income generation. The country has faced a dramatic expansion of potato bacterial wilt in the past few years (CIP, 2016; Gorfu et al., 2013). Following the expansion of potato production in the country, the disease has spread aggressively, posing a threat to the country's ware and seed potato production systems (Abdurahman et al., 2017; CIP, 2016; Gorfu et al., 2013). It is currently causing a significant reduction in potato yield in many districts, affecting the income and food security of millions of potato farmers (Abdurahman et al., 2017; CIP, 2016; Gorfu et al., 2013). Despite the detrimental effect of the disease in the country, so far, only limited research and extension efforts have been made to tackle it.

Limited knowledge of farmers and extension workers on various aspects of the disease and its management methods, coupled with a weak extension system, have been identified as major constraints to effective disease management (CIP, 2016; Gorfu et al., 2013; Tafesse et al., 2018). Most of the farmers recognise only the importance of rogueing infected potato plants as an effective management method without understanding the diverse technical and social dimensions of the disease and its management methods. In this regard, many farmers simply rogue an infected plant and throw it away at the farm side, which appears to facilitate the spreading of the disease instead of controlling it (Tafesse et al., 2018).

Many studies have underscored the importance of a community-based approach to control potato bacterial wilt effectively. Since the disease is contagious and a collective risk problem, a concerted effort among farmers is required (Lemaga et al., 2005; Tadesse et al., 2019; Van de Fliert, 1993; Van der Plank, 2013; Yuliar et al., 2015). To this end, the farmers need to recognise their interdependency, which is currently not the case (Damtew et al., 2018). They also need to have a good understanding of the causal agent, symptoms, spreading mechanisms, and management methods of the disease (Tafesse et al., 2018). This may not be realized without meaningful learning. In the Ethiopian potato production system, previous efforts towards enhancing farmers' capacity have been primarily concentrated on promoting technical solutions through training targeting seed potato farmers. The key actors in the system tend to overlook the social dimensions of the problem (CIP, 2016; Damtew et al., 2018). Ethiopian agricultural extension is hierarchical and follows primarily linear approaches for knowledge and technology transfer (Damtew et al., 2018: Spielman et al., 2011).

Such conventional approaches oversimplify the complex and non-linear learning processes and have been strongly criticized by several scholars (Leeuwis, 2004; van Mierlo et al., 2010; Spielman et al., 2011). Scholars of agricultural extension, knowledge systems, socio-ecological systems, and innovation systems emphasize the importance of learning collectively instead (Colding and Barthel, 2019; Leeuwis, 2004; Pahl-Wostl, 2006; van Mierlo et al., 2010). Learning linked to innovation is regarded as an interactive process (van Mierlo et al., 2010). Several learning approaches for searching solutions for complex agricultural problems have been proposed and discussed in the literature (Leeuwis and Pyburn, 2002; Röling and Wagemakers, 1998; van Mierlo and Beers, 2018). In this literature, an innovation systems approach is suggested for sustainable crop protection in which farmers are considered as partners in the innovation process, instead of adopters of knowledge and technologies. In line with this view, learning interventions to foster social and technical innovations that fit the local context need to acknowledge and integrate farmers' local knowledge to be effective and sustainable.

Experiential learning is a prominent learning approach that has been widely applied in integrated management of crop pests and natural resources (Percy, 2005; Pincus et al., 2018). Using experiential learning as an underpinning theoretical perspective, the farmer field school (FFS) approach has been implemented in many developing countries. It has been shown that this approach has positive impacts on crop pest management, agricultural productivity, and income of smallholder farmers (Davis et al., 2012; Ortiz et al., 2004; Ortiz et al., 2019; Palis, 2006). But since experiential learning largely focuses on learning through concrete experience when a learner interacts with a phenomenon or the environment, it is usually criticized for neglecting the social processes required to solve collective action problems (Fenwick, 2000; Michelson, 1999; Roberts, 2006; Seaman, 2008).

As crop disease management has complex social and ecological dimensions, experiential learning of individual farmers alone can, therefore, not be sufficient to enable learning of all aspects of the disease and innovations to address it (Leeuwis, 2004). Learning among groups of interdependent farmers is also needed for effective coordination of collective action (Leeuwis, 2004). Hence, experiential learning needs to be combined with learning techniques that foster interactions to develop shared meanings that serve as a basis for collective action.
For collective management of complex socio-ecological problems, the concept of social learning has become increasingly important (Keen et al., 2005; Leeuwis, 2004; Leeuwis et al., 2002; van Mierlo and Beers, 2018). In social learning, interdependent actors interact, learn together, and reach consensus to deal with joint complex problems collectively. Besides, social

learning enables reflection of diverse views, instigates new relationships, and fosters the development of trust among different actors (Keen et al., 2005; Leeuwis et al., 2002; Reed et al., 2010).

To effectively manage potato bacterial wilt, seed and ware potato farmers need to have a good understanding of various aspects of the disease and its management methods. It is also essential to build new relationships and act collectively. To this end, a learning approach that combines elements of experiential and social learning can foster effective control of the disease. This study was, therefore, conducted to show how the integration of experiential and social learning approaches could stimulate learning to control complex crop diseases such as bacterial wilt in smallholder farmers' context.

The structure of the remaining parts of the article proceeds as follows: Section 6.2 describes the concepts of experiential and social learning and explicates how changes in reasons for action are used as evidence of learning. This leads to the conceptual framework of this study. Section 6.3 describes the research methodology, including study setting, learning intervention, data collection, and analysis. Section 6.4 and Section 6.5 present the results of the study and discussions of the findings, respectively. Finally, the conclusion is provided in Section 6.6.

6.2. Conceptual framework

This section discusses the theoretical foundations of the study and describes how the concepts of experiential and social learning are combined and operationalized for designing a learning intervention on the management of potato bacterial wilt. Further, this section explains the concept of learning and changes in reasons for action as areas of learning.

6.2.1. Experiential learning

Experiential learning theory is commonly defined as a process in which learning is embedded in a learner's experience (Kolb, 1984). Several scholars have described the relationship between experience and learning. For instance, according to Kolb (1984), the experience is transformed to create knowledge through a learning process. A similar perspective is also held by Boud et al. (1985), who explicates experience as a source of learning. In experiential learning, a learner is actively involved in making a choice and applies the knowledge gained from experience (Beard and Wilson, 2006; Kolb, 2015). In the literature, experiential learning is broadly characterised in two ways: the process of experiential learning, and how the process can be supported for experiential learning to happen (Beard and Wilson, 2006; Kolb, 2015).

Kolb (1984) describes the experiential learning process as a learning cycle with four phases that represent the order in which learning takes place: 1) concrete experience, 2) reflective observation, 3) abstract conceptualization, and 4) active experimentation. Concrete experience is considered as a starting point for experiential learning to take place. Various methods have been described in the literature to support each learning stage of the experiential learning cycle. The methods include direct experience, field trips, demonstrations, dramatic participation (role plays), visual symbols, pictures, recordings, information and communication technologies, and exhibits (Kolb, 2015; Lie and Witteveen, 2018; Roberts, 2006). Leeuwis (2004) expands how extension workers can support farmers to be able to go through the learning cycle. Among others, concrete experiences can be supported by visualizing a phenomenon, while reflective observation can be supported by facilitating discussions. Likewise, abstract conceptualization and experimentation can be supported by crafting a pattern and organising an experiment, respectively (Leeuwis, 2004).

In rural settings, many scholars consider experiential learning as a pertinent feature of learning approaches to enhance farmers' capacity to effectively deal with various complex farming problems (Leeuwis, 2004; Percy, 2005; Pincus et al., 2018; Roberts, 2006). Consequently, experiential learning has been widely applied as a theoretical basis for communication for innovative interventions in the context of adult learning (Leeuwis, 2004; Roberts, 2006). For instance, the theoretical perspective underlies farmer field schools (FFS), an approach that focuses on discovery learning to support farmers to become better decision-makers (Nederlof and Odonkor, 2006; Ortiz et al., 2019). Over the last decades, FFS has been widely promoted in rural settings in many developing countries (Ortiz et al., 2004; Palis, 2006). Despite this extensive application, experiential learning has also been criticized. It is a model that explains how individuals learn, and it does not consider social processes (Roberts, 2006; Seaman, 2008) which are critical to deal with complex problems that require collective agreement among interdependent actors for concerted action (Leeuwis and Pyburn, 2002; Pahl-Wostl, 2006).

6.2.2. Social learning

Social learning is a widespread concept in the literature on the management of natural resources

(Noguera-Mendez et al., 2016; Rodela, 2013; van Mierlo and Beers, 2018). It has predominantly been described in multi-stakeholder processes for the development of joint actions. The literature shows that social learning occurs when interdependent actors come together and interact in facilitated meetings or workshops (Beers et al., 2016; Pahl-Wostl, 2006; Reed et al., 2010). Hence, mutual dependence for effective natural resource management is a key precondition for social learning to take place. The interaction among diverse actors can be regarded as the input of social learning (Beers et al., 2016). Furthermore, similar to the case of experiential learning, social learning benefits from deliberate facilitation. During the facilitation process, learning can be stimulated through interactive approaches like role plays (Leeuwis and Pyburn, 2002; Pahl-Wostl et al., 2007).

A collective agreement among the actors as a way to go or as a solution for complex socio-ecological problems is considered an outcome of social learning. In this regard, scholars distinguish two types of social learning outcomes: cognitive and relational. The cognitive outcome refers to new knowledge and solutions for the common problem. The relational outcome includes the development of trust and recognition of the interdependency among the actors (Beers et al., 2016; Keen et al., 2005). The learning outcomes serve as a basis for collective action (Keen et al., 2005; Leeuwis and Pyburn, 2002). Collective action among interdependent actors is, therefore, imperative since individuals cannot have all the answers to deal with complex problems (Pahl-Wostl et al., 2007). Several studies show that social learning enables negotiations and fosters development of new institutions required to guide the relationships among the actors with different perspectives and their roles (Colding and Barthel, 2019; Pahl-Wostl, 2006; Pahl-Wostl et al., 2008). This perspective is also relevant to the management of potato bacterial wilt; an effort of an individual farmer alone cannot be effective unless other farmers in the same community make concerted efforts.

6.2.3. A framework for learning interventions and learning evidence

From a learning process point of view, learning can well be studied from both an experiential and a social learning point of view, as explained above. Evidence for learning tends to be only considered as a change in an individual's or group's knowledge and understanding in relation to the social, economic, biophysical and technical aspects. This narrow perspective focuses only on the cognitive elements of learning (Leeuwis, 2004; van Mierlo et al., 2010). According to Leeuwis (2004), learning includes diverse social drivers and the relationships between understanding and action. Hence, what people do and do not do is influenced not only by their knowledge (perception of reality) and their capacities, but by their perceptions regarding social pressure, aspirations, trust, and roles and responsibilities as well. Evidence of learning, therefore, can be broadly defined as a change in any of these perceptions (Leeuwis, 2004).

Based on the above perspective, we developed a conceptual framework for this study as portrayed in Figure 6.1. Experiential learning is mainly seen to occur when farmers' knowledge about diverse technical aspects of bacterial wilt is changed, when farmers experiment disease management methods, and when they are able to identify local conditions that contribute to disease spread, and the feasibility of different management methods of the disease in their context. Social learning may also contribute to these learning outcomes (indicated by the broken line in Figure 6.1). On the other hand, social learning is mainly seen to take place when farmers recognise their interdependency, when collective goals or solutions are defined, and when the relationships among seed and ware potato farmers are changed as well as their perceptions on social pressure, trust in their social environment, and their roles and responsibilities. Experiential learning can also contribute to social learning outcomes (indicated by the broken line in Figure 6.1). Changes in reasons for action are taken as evidence of experiential and social learning processes. They are essential conditions for the effective management of potato bacterial wilt.

6.2.4. Research questions

This study was conducted to answer the following research questions:

1. How does a learning intervention with a combination of experiential and social learning approaches influence farmers' reasons for action regarding bacterial wilt disease dynamics and its management?
2. What is the implication of combining experiential and social learning approaches for effective control of complex crop diseases?

6.3. Research methodology

This section describes the study context and the methodology employed for data collection and analysis.

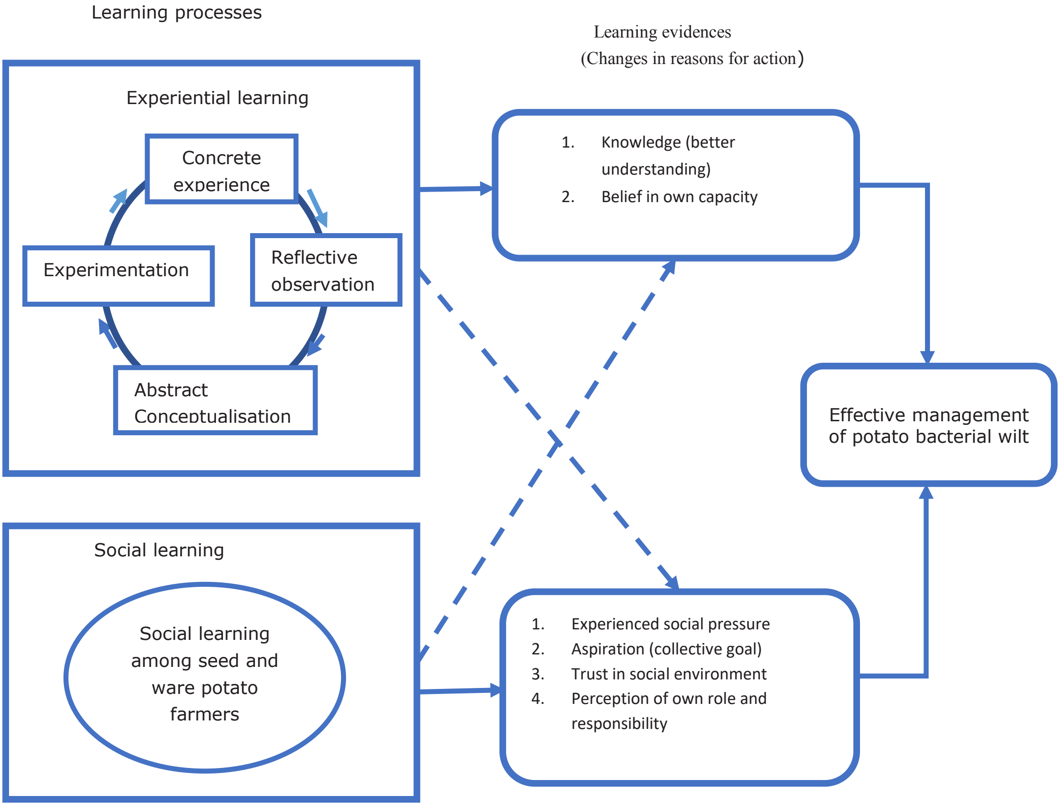

Figure 6.1. Conceptual framework developed for this study.

6.3.1. Description of study settings

Two villages, Agota and Wanjala, with different socio-ecological conditions were selected from Wolmera and Doyogena districts, respectively. The two districts are located about 300 kilometres apart. They are among the major potato growing districts in the central highlands of Ethiopia, where the problem of bacterial wilt is prevalent. The two districts were selected because of (1) high prevalence of bacterial wilt in the areas, (2) limited farmers' knowledge of bacterial wilt and its management methods, and (3) presence of seed and ware potato growers. Also, the two districts provide contrasting disease management challenges and opportunities due to their differences in farming systems and socio-ecological conditions. Wolmera district has a cereal-based farming system, while Doyogena district has an enset-based (*Ensete ventricosum*) farming system. Moreover, farmers in Wolmera district own relatively larger potato fields than the farmers in Doyogena district.

The study focuses on both seed and ware potato producers because both should be involved in concerted efforts for disease management. The farmers in Wanjala village are quality declared seed (QDS) producers and ware potato producers whereas the farmers in Agota village are regular seed producers and ware potato producers. Quality declared seed producers are members of a registered cooperative and conform to more strict seed quality standards. Regular seed producers are also members of a registered seed cooperative, but seed quality standards are less stringent. Concerning bacterial wilt infection, QDS producers need to meet a zero-tolerance level, whereas it is usually acceptable for normal seed producers as long as they remove infected potato plants from potato fields. In both villages, the farmers were organised to involve in a community-based approach for the learning intervention. Overall, 36 (29 males, seven females) and 25 (21 males, four females) farmers participated in the learning intervention from Agota and Wanjala villages, respectively. The farmers of these villages grow potatoes both in *Meher* (main rainy season) and in *Belg* (short rainy season).

6.3.2. Learning intervention

This learning intervention was informed by the previous study that has examined farmers' knowledge and practices of potato bacterial wilt management in the study areas (Tafesse et al., 2018). Moreover, the learning intervention was designed to be interactive and to acknowledge farmers' local knowledge and integrate it with the provided knowledge built on scientific insights. We designed and facilitated a learning intervention based on experiential and social learning theories. In both villages, a season-long community-based learning intervention was implemented from May to November 2018, during the main potato growing season (*Meher*). The farmers who participated in the learning intervention were selected voluntarily in consultation with the respective district offices of agriculture and extension workers. The learning intervention was conducted in both villages using a manual prepared to facilitate the learning process. We developed the content of the manual based on the gaps identified by the previous study and the literature on potato bacterial wilt management. The major learning sessions include various aspects of potato bacterial wilt disease dynamics and its management methods through concerted efforts in a community-based approach, as indicated in Figure 6.2.

The learning sessions were structured to address all aspects of the disease dynamics and what it takes to manage the disease in the farmers' local context effectively. In line with experiential learning theory, to stimulate this type of learning, there were many hands-on activities for

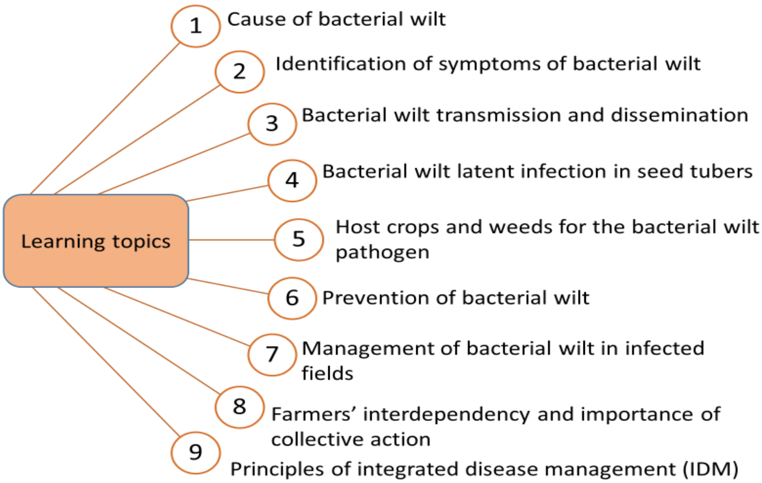

Figure 6.2. Learning topics introduced in the community-based learning intervention.

farmers to gain new experiences and reflect on them in the light of their actions and results. Similarly, to enable social learning, reflective meetings were facilitated in which participant farmers performed role-plays and interacted with each other to recognise their interdependency and the importance of collective action to manage the disease.

Nine learning sessions were conducted; each of them lasted between two and four hours. Furthermore, there was a demonstration field (about 0.5 ha) owned by the participating farmers where they interacted and jointly implemented various types of bacterial wilt management methods. The group learning sessions also included theoretical discussions supported by colour pictures and videos, practical field works, dynamic sessions, and role-plays in which the participating farmers performed and interacted to reinforce the topics of learnings. Furthermore, a reflective workshop was conducted to enable the farmers to reflect on what and how they learned various aspects of the disease and its management methods, and the way forward to manage the disease. Also, based on what they learned, the farmers gave their perspectives on which bacterial wilt management measures could (not) be feasible in their local context.

6.3.3. Data collection

Multiple methods of data collection were used (Table 6.1) to assess what farmers learned about bacterial wilt and its management. During the learning sessions, participant observation was carried out by observing the farmers engaging in discussions and interactions between seed and ware potato farmers as well as by asking questions and participating in practical learning activities. Furthermore, farmers' potato fields and farmers' actions with respect to disease management methods were observed. The discussions during learning sessions were transcribed, coded, and analysed. Quotes were also included around each evidence of learning.

Table 6.1. Description of the research design

Data collection methods	Number of farmers (males and females)	Village	Issues addressed based on the learning approaches
Post-intervention interviews	36 (29 M, 7 F)	Agota	• Bacterial wilt dynamics (cause, spreading mechanisms, symptoms, latent infection, host plants) • Disease management methods • How and what did the farmers learn • Importance of collective action • Change in perceptions about social pressure, trust in social environment, and their roles and responsibility
	25 (21 M, 4 F)	Wanjala	
Reflective workshops	30 (24 M, 6 F)	Agota	• Feasibility of a range of disease management methods • Conditions that affect the feasibility of recommended disease management methods • Importance of collective action • Change in perceptions about social pressure, trust in social environment, and their roles and responsibility
	18 (15 M, 3 F)	Wanjala	
Participant observation discussions during learning sessions	36 (29 M, 7 F)	Agota	• Identification of local conditions that contribute to spreading of the disease • Reflection of farmers on different topics of learning
	25 (21 M, 4 F)	Wanjala	
Participant observation in both villages			• Implementation of disease management methods • Interactions among farmers during learning sessions, hands-on activities, and reflective workshop

Post-intervention in-depth interviews of farmers were used to provide qualitative data from the farmers who participated in the learning intervention. The interviews were used to capture how and what they learned about various aspects of the disease and its management.

At the end of the growing season, reflective workshops were organised to reflect on what and how the farmers learned concerning bacterial wilt disease dynamics, disease management methods, recognition of interdependencies, trust in the social environment, collective aspiration, and change in perceptions about their roles and responsibilities. The reflective workshops provided an important platform for discussions and reflections on the learning processes and evidences of learning. The reflective workshops were facilitated to collect data using well-prepared questions by guiding the discussions around each thematic area.

6.3.4. Data analysis

The collected data were analysed with a qualitative approach. They were coded and grouped into different themes and the learning processes, as portrayed in the conceptual framework introduced in section 6.2.3. Transcripts from the in-depth interviews and notes from the discussions during learning sessions and reflective workshops were analysed to obtain farmers' reasons for action about potato bacterial wilt and its management in their context. Further, notes from field observations were used to understand farmers' reasons for action in relation to the implementation of various methods of bacterial wilt management.

6.4. Results

In this section, the extent to which experiential learning and social learning influenced farmers' reasons for action concerning bacterial wilt disease dynamics and its management are reported.

6.4.1. Change in farmers' knowledge on potato bacterial wilt disease

Causal agent of bacterial wilt and its spreading mechanisms

During reflective meetings and interviews, the farmers articulated a good understanding of the pathogen that causes bacterial wilt and its nature. Farmers described that they acquired new knowledge about the causative agent of the disease. They explained that they were surprised to learn that the disease is caused by a pathogen, a living thing, which grows and multiplies. In addition, before the learning intervention, they thought that this disease was caused by improper post-harvest handling of seed potato and due to high moisture during harvesting time. The statement of a seed potato farmer from Agota village is illustrative of many farmers. He said:

> "I am surprised to learn that this disease (bacterial wilt) is a contagious disease caused by an organism that lives in soil, water and seed potato."

Concerning the spreading mechanisms of bacterial wilt, farmers reported acquiring new knowledge of different spreading mechanisms. Many farmers explained that infected seed potato and contaminated farm tools as major spreading mechanisms. The farmers explained that they did not know as their neighbour's potato fields infected by bacterial wilt could be a source of infection to their potato fields. They underlined the importance of keeping an eye on what is happening on their neighbours' potato fields.

On top of the spreading mechanisms that were presented during the learning sessions, the farmers indicated some additional mechanisms that are relevant in their local context. Farmers in Agota village explained that ravens usually eat potato tubers at the germination stage and move from one potato field to the other; flying and landing on many potato fields. Hence, they asked whether ravens may spread bacterial wilt through their beak and nails. Similarly, farmers in Wanjala village stated that in their village, most farmers rely on one or two farmers who own knapsack sprayers to spray their potato fields. The farmers wondered whether this practice could spread bacterial wilt because these farmers move from one potato field to the other without cleaning their shoes.

Some farmers also mentioned that they now understood why the extension workers were telling them to remove a wilted potato plant from their potato fields, which they did not understand before; that is, to avoid transmission of the disease to other plants. Moreover, the farmers mentioned that before the learning sessions they were expecting that some wilted potato plants would get healed. They had learned that keeping a wilted potato plant in the field would make the disease spread to other potato plants. The farmers also reported that bacterial wilt has no treatment once the plant is infected. A statement by a seed potato farmer from Wanjala village provides further illustrative evidence of the new knowledge that the farmers acquired about the causes and transmission mechanisms of the disease. He described it as follows:

> "This disease (bacterial wilt) is like AIDS. Because as AIDS transmits through sharp materials, bacterial wilt transmits through farm tools and it kills potato plants."

Latent (symptomless) infection of bacterial wilt

The farmers noted that they were amazed to learn the symptomless infection of the disease. Various comments by the farmers illustrate that they learned the symptomless infection of the disease. For example, during the fieldwork on the demonstration plot, a farmer from Agota village said, "This potato is very healthy'', pointing to a very vigorous potato plant. But other farmers reacted to this farmer's statement by uttering we cannot be sure if it is healthy or not, the disease may not show symptoms. Maybe it is now sleeping and will wake up in the weeks to come.

On the other hand, during the reflective workshop, the farmers stated that understanding the possibility of symptomless infection of the disease would help them become cautious when they buy seed potatoes from the local market or from neighbour farmers. They remembered well the analogy, a sleeping man and potato with latent infection, used to explain the nature of the disease during the learning intervention. Further, many farmers expressed their concern about the difficulty to identify latently infected seed potato tubers when they buy seed.

Host plants of bacterial wilt

The farmers were able to identify different host plants that could be affected by the pathogen that causes bacterial wilt. When asked to explain plants that could serve as hosts for the disease in their village, other than potato, the farmers in Agota village mentioned tomato and tobacco, as farmers in this area grow these crops. Similarly, the farmers in Wanjala village mentioned tomato and pepper as host plants that could be affected by the disease. Further, the farmers were able to describe that potato should not be rotated with these host plants. Farmers from Agota village mentioned that potato should be rotated with cereals like wheat, maize, barley, and teff. Similarly, the farmers in Wanjala village were able to note appropriate crop rotation patterns excluding host plants.

6.4.2. Farmers' belief in their own capacity to manage bacterial wilt

Implementation of disease management methods

Farmers asserted that they were equipped to protect their potato from the disease and sustain its production. They reported that, as a result of the learning intervention, they felt confident and capable of managing bacterial wilt using their new knowledge of the disease and its management methods. They specifically stated that the practical learning activities on the demonstration plot helped them to sufficiently learn how to diagnose the disease and control it. During the interviews, the farmers could describe a range of bacterial wilt management methods and their feasibility in their local context.

The farmers implemented farm hygiene and sanitation measures that would help them manage the disease. During the reflective workshops, the farmers asserted that they kept the hygiene of their potato fields. For instance, one farmer from Agota village explained that he put a fence around his potato field to avoid interference from humans and cattle, to avoid the disease. Besides, many farmers constructed ditches around their potato fields to divert surface runoff from their potato fields. Further, the farmers reported that they decontaminated farm tools using fire and hot water.

The farmers also reported that they cleaned their shoes before entering their potato fields. But they stated that they used water alone to clean their shoes. They also mentioned that monitoring committee members who used to visit each farmer's field by walking on potato fields without considering the importance of cleaning their shoes started cleaning their shoes. During the interviews, a lot of farmers were smiling thinking about what they used to do due to the limited knowledge they had. Overall, as noted in the quotes below, farmers developed confidence by learning how to manage the disease. The following illustrative quote is what many farmers asserted during the interviews and the reflective workshops.

> "I did not know how to manage this disease aside from removing wilted plants from my potato field. But now, I have learned many disease management methods."

Furthermore, the farmers, particularly ware potato producers, reported that they learned the importance of crop rotation and using a clean seed. However, they reported that due to the unavailability of quality seed potato, using clean seed was difficult. Concerning crop rotation, the farmers stated that they usually practice one or two seasons of crop rotation interval and they would try to increase the interval although land shortage would constrain this practice as highlighted below:

> "I have been practising crop rotation to improve soil fertility. I did not know that crop rotation could help us manage this disease but now, I have learned, and I will surely implement it starting from next season."

Further, the farmers modified their practice of roguing infected plants from their potato fields. They mentioned that they started roguing and properly disposing of the infected potato plants either by burying in a deep pit or by burning. But they described the difficulty of undertaking uprooting of the infected potato plants when they are too many. They said it is a very laborious activity to uproot and bury or burn infected potato plants regularly.

Diagnosis of bacterial wilt incidence

The interviews with farmers revealed that they developed practical skills to conduct proper disease diagnosis. During fieldworks on demonstration plot and their potato fields, the farmers were able to identify disease symptoms. They could diagnose the disease on potato leaves and tubers. However, many farmers explained the difficulty of making bacterial wilt disease diagnosis when their potato field is affected both by late blight and bacterial wilt at the same time. This is true because severe infection of late blight destroys the whole potato leaves and stems.

Identification of local conditions that spread bacterial wilt

Discussions held with farmers after the learning sessions and during the reflective workshops revealed that they could identify many local conditions that spread bacterial wilt in their village and beyond. The farmers mentioned the practice of seed potato exchange between seed potato farmers and ware producers as one of the conditions that may aggravate the spreading of the disease. Other local conditions that were identified by the farmers as contributing to the spread of the disease include the exchange of labour, sharing of farm tools, and free-grazing of cattle on potato fields. The following illustrative statement given by the farmers shows how they demonstrated their enhanced capacity in recognising local conditions that may spread the disease.

> "We usually work together through a labour exchange approach for planting, weeding and harvesting potatoes. In this case, all the farmers bring their farm tools to work on their neighbour's fields. We now recognise that this practice can contribute to the spreading of the disease and we need to clean the farm tools and our shoes."

Furthermore, seed potato farmers who have relatively big potato fields hire labour for weeding and harvesting, which can open a way for the disease to spread. Farmers described that this practice could spread bacterial wilt since hired-labourers did not clean their shoes when they work for many farmers in different potato fields. The farmers expressed that it would be challenging to stop labour exchanging. But they asserted to try their best to make sure that farm tools are cleaned enough not to spread the disease. Likewise, concerning seed potato exchange, the farmers explained that stopping this practice would be very difficult. This was because most farmers strive to grow improved potato varieties that they usually buy or get from their neighbours. In this regard, the farmers suggested trying to buy seed potato from the agricultural research centre or from farmers whom they know that their potato fields are not affected by the disease. Based on the discussions held with farmers and field observations, analysis of the routes of disease spreading among potato fields owned by different types of farmers in the study villages is indicated in Figure 6.3 below.

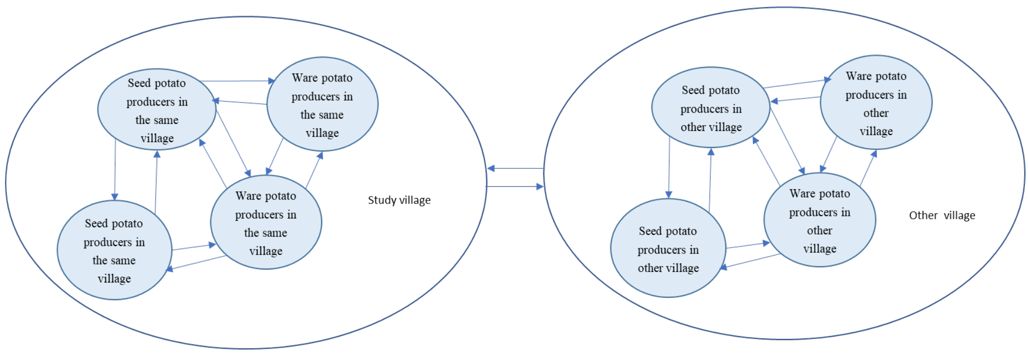

Figure 6.3. Schematic representation of the possibility of the spreading of bacterial wilt of potato from seed producers to ware potato producers and vice versa in the study villages and beyond.

6.4.3. Identification of the feasibility of bacterial wilt management methods

During the reflective meetings, the farmers demonstrated their learning by describing the feasibility of various recommended bacterial wilt management methods considering their context. They were asked to rank the feasibility of several methods as extremely difficult to implement, slightly difficult to implement or easy to implement. They demonstrated their capacity by rating the feasibility of the recommended methods for management of the disease considering their local context as indicated in Table 6.2.

Farmers in both study villages rated disease management methods such as the use of disease-free seed potato and planting potato on disease-free fields as extremely difficult to implement. Using disease-free seed potato is not possible due to a lack of access to certified seed potato in

Table 6.2. Farmers' rating of the feasibility of potato bacterial wilt management methods in their local context.

Recommended methods for management of potato bacterial wilt	Agota Village (Wolmera district)	Wanjala Village (Doyogena district)
Decontamination of farm tools	*	*
Washing oxen hooves	***	***
Planting potato on disease-free fields	***	***
Roguing and burning or burying infected potato plants	**	*
Using disease-free seed potato	***	***
Preparing cut off drains to divert surface runoff	*	*
Practicing crop rotation with non-host plants		
❖ Three seasons	**	***
❖ Two seasons	*	*
❖ One season	*	*
Cleaning shoes before entering potato fields	*	*
Eradicating host weeds	***	***
Controlling free grazing of cattle on potato fields	***	**

***Extremely difficult to implement **Slightly difficult to implement *Easy to implement

the country. The wide prevalence of the disease in the study areas also made it very difficult finding a potato field free from the infestation of the disease by the farmers in their respective village. Similarly, eradicating host weeds and washing oxen hooves were rated by the farmers in both villages as extremely difficult to implement. The farmers mentioned that since there were many types of weeds in their potato fields, it was very difficult to eradicate them in such a way that the disease would not get spread in the process of weed management. Further, they mentioned that they did not know specific host weeds for the disease in their villages. Concerning washing oxen hooves, the farmers in both villages expressed their concern about the feasibility of the practice. They mentioned that some oxen could be aggressive and trying to wash their hooves is unsafe. Furthermore, farmers think that washing oxen hooves is quite labour-intensive and thus, it is nearly impossible and challenging to implement.

On the other hand, farmers in both villages rated bacterial wilt management methods such as decontamination of farm tools, preparing cut-off drains to divert surface runoff, and cleaning shoes before entering potato fields as easy to implement. They mentioned that implementing these practices was easy and they managed to implement all of them in their potato fields. Interestingly, farmers in Agota village rated roguing and safely disposing of infected potato plants as slightly difficult to implement. Their reason was that since there were many infected plants per field, it was not easy to uproot and burn or bury in deep pits. But the farmers in Wanjala village rated this method of bacterial wilt management as easy to implement, indicating the relatively less disease severity in the area.

The farmers in Agota village rated controlling the free-grazing of cattle on potato fields as an extremely difficult method to implement. This was because in this village free grazing of cattle is a common practice and it is not easy to change it just to manage potato bacterial wilt. Particularly during dry season, cattle herds from different areas graze freely on crop fields due to a shortage of animal feed. Further, the cut-and-carry system (where the grass is cut and fed to livestock) is not common in this village and the farmers mentioned the difficulty of stopping this practice in the face of bacterial wilt prevalence. In Wanjala village, farmers rated the same practice as easy to implement. This is because the number of cattle per household in this village is few compared to that of Agota village. Also, cattle are usually kept in a confined area and free-grazing of cattle on several crop fields is not common in Wanjala village.

Concerning crop rotation, the farmers in both villages rated up to two seasons of interval between potato and non-host crops as easy to implement. But the farmers in Agota village felt that three seasons of crop rotation was slightly difficult to implement due to land shortage and land fragmentation. Due to the same reason, farmers in Wanjala village considered crop rotation of three seasons as extremely difficult to implement in in their local context.

6.4.4. Change in social pressure

The farmers became vigilant about what is happening in their neighbours' potato fields. Recognising their interdependency, both seed and ware potato farmers started putting pressure on each other to manage the disease in their community. Particularly, seed potato farmers reported putting pressure on ware potato farmers to properly implement disease management methods to prevent it from further spreading. Ware potato farmers also urged seed potato farmers to give more attention to the quality of seed instead of the quantity they sell. Interestingly, farmers responded more to the pressure from their fellow farmers than to the technical advice provided by agricultural researchers and extension workers. During the reflective workshop, many farmers stated the importance of monitoring each other's potato fields for disease occurrence.

When asked the reason why they implemented different methods of bacterial wilt management, seed potato producers stated that they wanted to get their produce accepted by seed potato cooperatives to be sold at a higher price. Seed potato growers became more worried and serious about the disease. These farmers explained that there was also a strong push from other fellow farmers to implement disease management methods due to the prevalence of bacterial wilt and its ramifications on the seed potato market. This shows that seed potato farmers who produce seed potato in the same village began compelling each other to control the disease. They also indicated that ware potato producers do not want to seed potatoes with symptoms of disease infection.

6.4.5. Change in aspiration (collective goal)

During the reflective workshops, farmers stated the importance of collaboration between seed and ware potato farmers. They described the disease as a common challenge that all potato farmers need to collaborate to control it. Seed potato farmers had a relatively better experience of working together for seed potato production, disease management, and marketing. Hence, they were more proactive about potato bacterial wilt and its management than ware potato producers.

Before the learning intervention, ware potato farmers did not recognise the importance of collective action to control the disease. Seed potato farmers also repeatedly noted that they did not consider the importance of collaborating with ware potato farmers before the learning intervention. But, during interviews and reflective workshops, the farmers stated that they would not be successful in controlling the disease through individual efforts alone as their potato fields are usually bordered by other farmers' fields. Both seed and ware potato farmers expressed the importance of collective action and agreed to make a concerted action. They proposed to work together to deal with the disease by developing bylaws. Regretting about the spread of the disease, a seed potato farmer from the Wanjala village, who is illustrative of many farmers, said:

> "If we had learned about this disease before starting seed potato multiplication, we would not have let it spread in our area and our seed potato business would have

> continued successfully. Unknowingly, we have put ourselves in a serious problem, but now we started correcting our past mistakes."

Similarly, a seed potato farmer from Agota villages said the following, indicating the importance of collective action to manage the disease:

> "When research centre and office of agriculture give us some trainings on seed potato production and disease management, they do not include ware potato farmers with us. Now I have understood the importance of learning together to jointly fight this disease."

6.4.6. Change in trust in social environment

The study revealed that the farmers changed their perception of the social environment. The interviews revealed that the farmers used to think that improved potato varieties supplied by seed potato cooperatives, the office of agriculture and individual seed potato farmers were clean and free from different potato diseases. However, after they learned about the nature of bacterial wilt and considering the prevalence of the disease in their community, the farmers reported that they would no more trust the quality of seed potato supplied by these actors. The farmers stated that they needed more help from the research centre to control this disease because the office of agriculture could not give them disease-free seed. Many farmers declared that they would put their trust in a seed potato from a research centre. Some farmers even suggested stopping buying seed potatoes from the local market because of disease prevalence. Many farmers expressed their frustration in the poor quality of seed potato they bought from local markets. This is illustrated by the following quote:

> "Last year, I bought Gudene (improved potato variety) from a seed potato producer in our village. But it was severely affected by a disease and the yield was less than a local variety."

On the other hand, seed potato producers expressed their worries about the lack of market for their seed production. They perceived that their seed potato business would be in trouble given the prevalence of the disease. It was also observed that many seed producers started selling their seed produce as ware potato fearing unavailability of market. Many seed potato farmers hesitated to store seed potato in diffused light store (DLS) due to the lack of a reliable market. They prefer to sell to ware potato traders to avoid the risk of market unavailability. As the seed potato farmers used to get appreciable income from seed potato business, they recurrently expressed their frustration about the devastating nature of the disease during the reflective workshop. A seed potato farmer from Agota village said in this regard:

> "Lack of market for seed potato has already discouraged us. We sell our seed potato produce to ware potato traders at a lower price."

During the reflective workshop, the farmers in both study sites expressed their dissatisfaction with the unavailability of disease-free seed potatoes in their area. They were also shocked to learn that at some point their fate of growing potato could be ruined by the disease if it is left unmanaged. Besides, the farmers expressed their concern about the disease pressure and they developed a sense of urgency to deal with the disease.

6.4.7 Change in perception of farmers' role and responsibility

Both seed and ware potato farmers demonstrated a change in perceptions about their role and responsibility in ways that confirmed their learning. Ware potato farmers described that they used to blame seed potato farmers for the poor-quality seed they produced and sold. On the other hand, seed potato producers were claiming to properly implement disease management methods and produce quality seed potato. But during the learning intervention, both types of farmers admitted to unknowingly contribute to the spreading of the disease, in one way or another and identified their roles and responsibilities they could have played. The farmers described playing the required role for effective management of the disease by properly implementing disease management measures in their potato fields. They also agreed to take responsibility to clean farm tools when they help each other through labour exchange, not to spread the disease to their neighbours' potato fields. Besides, the farmers agreed to take responsibility to tell their respective family members not to use a hoe without cleaning it, and not to enter potato fields without cleaning their shoes. For instance, a seed potato farmer said:

> "When my neighbour helped me in hilling of potato, I reminded him to clean his hoe and shoes before he started working."

6.5. Discussion

In this section, the results of the study on the impact of the learning intervention on farmers' reasons for action related to bacterial wilt management of farmers are discussed. We present the probable effects of the experiential learning characteristics, then of the social learning characteristics, and finally, the synergy between the two approaches.

6.5.1. The role of experiential learning in bacterial wilt management

The study showed that experiential learning contributed to farmers' understanding of bacterial wilt disease dynamics and management. The farmers reported that hands-on activities on the demonstration plot motivated and enabled them to implement disease management methods in their potato fields. For example, they removed and buried or burned infected potato plants, cleaned their shoes before entering potato fields, decontaminated farming tools, and diverted surface run-off from their potato fields, among others. Before the learning intervention, farmers of the same area had very limited knowledge of the disease characteristics, its spreading mechanisms, and its management, as the previous study on their knowledge and practices showed (Tafesse et al., 2018). The study indicated that none of the farmers could recognise the cause of the disease, and most did not identify any other control methods apart from rogueing.

This finding aligns with other studies that indicate that experiential learning improved the problem-solving capacity of farmers for integrated pest management in farmer field schools in Africa (Davis et al., 2012; Ortiz et al., 2019). Similar findings were also reported improvement of farmers' pest management practices in South America and Asia (Feder et al., 2003; Ortiz et al., 2019). Moreover, the importance of hands-on practical learning based on experiential learning principles has been reported earlier to improve the decision-making capacity of smallholder farmers in a complex farming system (Gallagher, 2003; Ortiz et al., 2019).

This study also shows that farmers applied their new knowledge of the nature of the pathogen to identify possible transmission mechanisms of the disease. It demonstrates that giving due attention to the nature of the pathogen that causes bacterial wilt and diseases of other crops has an additional advantage for learning interventions to improve the capacity of smallholder farmers (Abo-Elyousr et al., 2014; Adam et al., 2015; Ortiz et al., 2019). Most other studies on farmers' knowledge and practices of crop diseases show whether the farmers know the diseases and how they try to manage them. Little or no attention has been given to farmers' understanding of the pathogens that cause crop diseases (Abang et al., 2014; Kromann et al., 2014; Penet et al., 2016; Schreinemachers et al., 2015). Hence, this finding has considerable implications for future interventions aiming to enhance the capacity of farmers to manage crop diseases.

The study further revealed that the experiential learning aspects of the training enabled farmers to reflect on and define the feasibility of a variety of recommended bacterial wilt management methods and consider what it takes to implement the methods in their local context. The farmers rated the recommended management methods as easy to implement, difficult to implement, and very difficult to implement (Table 6.2). In both study sites, the farmers categorized crop rotation up to three seasons, the use of disease-free seed potato and planting on disease-free fields as very difficult to implement in their context. This reveals that the implementation of recommended methods is much more complex than extension workers and natural scientists assume. The identification of the feasibility of disease management methods by the farmers is in line with the theoretical notion that know-how is a context-specific type of knowledge and hence unknown to researchers and experts (Lundvall, 1992; Tafesse et al., 2018). Therefore, farmers' capacity to rate the feasibility of the methods should not be considered only as an outcome of the current learning intervention. It is important to recognise that farmers' local experiential knowledge has largely contributed to their perspectives on the feasibility of the methods. Several studies also show that that farmers' local experiential knowledge is more practical and relevant for sustainable agricultural development in their context (Lwoga et al., 2010; Šūmane et al., 2018; Stuiver and Leeuwis, 2004).

Rating bacterial wilt management methods such as crop rotation, the use of disease-free seeds, and planting potato on disease-free fields as very difficult methods to implement have huge implications for the efforts to contain the disease. These methods are important to reduce the inocula of the pathogen that causes the disease and to control it from spreading further. If the farmers do not integrate these methods with other sanitation measures, it would be difficult to contain the disease from spreading fast and wide. Hence, more efforts are needed to explore alternative options and to enhance the availability of disease-free seeds.

Moreover, the evaluation of the longer-term effects of similar learning interventions is recommendable. During the training, the farmers were given an opportunity to gain concrete experience with various management methods. A limitation of this study is that it was not possible to let the farmers in the two villages go through the whole experiential learning cycle of Kolb's model (concrete experience, reflective observation, conceptualization, and experimentation). They could not yet experience the results of the implemented methods. Moreover, because the learning intervention was facilitated just for one season, the farmers did not implement or test some methods like crop rotation. The farmers might test these practices in the next growing-seasons depending on the feasibility of the suggested methods.

6.5.2. The role of social learning in instigating collective action

Crop protection researchers promote an integrated disease management (IDM) approach as an effective way to deal with bacterial wilt. IDM is a combination of a range of methods such as using clean seed, planting of uninfected soil, crop rotation, sanitation, and soil amendments to suppress the pathogen. Our research shows, however, that unless interdependent farmers implement these measures through collective action, effective management of the disease does not happen. Hence, for plant diseases that pose a collective risk such as potato bacterial wilt, an IDM needs to be complemented by collective action. Therefore, the findings of this study suggest that both seed and ware potato farmers need to be involved in a well-designed learning intervention.

The findings of this study show that the social learning features of the learning intervention indeed instigated collective action among seed and ware potato farmers to manage potato bacterial wilt. It was revealed that social learning helped seed and ware potato farmers recognise their interdependency and the importance of making a collective effort to deal with the disease. Further, the study indicated that the farmers identified their roles and responsibilities for effective control of the disease. Both seed and potato farmers agreed to collectively act to manage the disease by developing a community-based bylaw. These effects are the result of the learning intervention. Before the learning intervention, none of the farmers recognised the importance of collective action to deal with the disease effectively (Tafesse et al., 2018). This finding is consistent with other studies in agriculture and natural resources management that show how social learning leads to collective agreements among actors about how to jointly address complex socio-ecological problems (Albert et al., 2012; Ensor and Harvey, 2015; Phuong et al., 2018; Rodela, 2011). However, since developing an institutional arrangement for a collective action takes time, this study did not capture what type of rules that seed and ware potato farmers will indeed develop to deal with the disease collectively.

6.5.3. Combining experiential and social learning to deal with complex crop diseases

Currently, most learning interventions are designed based on either experiential learning or social learning or other learning approaches (Kolb, 2015; Leeuwis and Pyburn, 2002; Noguera-Mendez et al., 2016). However, a single learning approach cannot be adequate to instigate learning to deal with complex crop diseases that require collective action. Learning to deal with complex crop diseases that pose collective risk involves understanding complex socio-ecological interactions, management methods, recognising interdependency among farmers, and making appropriate institutional arrangements to enable collective action. For instance, infectious plant diseases caused by bacterial, fungal, oomycete, and viral pathogens have diverse spreading mechanisms (Van der Plank, 2013) and they are difficult to control through individual efforts, particularly in smallholder farmers' context. On the other hand, plant pathologists usually consider various abiotic and physiological disorders of plants as non-infectious (Howard et al., 1996). Non-infections plant diseases do not have collective risk since they do not spread from one area to the other. Hence, non-infectious diseases can be managed through individual efforts alone and may not require cooperation among farmers.

This study indicates the synergy between experiential and social learning approaches for effective management of complex crop diseases. Without social learning, smallholder farmers would not have reached a consensus to deal with the disease collectively. On the other hand, without experiential learning, they would not understand the dynamics of the disease, develop the skills to diagnose the disease, and evaluate the feasibility of the recommended methods and implement them to control the disease. The finding of this study matches those observed in earlier studies on complex socio-ecological problems that indicated the importance of social and technical innovations (Leeuwis, 2004; Noguera-Mendez et al., 2016; Pahl-Wostl, 2006). These findings suggest that learning interventions for the management of complex crop diseases in smallholder farmers' context could benefit from combining experiential and social learning approaches. Therefore, researchers, development practitioners, and policymakers need to consider the synergy between experiential and social learning approaches for sustainable management of infectious crop diseases. It is also essential to distinguish what can be learned better through which learning approach to design a relevant learning intervention. Moreover, it is essential to value and integrate farmers' local knowledge about the feasibility of the diverse measures in the local context into learning interventions.

The study shows that change in farmers' knowledge and social relations due to the learning intervention makes an essential contribution to effective control of the disease by improving their disease management practices. However, a learning intervention alone will not suffice for the effective management of crop diseases. Several conditions impede effective bacterial wilt management in the context of Ethiopian smallholder farmers. For instance, the existing seed systems do not guarantee disease-free seed supply to the farmers (CIP, 2016; Schulz et al., 2013; Woldegiorgis et al., 2013). A recent study conducted in the Ethiopian potato production system also showed that the distribution of latently infected seed potatoes has contributed to the spreading of bacterial wilt into different parts of the country (Abdurahman et al., 2017). Moreover, the unavailability of quality seed potato has been reported by several previous studies (Gildemacher, 2009; Hirpa et al., 2010; Tadesse et al., 2019). Thus, if the farmers are not able to access disease-free seed potato and continue to plant infected seeds, the efficacy of the efforts being made through the implementation of farm hygiene and cultural practices cannot effectively suppress the pathogen. Absence of a quarantine system and compromise on the quality of seed potato production due to immediate needs for food security purposes (Gorfu et al., 2013; Schulz et al., 2013) could also constrain the success of farmers' aspirations to improve management the disease. This suggests the need to explore further how other factors (economic and institutional) that may influence the efficacy of disease management efforts could be addressed.

6.6. Conclusion

The evaluation of the community-based learning intervention provides a good understanding of the importance of combining experiential and social learning approaches in designing interventions seeking to enhance farmers' capacity to effectively respond to complex crop diseases like potato bacterial wilt.

The study has shown that the combination of experiential and social learning approaches enabled farmers to learn how to deal with the disease. Experiential and social learning approaches complement each other and integrating these learning approaches can support farmers to understand what effective management of a complex crop disease entails and how socio-ecological interactions aggravate the disease incidence. Most researchers usually underestimate how important it is for the farmers to have a good understanding of the pathogens that cause crop diseases. But this study has found that learning about the causal agent of potato bacterial wilt and its nature has significant implications for the identification and implementation of effective disease management methods. It is also indispensable to give due attention to farmers' local knowledge while facilitating a learning intervention to control this complex disease. Due to the diverse spreading mechanisms of potato bacterial wilt and the interdependency among farmers for effective control of the disease, it is important to involve both seed and ware potato farmers together in a learning intervention to foster collective action. In terms of future research, exploring tailor-made solutions that fit the smallholder context is needed, considering the biophysical and social dimensions of the disease.

Chapter 7

Synthesis

7.1. Introduction

Bacterial wilt in potato has rapidly spread to all potato growing areas in Ethiopia. Due to the devastating impact of this disease, the Ethiopian potato production is under pressure. Smallholder farmers and other actors in the country's potato innovation system have made limited efforts to control the disease, and there has been little information on the conditions contributing to the rapid expansion of the disease. The main objectives of this thesis were to systematically investigate biophysical and social factors that spread the disease in the country and to analyse how it could be combated effectively in the smallholder farmer's context. Analysis of the biophysical and social conditions that spread the disease in the country was undertaken at different levels (system, community/local, household, and field) (Figure 7.1).

This chapter recalls the research questions addressed by this thesis and discusses the answers to the questions. The overall research question is: what biophysical and social factors contribute to the spreading of bacterial wilt in potato and what technical and social innovations may enhance the management of the disease in smallholder farmer potato production in Ethiopia?

This thesis provides answers to the following five sub-questions derived from this overall research question:

1. How do different actors in the potato innovation system understand the problem of bacterial wilt and its management? (Chapter 2)
2. How do farmers' knowledge and practices affect the spreading of bacterial wilt? (Chapter 3)
3. How do seed potato cooperatives monitor the occurrence of bacterial wilt and its management, and what are the challenges associated with the monitoring activity? (Chapter 4)
4. What biophysical conditions aggravate the occurrence of bacterial wilt and what technical innovations can improve the biophysical conditions? (Chapter 5)
5. How does a learning intervention enhance farmers' capacity to deal with bacterial wilt through collective action? (Chapter 6)

This Chapter 7 is structured based on the answers to the overall research question of the thesis. First, an overview of the major findings of the individual chapters is presented. Then, biophysical and social factors that contribute to the spreading of the disease are discussed by connecting the results of the different studies. This is followed by a reflection on technical and social innovation that may improve the management of the disease. I also briefly reflect on similarities and differences for the management of bacterial wilt and late blight in the Ethiopian context. Finally, I discuss implications for current knowledge and policy interventions and draw conclusions.

7.2. Main findings of the thesis

In this section, the main findings from each empirical chapter of the thesis are presented. The findings are summarized with regard to the different levels at which the analysis of the biophysical and social dimensions of the disease problem was conducted (Figure 7.1).

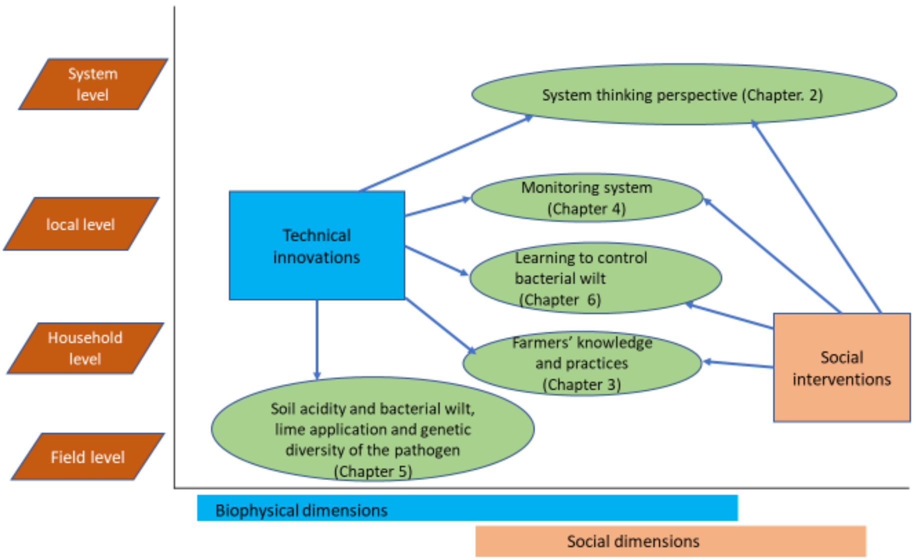

Figure 7.1: The thesis' chapters at different levels (system to field), dimensions (biophysical and social) and innovations to enhance management of the disease.

7.2.1. How actors understand bacterial wilt and late blight and their management

Bacterial wilt and late blight in potato are complex agricultural problems that involve multiple actors. A diagnostic study was conducted using a soft system thinking perspective to explore how actors in the Ethiopian potato innovation system understand the diseases and their management methods. Chapter 2 describes that the actors largely overlooked the key systemic problems in the management of the diseases. There was also limited recognition of their interdependencies regarding their activities. There was no agreement about who should and would be able to diagnose and manage the diseases. High-level experts in the Ministry of Agriculture, agricultural research institutes, and non-governmental organisations (NGOs) thought that the diagnosis of both diseases should be primarily done by agricultural extension workers and the farmers themselves. But extension workers and farmers mentioned that high-level experts and researchers needed to be dominant in disease diagnosis and risk assessment. Extension workers explained that the farmers had limited knowledge on how to diagnose the diseases, particularly bacterial wilt. Farmers also felt that extension workers did not have adequate knowledge about bacterial wilt, and they expected more support from agricultural researchers (see Chapter 2).

Researchers assumed that the farmers could manage bacterial wilt, and they recommended a range of management practices, including using disease-free seed, crop rotation, eliminating host weeds, and using uncontaminated irrigation water. Furthermore, researchers emphasised that their main focus is on technology generation, whereas technology transfer is the mandate of agricultural extension offices. Overall, according to the researchers' perception, the disease could be controlled if smallholder farmers would adopt the recommended methods. But farmers stated that the management of bacterial wilt is difficult, and there is no solution to save the plant once it is affected by the disease. Extension workers also share farmers' opinions, and they commonly advise farmers to rogue and throw away an infected plant. Likewise, district-level agricultural experts feel that management of the disease is difficult, contrary to the researchers' perception (see Chapter 2).

Unlike bacterial wilt, researchers and extension workers confidently mentioned that late blight could be controlled by applying chemicals. They also described that resistant potato varieties that have been released by research institutes would help farmers to control the disease. Farmers were of a similar opinion about the use of chemicals and resistant varieties, but they were concerned about the unavailability of good quality chemicals (see Chapter 2). Furthermore, farmers mentioned shifting potato production to the short rainy season and early planting as strategies to minimize the risk of late blight problem since the disease does not occur during dry seasons (see Chapters 2 and 3).

Concerning seed quality control, many actors (researchers, farmers, NGOs, and extension) felt the implementation of seed proclamation and quality declared seed (QDS) standards should be overseen by regional government regulatory offices. But, the regulatory bodies indicated that they had limited capacity to enforce seed potato related rules and regulations (see Chapter 2). They explained that they had constraints in logistics and the necessary laboratory facilities, coupled with scattered potato plots, to make appropriate inspections, disease diagnosis, and seed quality assurance. There is no formal seed potato certification system in the country. In this regard, seed potato cooperatives mentioned that they had a monitoring system to ensure quality seed production. NGOs also mentioned that the capacity-building support they provide to seed potato producers such as training and seed storage facilities is not sufficient (see Chapter 2).

With regards to communication and information sharing with farmers, many actors (research institutes, NGOs, and extension offices) assumed that model farmers could disseminate information to other farmers in their locality. Hence, training and extension services mostly targeted model farmers. But many smallholder farmers had strong reservations about this assumption stating that model farmers are usually reluctant to share the information they received from different sources. Furthermore, research, extension, and NGOs asserted that communication and collaboration among actors in the innovation system were weak (see Chapter 2).

All in all, the existing perceptions and understandings of the different actors in the country's potato innovation system and their approaches hinder collective management of bacterial wilt and late blight. The actors overlooked key systemic conditions that spread or aggravate the diseases. They also did not sufficiently recognise their interdependency and multiple technical and institutional dimensions of the diseases.

7.2.2. Farmers' knowledge and practices of bacterial wilt and late blight management

Chapter 3 explains what happens at household level zooming in on farmers' knowledge and practices of bacterial wilt and late blight management. Three types of farmers were identified: ware potato producers, regular seed producers, and quality declared seed (QDS) producers. There was limited knowledge among all categories of farmers, and most of the farmers' practices spread bacterial wilt instead of controlling it. Besides, none of the farmers recognised the cause of bacterial wilt as a pathogen that can grow and replicate. Most farmers thought that the wilting of potato happens when the moisture content of the seed is high. Many farmers confused the disease with a shortage of water and waterlogging during dry and rainy seasons, respectively (see Chapter 3). Strikingly, even the farmers involved in quality declared seed potato production did not recognise the pathogen that causes the disease. Relatively, farmers had better knowledge of late blight management methods such as the use of chemicals and resistant potato varieties. However, the farmers were unaware of the spreading mechanisms of both diseases.

More than 80% of the farmers did not regularly renew seed potatoes, and they repeatedly used seeds with poor seed health and poor physiological quality for an unspecified number of generations. Many farmers (48%) practised crop rotation of one season interval only. There was also an incongruence between farmers' knowledge and scientific knowledge. About 42% of the farmers reported that they would leave infected potato tubers on their field after sorting during harvesting, which enables a further spread of the disease. Some farmers even stated that leaving infected/damaged potato tubers in the field would improve soil fertility status. Furthermore, statistically, there were no significant differences among the different categories of farmers (see Chapter 3) in terms of most of their practices apart from crop rotation.

Concerning sources of information on both diseases and their management methods, farmers mentioned extension workers (64%), fellow farmers (42%), NGOs (22%), and researchers (19%). Researchers and NGOs were mentioned by seed producers as the main sources of information. But the kind of information that the farmers accessed was primarily about disease management methods. In terms of seed quality, most of the farmers assumed that a seed potato tuber is clean if it does not show disease infection symptoms. However, healthy-looking seed potato tubers can be latently infected by the pathogen that causes bacterial wilt and may not show symptoms (see Chapter 3). Generally, previous extension efforts did not bring the required results.

For bacterial wilt, the extension workers were telling farmers to remove and throw away a plant with symptoms of infection. However, this practice spreads the disease further rather than controlling it. With regards to late blight management, more than 92% of the farmers reported the importance of spraying fungicides to control the disease when they observed symptoms of disease occurrence. But the application of fungicides after disease occurrence is less effective. In addition, most farmers did not recognise the differences between systemic and contact fungicides (see Chapter 3). The farmers made only individual efforts and did not recognise the importance of collective action among seed and ware potato farmers. The findings imply the importance of improving farmers' knowledge and practices for management of both potato diseases through appropriate extension approaches (e.g., social learning, experiential learning).

7.2.3. Monitoring systems of seed potato cooperatives

An in-depth analysis of how seed potato cooperatives operationalize essential elements of a monitoring system at a community level, which is one of the design principles for common-pool resources (Ostrom, 1990), shows that seed potato cooperatives have an organised monitoring system (Chapter 4). A novel framework consisting of essential elements of a monitoring system for the management of complex diseases like bacterial wilt in potato crops was developed and applied. The framework is useful for describing and analysing how seed potato cooperatives in Ethiopia engage with disease monitoring. The study adds to the understanding of the monitoring system by explaining the essential elements of a self-monitoring system for collective management of crop diseases that pose collective risks to smallholder farmers (see Chapter 4).

All the investigated cooperatives have a committee in charge of the monitoring activities. On top of face-to-face communication, mobile phones play a vital role in communication for monitoring collective action by seed potato cooperatives. Chapter 3 also shows that most of the potato farmers (73%) owned a mobile phone. However, despite the interdependency among seed and ware potato farmers, the monitoring system did not include ware potato producers. Furthermore, the committees did not have kits to make a disease diagnosis, and they relied only on visual inspection. The committees faced challenges in enforcing sanctions as some farmers refused to accept their decisions. The incentive that the committee gets from their respective cooperatives was also insufficient.

Moreover, the monitoring committees rarely rejected seed potato fields based on bacterial wilt incidence. Lack of trust among the farmers and committee members was another main problem hindering the effectiveness of the monitoring system. On the basis of these findings, strengthening the monitoring systems of farmers' seed potato cooperatives is mandatory, given their important role in the Ethiopian seed potato systems. The current role of seed cooperatives will also continue to be substantial in potato seed systems since developing a formal seed certification system is unlikely in the near future.

7.2.4. Characterisation of *Ralstonia solanacearum* strains and management of bacterial wilt using lime

Chapter 5 explains the correlation between soil acidity and bacterial wilt incidence at the farm level. The survey conducted to assess soil acidity in potato fields indicated that soil acidification is pervasive in major potato growing areas in Ethiopia, contributing to the high incidence of bacterial wilt (see Chapter 5). Fifty percent of the potato fields had very strongly acid pH values (4.5-5.0), whereas 30% of the fields were strongly acid (5.1-5.5), as indicated in Chapter 5. Low soil pH favours the growth and development of *Ralstonia solanacearum*. Aside from the relationship between soil acidity and bacterial wilt incidence, this chapter shows that application of lime reduces bacterial wilt incidence, suggesting the importance of dealing with soil acidification to suppress the disease effectively. Furthermore, based on molecular laboratory analysis, this chapter shows low genetic diversity among *R. solanacearum* strains affecting potato in the country (see Chapter 5). All strains belonged to phylotype II. This implies that the genetic diversity of the pathogen is low, and a similar strain is spreading across the country. This shows that the disease has spread recently, and its management needs to focus on addressing the factors that spread the disease.

7.2.5. Learning to control bacterial wilt in potato

Chapter 6 adds to the understanding of learning among farmers that fosters social and technical innovations to deal with a complex plant disease based on the findings from a learning intervention designed and facilitated at community (village) level in two villages of the central highlands of Ethiopia. The intervention was evaluated to understand what and how farmers learned about the disease and its management based on experiential and social learning theories' point of view. Seed and ware potato farmers were involved in the learning intervention together, and they recognised their interdependency and the importance of collective action for effective management of the disease. Learning about the nature of the pathogen that causes bacterial wilt and its spreading mechanisms also helped farmers identify local conditions that spread the disease and the feasibility of various methods to manage the disease in their context (see Chapter 6).

The findings of Chapter 6 demonstrate the importance of integrating social and experiential learning approaches when designing a learning intervention to improve smallholder farmers' capacity to deal with the disease. Further, they show the importance of involving both ware and seed potato farmers together in a learning intervention to develop socially acceptable and effective strategies of disease management in their context. The chapter revealed that farmers acquired new knowledge on bacterial wilt disease dynamics and management methods. They also recognised their interdependency and the importance of collective action among seed and ware potato farmers (see Chapter 6). Moreover, farmers identified the feasibilities of recommended methods to control bacterial wilt in their context. This was not only the outcome of the learning intervention, but the role of farmers' local knowledge was significant.

7.4. Discussion

The thesis analyses social and biophysical factors that play a key role in the spreading of bacterial wilt in potato production, and how the disease can be managed through social and technical interventions in smallholder farmers' context. It contributes to the debates around systems approaches, extension approaches, and collective action to foster social and technical innovations that deal with complex agricultural problems like bacterial wilt.

One of the dominant approaches, widely proposed in the literature on plant disease management, is an integrated disease management approach. That is a combination of various disease management methods, including physical, chemical, cultural, and biological methods to control plant diseases. This thesis shows the complexity of bacterial wilt in potato production and how its spread and occurrence are driven by various social and biophysical factors and socio-ecological interactions. Furthermore, this study shows the importance of going beyond an integrated approach (a combination of different methods) and embarking on learning, monitoring, collective action, and multi-stakeholder collaborations to control the disease effectively. The disease poses a mutual risk to the interdependent potato farmers. Thus, the farmers need to make a joint effort, as individual practices alone are not sufficient to combat the disease.

To foster social and technical innovations, appropriate methods for communication are needed. In this regard, farmers need to learn through a combination of experiential and social learning approaches to enable them to carry out successful collective action. Social arrangements (rules or bylaws) should also be developed to allow for collective action at the local (village) level.

In the following section, in line with the overall research question, biophysical and social factors that affect the spreading of bacterial wilt, and technical and social/interventions that may enhance the management of the disease in smallholder farmer potato production in Ethiopia are discussed. Finally, a discussion on similarities and differences between the management of bacterial wilt and late blight in Ethiopian potato production is presented.

7.4.1. Biophysical factors contribute to the spread of bacterial wilt in potato

In this section, several biophysical factors that contribute to the spread of bacterial wilt in smallholder potato production in Ethiopia are discussed based on the findings of the studies conducted.

Lack of regular seed renewal

Regular renewal of seed potato plays a crucial role in controlling the spreading of seed-borne diseases like bacterial wilt. In developed countries where high quality seed is produced through a formal seed system, there is a constant renewal of seed stock (Struik and Wiersema, 1999). In Ethiopia, Chapter 3 indicates that most of the farmers do not renew seed potatoes for many seasons. Moreover, potato farmers did not recognise the relationship between bacterial wilt incidence and seed renewal.

In relation to seed renewal, the problem in Ethiopia is twofold. On the one hand, seed potato producers do not regularly renew their seed stock and on the other hand, ware potato farmers repeatedly grow the same seed without renewal for many seasons (Chapter 3). These practices create a gradual build-up of the pathogen that causes bacterial wilt (*Ralstonia solanacearum*) in the seed and spread the disease (Gildemacher et al., 2009; Kassa and Chindi, 2013). The problem of lack of seed renewal is exacerbated by the lack of knowledge among farmers on the importance of clean seed and this also contributes to the spreading of bacterial wilt (see Chapter

3). It is essential to enhance the supply of disease-free seed to farmers in order to replace the existing seed stock with disease-free planting materials from known and reliable sources.

Short crop rotation interval

Chapter 3 indicates that about half of the farmers (48%) practised a one-season crop rotation interval, while only 13% of the farmers practised three-season intervals. This has considerable implications for the accumulation of the pathogen in potato fields. Studies show that a one-season interval reduces bacterial wilt incidence only by 10%. Rotations with long intervals with non-host plants are promoted as part of integrated bacterial wilt control to suppress the pathogen (Lemaga et al., 2001; Katafiire et al., 2005: Verma et al., 1991). But the currently common practice of smallholder farmers is far below what is needed to contain the disease. Farmers give different reasons for this practice, including land shortage, and lack of information about the nature of the pathogen (Chapter 3). The recently developed quality declared seed (QDS) production guideline requires at least five years of crop rotation with non-Solanaceous crops if bacterial wilt is observed in a potato field (ESA, 2015). Also, the findings of our action research, Chapter 6, confirms that a long interval of crop rotation is not feasible for most of the farmers, including both seed and ware potato producers. This practice makes the implementation of the QDS scheme impractical and contributes to the disease spreading.

Latently infected seed potato

Infections of bacterial wilt in potato may not show symptoms under some conditions. Latent infections are caused by complex plant-environment interactions, although they are not well understood. But such infections pose a serious risk by spreading the disease widely unnoticed. A recent study conducted in the Ethiopian potato innovation system has shown that latently infected seeds of improved potato varieties distributed to different parts of the country facilitated the spread of the disease (Abdurahman et al., 2017). Chapter 5 shows that the genetic diversity of *Ralstonia solanacearum* isolated from potato samples collected from different potato growing areas in the country is Phylotype II alone, which implies a low genetic diversity and confirms the distribution of the same strain across different areas in the country, meaning that the spread was recent. Also, Chapter 4 shows that monitoring committee members only rely on visual observation to diagnose disease occurrence, failing to notice the latent infection. Previous studies have also identified the latent infection as a major factor for the dissemination of the disease in many countries (Elphinstone, 2005; Janse, 2012). Thus, proper procedures for detection of the pathogen need to be followed either in the laboratory or by using appropriate kits in the field.

Soil acidity

Soil acidity affects various soil biological and chemical properties. The soil microbial population depends on the soil pH (Weil and Brady, 2016). Since *Ralstonia solanacearum* is (also) a soil-borne pathogen, its growth and multiplication depend on soil pH and the role of diverse micro-organisms in the soil. Some micro-organisms have antagonistic effects on *Ralstonia solanacearum* (Rousk et al., 2010; Wang et al., 2017). Soil acidity, on the one hand, affects the activities of antagonistic micro-organisms, and on the other hand, it affects the growth of *Ralstonia solanacearum* itself. Chapter 5 adds to the understanding of the biophysical conditions that aggravates bacterial wilt by explaining the association between soil acidification and the incidence of the disease. Bacterial wilt incidence has been found to be high under highly acidic soil conditions. Moreover, it shows that the soil acidification in Ethiopia is pervasive, partly explaining the high incidence of bacterial wilt. Thus, the expansion of soil acidification in the country has intensified the incidence of bacterial wilt in major potato growing areas (Chapter 5). This finding confirms the importance of considering ecological conditions to understand the epidemiology of the disease.

Ecological interdependencies between seed and ware potato farmers

Chapters 3, 4, and 6 add to the understanding of the importance of collective action among seed and ware potato farmers to deal with bacterial wilt due to the ecological interdependencies among them. Seed potato and ware potato producers reside in the same villages and their potato fields boarder one another (Chapters 3, 4, and 6). Due to the interdependencies, bacterial wilt can easily reach seed potato fields when it occurs in ware potato fields and vice versa. The mechanisms through which the disease spreads from one potato field to the other include surface runoff, irrigation water, and free-grazing of livestock on potato fields (Chapters 3 and 6). Once a seed potato lot is infected, the disease can easily go beyond a particular village as the seed is sold to buyers from different areas. Pests such as porcupines could also spread the disease within and between seed and ware potato fields. These pests are common in potato growing areas in the country (Gebru et al., 2017). This challenge is also aggravated by the limited knowledge among farmers regarding the spreading mechanisms of the disease (Chapter 3). The finding of Chapter 4 also shows that despite the ecological interdependency among seed and ware potato growers, the monitoring committee does not monitor what is happening in ware potato producers' fields. This, in turn, affects seed and ware potato producers in other areas who use seed produced in such a condition.

7.4.2. Social factors contributing to the spread of bacterial wilt in potato

In this section, I discuss a range of social factors that have contributed to the spread of bacterial wilt in potato in smallholder potato production system in Ethiopia.

Seed sharing among farmers

Chapter 3 confirms that seed potato sharing is a common practice among smallholder farmers in the country. Farmers share seed potatoes with their neighbours and relatives. Particularly when only a few farmers get access to improved seed potato varieties introduced by governmental or non-governmental organisations, diffusion of improved potato varieties is high among many in the country (Abebe et al., 2013; Tadesse et al., 2017; Tesfaye et., 2013).

A study conducted to trace the diffusion of improved seed potato among farmer' networks in Chencha, Ethiopia, showed that, on average, one farmer shares seed with six other farmers, both within the same village and outside their village (Tadesse et al., 2017). According to Berihun and Woldegiorgis (2013), farmer-to-farmer seed exchange is one of the important means for the diffusion of improved potato varieties in the country. Chapter 2 shows that NGOs and governmental organisations distribute big volumes of seed potatoes and facilitate seed exchange among farmers. Moreover, many emergency seed provision programmes encourage farmer-to-farmer seed sharing in food-insecure areas without due consideration of the need for seed potato quality control, particularly during times of crisis (Worku, 2013). Seed potato sharing among farmers is, therefore, one of the important social factors that contribute to the spread of bacterial wilt in Ethiopia.

Labour, oxen and farm tools exchange

Another social factor that contributes to the spread of bacterial wilt is the exchange of labour, oxen for ploughing and farm tools among potato farmers. In Ethiopia, smallholder farmers exchange labour and farm tools for performing different agricultural activities. Chapters 3 and 6 show that farmers exchange farm tools and labour during planting, weeding and harvesting. The labour exchange arrangement is locally called 'debo'. Due to lack of knowledge about disease spreading mechanisms, farmers do not make any effort to decontaminate farm tools, as shown in Chapter 3. According to Wenneker et al. (1998), *Ralstonia solanacearum* can survive on wood and metals for four and fourteen days, respectively. Hence, contaminated farm tools are an important source of inoculum for the pathogen, and the practice of exchange of labour, oxen for ploughing and farm tools contributes to the spreading of the disease.

Seed potato cooperatives' compromise in enforcing sanctions

Seed potato cooperatives have played a vital role in the diffusion of improved potato varieties by increasing the availability of seeds in Ethiopia (Sisay et al., 2017; Woldegiorgis, 2013). Chapter 4 adds to the understanding of social factors that contribute to the spread of bacterial wilt in potato by analysing how seed potato cooperatives monitor disease occurrence and related challenges. The monitoring committee usually compromises in enforcing sanctions based on bacterial wilt occurrence in seed potato fields. This allows the marketing of infected seeds through cooperatives, as shown in Chapter 4.

Furthermore, Chapter 4 shows that decisions of committees to enforce sanctions are disputed, and the process lacks transparency. Monitoring committee members are also responsible for approving their own potato fields, which raises questions of impartiality. These practices, compounded by a lack of proper disease diagnosis tools, could considerably contribute to the spread of the disease.

Storing seed potato in a common diffused light store

Diffused light store (DLS) has been a plausible technology promoted by research institutes and NGOs operating in the country's potato innovation system. This technology helps farmers store seed potato for more than six months. With the support of different projects and member farmers' contributions, seed potato cooperatives have built DLS for communal use (Woldegiorgis et al., 2013). Seed potato cooperatives aggregate seed produced by their members and store it together in the communal DLS, as shown in Chapter 4. Seed cooperatives search markets and sell the produce collectively (see Figure 7.2). In addition to seed cooperatives, regional bureaus of agriculture and NGOs organise seed farmers' groups to become involved in seed multiplication, give them starter seed obtained from research centres and support them in constructing communal DLS (Abebe et al., 2013).

This practice has a serious implication from the point of view of spreading bacterial wilt. If one farmer brings in infected seed, it can be easily mixed with the produce of other farmers in the communal DLS. Besides, some farmers could bring their neighbours' or relatives' ware potatoes to be stored and sell through the cooperatives, as revealed in Chapter 4. Therefore, due to limitations in the monitoring system developed by seed cooperatives, communal use of DLS is a risk factor that contributes to the spread of the disease. Recently, quality declared seed cooperatives have started labelling and tracing individual farmers' seed produce, and this practice would help make farmers responsible to some extent.

Figure 7.2. Communal diffused light store (DLS) among seed potato cooperatives.

High demand for improved potato varieties

In Ethiopia, there is a high demand for improved potato varieties. But the supply of good quality seed is insufficient. Many farmers are eager to become seed producers since the seed potato business is lucrative as the price of seed potato is more than twice that of ware potatoes. Chapter 4 shows that many seed farmers try to manipulate their potato field and hide the occurrence of bacterial wilt before a field visit by the monitoring committee. They usually try their best to remove all wilting plants.

When the monitoring committee rejects seed potato fields on the basis of infestation by bacterial wilt, farmers whose fields are rejected do not readily accept the decision due to their keen interest to sell as seed, as revealed in Chapter 4. When the committee rejects seed potato fields, those farmers cannot sell through cooperatives. But they can still sell it as seed at a local market to individual farmers since there is a high demand for improved high yielding potato varieties, despite its poor seed quality. This supports earlier findings by Schulz et al. (2013), who indicated that some traders buy ware potatoes from smallholder farmers during harvesting time, store in DLS, and sell them to farmers and other buyers during planting season. This practice of selling ware potatoes as seed because they are improved varieties contributes to the spread of the disease.

Weak extension services

Chapter 3 reveals that farmers have limited knowledge about bacterial wilt disease dynamics and management methods. Due to a lack of knowledge about the disease and how it spreads, many farmers rogue an infected plant and throw it away at their farm side or in ditches. This practice spreads the disease further instead of controlling it. The limited knowledge among farmers is explained mainly by weak extension services on crop disease management.

In Ethiopia, extension service is largely provided by government agricultural offices. NGOs and research institutes also offer extension services to a limited extent. The extension service delivery is driven by the technology transfer perspective, as explained in Chapter 2. In the extension service, more focus is given to seed potato producers who actively participate in trainings, participatory variety evaluations, and participatory seed multiplication through farmer research groups. Ware potato farmers are seen as technology adopters, and they are only invited to attend farmers' field days organised to demonstrate various potato related technologies, including improved potato varieties, use of fertilisers, and quality seed multiplication and post-harvest handling practices (Berihun and Woldegiorgis, 2013; Kebede et al., 2013; Woldegiorgis et al., 2013). But the technology transfer approach is not enough to help farmers deal with complex bacterial wilt, which is a complex socio-ecological problem, as indicated in Chapter 6.

Chapter 3 shows that potato farmers get information on bacterial wilt from different sources, including extension workers, researchers, fellow farmers, and seed cooperatives. But the information that the farmers get is primarily on disease management methods such as roguieng of infected plants, use of disease-free seeds and crop rotation. Further, as revealed in Chapter 6, farmers think that most of the recommended disease management methods that researchers and extension workers advise them to implement are not feasible in their context. The existing extension approach did not bring the required result, as confirmed in Chapter 3. As a result, farmers' practices to deal with bacterial wilt are ineffective and even contribute to the spread of the disease.

7.3. Technical innovations for management of bacterial wilt in potato

In this section, technical innovations that could enhance the management of bacterial wilt in smallholder potato production in Ethiopia are discussed.

Ameliorating soil acidity

Chapter 5 shows that lime application has significantly improved soil pH and reduced bacterial wilt incidence. This finding adds to the understanding of alternative management methods to suppress the pathogen, *Ralstonia solanacearum*. Hence, addressing the soil acidity problem is required to reduce the incidence of bacterial wilt. To this end, lime application needs to be taken as one of the important components of an integrated disease management approach to deal with bacterial wilt in potato production in Ethiopia. There is currently a limited supply of lime in the country since there are only a few lime crushing plants. According to Agegnehu et al. (2019), the price of lime is about 1000 Ethiopian Birr/ton at a lime crushing plant (~ 30 Euro/ton). This appears to be beyond the purchasing power of subsistent farmers given the large quantities of lime required to improve soil acidity within a short time considerably. However, lime has a residual effect and its effect can last for more than five years. Unlike fertilisers, the application of lime is not needed every season (Kisinyo et al., 2014; Lukin et al., 2003).

Potato is an acid-tolerant crop and grows well under acidic soil conditions (4.5-6.0). Hence, farmers in the highly acidic highlands of the country can expand potato production as it is a good alternative to cereals, which are sensitive to acidic soil conditions. However, if the disease is not controlled well, acidic conditions would further intensify disease incidence, resulting in considerable yield loss. Therefore, dealing with soil acidity could help reduce the impact of the disease in areas affected by soil acidification and sustain potato production.

Changing potato cooperatives' existing seed stock

The gap between the demand and supply for early generation seeds (pre-basic and basic) is huge in the Ethiopian potato innovation system (Woldegiorgis, 2013). As a result, many seed potato cooperatives could not manage to renew their seed stock regularly. Several studies show that a lack of frequent renewal of seed stock leads to genetic degradation and disease build-up

(Kassa and Chindi, 2013; Gildemacher et al., 2009; Struik and Wiersema, 1999).

In Ethiopia, limited capacity among the research institutes has been a critical constraint concerning the supply of clean and adequate early-generation seeds. Recently, efforts to enhance the production of mini tubers through aeroponics is an important step, but it is insufficient. However, the current capacity of the research institutes is by far too low, given the demand. Additional efforts need to be made to enhance the supply of disease-free early-generation seeds. Since bacterial wilt is embedded in the seed system infecting the cooperatives' seed stock, it is imperative to support seed cooperatives to replace their entire seed stock with disease-free seed completely. But this may not be feasible to implement at one time due to the limited supply of early-generation seed as mentioned earlier. Coordinated efforts among research institutes and NGOs could help alleviate the shortage of clean seeds. Encouraging the private sector to get involved in seed potato business could also enhance the supply of disease-free early-generation seeds.

Positive selection and rogueing

Positive selection is a practice of selecting healthy looking plants and harvest them separately to use for seed. This practice reduces seed degeneration and improves seed stock. It is also vital to avoid further spread of seed-borne diseases such as bacterial wilt (Struik and Wiersema, 1999). Particularly, ware potato producers could considerably benefit from this practice to improve their seed stock and reduce bacterial wilt incidence. A study conducted by Gildemacher et al. (2011) showed that positive selection could be a promising approach to reduce bacterial wilt and improve seed stock in smallholder potato production. Besides, the farmers' current practice of rogueing does not help to prevent further spread of the disease, as shown in Chapter 3 because of poor disposal methods. Hence, it is essential to improve the practice of rogueing. Farmers need to dispose of diseased plants by burning them safely.

Controlling the quality of early generation seed

Regional seed regulatory bodies are responsible for seed quality assurance and seed related regulatory activities in their respective regions. However, they have limited technical capacity, only a few inspectors, logistics, and laboratory facility constraints. They also mainly focus on cereals such as maize and wheat, as shown in Chapter 2. Although regional seed regulatory bodies are mandated to inspect and regulate the quality of early generation seed potatoes produced by agricultural research institutes, so far, they have not done significant work in this regard. Given the current wide prevalence of bacterial wilt in the country, it is crucial to test the quality of early generation seeds before they are distributed to seed producer farmers.

Similarly, cooperatives' seed stock needs to be regularly tested through appropriate methods such as enzyme-linked immunosorbent assay (ELISA) to detect latent infection of *Ralstonia solanacearum*. A recently established national molecular laboratory could also support the quality checking of early generation seeds if appropriate reagents are made available to make use of polymerase chain reaction (PCR) – based methods (Prior and Fegan, 2015; Opina et al., 1997). Aside from improving the supply of laboratory chemicals, training laboratory technicians on optimized protocols to detect the pathogen is needed.

7.4. Social innovations for management of bacterial wilt in potato production

This section presents discussions on social innovations that could enhance the management of bacterial wilt in smallholder farmer potato production in Ethiopia. Technical innovations discussed above (Section 7.3) may not necessarily be feasible and acceptable due to the lack of appropriate social arrangements discussed in this section.

Collective and coordinated action

As noted in Chapter 4, smallholder farmers cannot control bacterial wilt effectively through individual efforts alone due to the interdependence relationship between seed and ware potato farmers. Efforts that have been made so far focused mainly on an integrated approach to manage the disease. An integrated disease management approach that includes a combination of crop rotation, removal of volunteer plants, removal of potato haulms, cut-off drains to divert surface runoff, and cleaning farm tools, is vital to deal with the disease in Ethiopian smallholder context. But the implementation of these measures can only be effective if all farmers (seed and ware producers) in the same village cooperate in implementing them.

Interventions that strive to deal with bacterial wilt in potato production should go beyond an integrated disease management approach and enhance collective action among seed and ware potato farmers. Farmers can also develop community-based bylaws and sanctions, as shown in Chapter 6, to enable collective action among themselves. A self-monitoring system could be organised to monitor adherence to the agreed actions. To this end, as noted in Chapter 4, essential elements of a monitoring system should be considered carefully. This is expected to foster collective action.

Furthermore, effective management of bacterial wilt requires coordinated action among multiple actors at different levels, as shown in Chapter 2. Therefore, aside from a village-level collective action among farmers, regional or national level multi-stakeholder collaborations are indispensable to contain the spreading of the disease in the country. This requires involving various actors in the potato innovation system and joint learning (social learning) towards shared objectives to respond to the disease problem effectively. To this end, innovation platforms of multiple actors could stimulate and facilitate a coordinated action to combat the disease (Kilelu et al., 2013; Klerkx et al., 2012; Van Mierlo et al., 2010). Moreover, the integration of scientific and local knowledge would enable effective management of the disease in a smallholder context, as shown in Chapter 6.

Arranging a compensation mechanism for seed producers

Seed producers are eager to get their seed sold through cooperatives due to the considerable price variation between seed and ware potatoes, as noted in Chapter 4. When their seed potato field is rejected on the basis of bacterial wilt or another disease infestation, farmers are required to sell seeds as ware potato. The problem is aggravated when infected seed potato stored in DLS has to be dumped due to bacterial wilt infection. In this case, farmers cannot sell it as ware because the tubers have already started sprouting and have turned green. Then, farmers try to find alternative ways to sell the infected seed at local markets. To avoid such risk, due to the current high prevalence of bacterial wilt, some seed producers prefer to sell their seed produce as ware at harvesting time, as shown in Chapter 4. This practice negatively affects the already undeveloped seed system.

One of the possible interventions that could help alleviate the above challenge is arranging a compensation mechanism for seed producers through an insurance scheme. Recently, several studies have reported the implementation of crop insurance to avert risk during extreme weather events such as drought (Degefa, 2016; Eze et al., 2020; Haile et al., 2020). Hence, compensation through insurance schemes is an innovative approach that could safeguard seed producers and support efforts to deal with bacterial wilt in potato production.

Strengthening a quarantine system to regulate the movement of seeds

Many countries have categorized *Ralstonia solanacearum* as a quarantine pathogen, and regulatory measures helped minimize the spread of the disease (Janse, 2012). Because of the stringent quarantine measures taken, bacterial wilt is currently considered as a manageable problem in many developed countries even though it used to be a devastating threat to their potato production some years back (Janse, 2012).

In Ethiopia, the quarantine system is weakly developed, and it controls only the movement of pests with the import and export of plant materials (Chapter 2). It lacks the capacity to address the movement of infected seeds from one region to the other within the country. Due to the lack of a quarantine system that controls seed potato movement within the country, a latently infected seed has been moving freely from one region to the other. Furthermore, the existing quarantine system is highly centralized, and it is the responsibility of the national Ministry of Agriculture and Natural Resources as it deals with the export and import of plant commodities. Given the current devastating problem of bacterial wilt, strengthening a quarantine system that involves regional bureaus of agriculture is needed to regulate movement of infected potato seeds across regions. This would contribute to efforts towards safeguarding the country's potato production by curbing the devastating disease.

Strengthening seed cooperatives' monitoring system

Formal seed certification does not appear to be implemented in Ethiopia shortly. Chapter 2 shows that strengthening the capacity of seed potato cooperatives is mandatory in the face of the current disease prevalence. Aside from improving the supply of disease-free early generation seeds to the seed potato cooperatives (as discussed above), effective management of the disease requires improving the monitoring system of the seed cooperatives (Chapter 4). Particularly, the technical capacity of the monitoring committee members needs to be enhanced to make correct disease diagnosis and enforce sanctions. The scope of the monitoring system should also go beyond seed farmers and include ware potato farmers. In addition, diagnostic kits that support disease diagnosis at a field level would improve the efficacy of the monitoring system. The existing self-monitoring system can also be supported by peer monitoring. This requires encouraging individual seed and ware potato farmers to monitor disease occurrence in their respective neighbours and communicate to the committee members. This could highly benefit from communication using mobile phones. If the monitoring system of seed potato cooperatives is strengthened, the possibility of producing and selling infected seeds is minimized, which controls the disease from spreading further.

Broadening extension approaches

The current technology transfer approach of the Ethiopian extension system is problematic in view of managing complex potato diseases like bacterial wilt. Organising extension through a combination of experiential and social learning is a prominent way to enhance the capacity of farmers to deal with bacterial wilt in potato effectively, as shown in Chapter 6. Experiential learning is an approach by which an individual learns through experience, whereas social learning is an interactive process through which interdependent actors learn for joint action (Keen et al., 2005; Leeuwis, 2004; Van Mierlo and Beers, 2018). Since bacterial wilt in potato is a complex socio-ecological problem, both social and technical innovations are needed to address it. To this end, involving seed and ware potato farmers in the same village together in a learning intervention is crucial. Technical issues such as management methods and disease diagnosis are better learned through experiential learning approach. Social arrangements like bylaws and sanctions to foster collective action among seed and ware potato farmers are developed through social learning process, as indicated in Chapter 6.

All in all, this thesis shows that the effective management of bacterial wilt requires an integration of different technical and social innovations, as discussed in the above section. Various factors at different levels (farm to the system) contribute to the spreading of the disease. A concerted effort is needed among the key actors in the country's potato innovation system, and measures need to be taken at different levels. As frontline actors to deal with the disease, seed and ware potato farmers need to organise themselves to act collectively in their respective villages.

7.5. Similarities and differences between bacterial wilt and late blight of potato in Ethiopia

In this section, a brief discussion on the similarities and differences between bacterial wilt and late blight is presented in view of their management in the context of the Ethiopian potato production system.

There are late blight resistant potato varieties in Ethiopia, which many farmers are planting to control the disease and to get better yields, as indicated in Chapter 3. However, there is no known resistant potato variety for bacterial wilt so far. Ethiopian smallholder farmers use chemicals (e.g., ridomil and mancozeb), whereas there is no chemical available to deal with bacterial wilt. Management of both late blight and bacterial wilt could be enhanced through appropriate learning interventions, as indicated in Chapter 6 and Damtew et al. (2020). To this end, social learning and experiential learning are appropriate approaches to organise extension that fosters effective management of both diseases. Furthermore, both seed and ware potato farmers are interdependent, and they need to make collective efforts to deal with both diseases, as noted in Chapters 3 and 6. Farm sanitation and hygiene practices such as crop rotation and removal of volunteer plants are also crucial for both diseases. Quality declared seed production scheme has no standards for field monitoring of late blight while there is a zero-tolerance level for bacterial wilt. This could be explained by the fact that late blight is primarily airborne, whereas bacterial wilt is soil-, seed- and water-borne. But the actual reason why a standard is not provided for late blight is not clear.

Adjusting planting time is possible to control late blight since it does not occur during the off-season (during a short rainy season). But bacterial wilt is not seasonal, and it always occurs both during the main growing season and the off-season, as shown in Chapter 3. Late blight and bacterial wilt are aggravated in seed storage if infected seed is stored (Elphinstone, 2007; Stevenson et al., 2002; Struik and Wiersema, 1999). Hence, proper post-harvest handling of seed is essential to control both diseases by smallholder farmers. Previous studies showed the presence of only the A1 mating type of *Phytophthora infestans* isolates in Ethiopia (Schiessendoppler and Molnar, 2002; Shimelis, 2015). This shows that the population of the pathogen is not diverse and thereby can be controlled by developing resistant potato varieties, provided resistance management is properly developed. Likewise, so far, only Phylotype II of *Ralstonia solanacearum* strains was reported in the Ethiopian potato production system, as mentioned in Chapter 5 and Abdurahman et al. (2017).

For late blight control, one of the main challenges is the lack of a decision support mechanism to optimize the application of chemicals. There are many decision support systems available allowing commercial farmers in developed countries to apply chemicals to control late blight in a tailor-made fashion (Cooke et al., 2011). The wide use of mobile phones by smallholder farmers could be considered as an opportunity for information sharing to try a decision support system in Ethiopia. But the feasibility of such novel technologies is hardly possible in the current context of Ethiopian smallholder farmers given lack of meteorological facilities to predict local weather conditions accurately. Monitoring of the inocula of the pathogen to forecast disease occurrence is also challenging. Furthermore, limited skills among farmers, ecological diversity, and poor economic conditions apparently constrain the implementation of an advanced decision support system in small-scale Ethiopian potato production. For bacterial wilt, there is no decision support system to address the problem. It is also difficult to develop due to the nature of the life cycle and the dissemination of the pathogen. In all, despite the variations between bacterial wilt and late blight, appropriate learning intervention could be organised together to control both diseases, involving seed and ware potato farmers in the same area.

7.6. Recommendations for policy and future research

The current wide spread of bacterial wilt is of significant concern to the country's potato production and food security initiatives. The finding of this thesis can serve as a wake-up call for the government and other actors to take coordinated steps to contain the current outbreak of the disease. It shows future directions that have significant policy implications for combating the disease in smallholder farmers' context and safeguarding food security efforts:

- The government and other actors in the Ethiopian potato innovation system need to take stringent measures to contain the disease and control it from spreading further. Aside from implementing feasible disease management methods, developing a strict quarantine system at national and regional levels enhances the efficacy of disease management at various levels.
- Development projects that strive to support the formation of seed potato cooperatives and the supply of improved seed potatoes to smallholder farmers need to pay more attention to the sustainability of seed production in the face of the widespread of bacterial wilt. It is important to keep the balance between agronomic practices and crop protection as the disease could jeopardize their efforts. Developing the capacity of the existing seed potato cooperatives to respond well to this devastating disease is also needed.
- The current linear extension approach that focuses on technology transfer alone will not solve the problem. New social arrangements (rules, sanctions, monitoring systems, etc.) are critically important to deal with the disease effectively. Bottom-up approaches have to be given due emphasis as steps to disease management. Farmers are better positioned

in identifying the feasibilities of the recommended disease management methods in their local context. Hence, appropriate learning mechanisms (combining experiential and social learning) should be considered to foster the integration of scientific and local knowledge and help them recognise their interdependency.

- Collective action should be encouraged among seed and ware potato farmers since the disease is a collective risk problem. The current focus on seed potato growers alone does not help the country's potato production respond to the disease. The interdependence between different types of farmers should be appreciated and inform development interventions that strive to improve potato production. Strengthening coordination among various actors is in the potato innovation system is also essential.
- Improving the quality and quantity of seed potato should be given a high priority. If subsistence farmers do not get access to quality seed, they would continue to use infected seeds. Particularly, food insecure farmers cannot afford to skip a single growing season without planting potato. They may decide to use any available seed tuber lot despite its low quality, which further spreads the disease and aggravates its incidence.
- Dealing with soil acidity is a prerequisite to enhance the efficacy of bacterial wilt in potato management efforts. Lime application helps reduce the incidence of the disease and improves soil acidity. The government and other actors, therefore, need to consider management of soil acidity as an additional package to their interventions striving to improve potato production.

7.7. Recommendations for future research

In this section, based on the findings presented in different chapters of this thesis, recommendations for further research are provided:

- Future research on a self-monitoring system through comparative analysis across multiple seed cooperatives (e.g., wheat, maize, potato) would be useful to improve the quality of seed produced by cooperatives. Such analysis can also provide interesting insights into how smallholder farmers could manage different complex crop diseases.
- Future research could determine the socio-economic impacts of the disease on smallholder potato farmers and on other actors along the potato value chain. A similar analysis should also identify the economic feasibility of lime application for soil acidity

amelioration and suppression of bacterial wilt.

- Future research could investigate biological control methods to support the management of bacterial wilt in countries like Ethiopia, where the genetic diversity of the pathogen is low. Biological methods could be combined with other strategies to suppress the disease, particularly in infected fields.
- It can also be useful for further research to investigate host weeds for *Ralstonia solanacearum* in Ethiopian potato production systems. The identification of host weeds has critical implications for the management of bacterial wilt.

7.8. Concluding remarks

Bacterial wilt in potato is a widespread complex problem that has currently threatened the livelihood of millions of smallholder potato farmers in Ethiopia. The current literature on crop protection shows an integrated disease management approach as an effective practice to control this disease. However, this thesis argues that focusing on the integrated disease management approach alone is insufficient to deal with bacterial wilt in potato production in the smallholder farmers' context. Aside from combining different disease management methods, collective action among the interdependent farmers, learning, monitoring, coordination, and communications involving various actors in the potato innovation system are essential to deal with the disease effectively. Collective action is not an optional approach for smallholder farmers; instead it is the only way to contain the disease. The thesis uncovered how biophysical processes and the practices and understandings of actors in the potato innovation system spread and reproduce bacterial wilt in Ethiopia. Also, it shows how soil acidity intensifies the disease, the importance of lime application to reduce disease incidence, and low genetic diversity of the pathogen (*Ralstonia solanacearum*) in the country. Also, the thesis contributes to the understanding of what monitoring collective action to address complex crop diseases entails by developing and applying a novel framework consisting of essential elements. All in all, this thesis has shed light on a roadmap to deal with bacterial wilt through the integration of social and technical innovations in smallholder potato production.

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Summary

Potato production is on the rise in developing countries due to its considerable contribution to global food security. The livelihood of millions of smallholder farmers is dependent on this crop. However, various diseases such as bacterial wilt and late blight are primary constraints to potato production. Scholars have been devising different management methods to deal with these and other crop diseases. But the efficacy of most of the recommended integrated disease management methods is limited due to the specific context of smallholder farmers. Even though the importance of considering social and technical dimensions of crop disease management is recognised in the literature, there is a lack of knowledge on how the interplay between social and biophysical conditions aggravate or spread crop diseases. Particularly, information on the management of complex crop diseases that pose a collective risk to the interdependent smallholder farmers is limited. Effective management of crop diseases does not happen in isolation for the broader system, and it requires an improved understanding of the dynamics of social and biophysical conditions and identification of innovations that enhance the management of the diseases. The key aim of this thesis was to examine the social and biophysical factors that explain the widespread of bacterial wilt in potato in Ethiopia and investigate what technical and social innovations could help deal with the disease.

In Chapter 2, I identified various actors in the potato innovation system and studied how they understood the problem of bacterial wilt and late blight. The actors did not recognise the interdependency among themselves for effective management of the diseases. The extension system primarily followed a top-down technology transfer approach with limited achievement. Furthermore, only seed potato producers were targeted despite the socio-ecological interdependencies among seed and ware potato producers. Seed potato quality control approach was also problematic as there was no formal seed certification system in the country.

Guided by the findings in Chapter 2, Chapter 3 focused on understanding farmers' knowledge and practices of bacterial wilt and late blight management. There was limited knowledge among farmers concerning the cause, spreading mechanisms, and management methods of the diseases. They did not recognise the causes of bacterial wilt and late blight as they did not link these diseases to living microorganisms that are contagious. Furthermore, farmers' practices such as rogueing spread the disease further instead of controlling it as many farmers were

uprooting and throwing away infected plants at the farm side. Crop rotation interval was also limited, and the majority of the farmers were practicing one season interval only.

Chapter 4 aimed at understanding how seed potato cooperatives monitor the occurrence and management of bacterial wilt. Seed potato cooperatives play a vital role in Ethiopian seed potato system. We developed a novel framework consisting of elements of a monitoring system for managing a complex disease like bacterial wilt in potato. The development of the framework was based on common-pool resource literature. The studied seed potato cooperatives had organised a self-monitoring system to address the problem of bacterial wilt. The cooperatives had committees which were responsible for enforcing sanctions on cooperative member farmers who did not adhere to the bylaws. The monitoring system's efficacy was questionable as the committees rarely rejected potato fields on the basis of disease occurrence or malpractices of the farmers. They also depended on visual observation to diagnose the disease, which failed to detect latent infection of the pathogen that causes bacterial wilt. Furthermore, many farmers did not trust the committees. The monitoring system did not address ware potato producers despite the interdependency among the farmers. The study indicated the importance of collective action among seed and ware potato producers. Hence, strengthening the capacity of seed potato cooperatives could enhance effective management of the disease by mitigating marketing infected seeds since the role of seed cooperatives will continue to be significant in the country’s seed system.

Chapter 5 adds to the understanding of the biophysical condition that has aggravated bacterial wilt incidence in the country—association between soil acidification and bacterial wilt as investigated. Most of the main potato growing districts were affected by soil acidity, and this, in turn, aggravated the incidence of bacterial wilt. Field experiments to test the effect of mitigating soil acidity using lime showed a significant reduction in bacterial wilt incidence. Furthermore, isolation and characterisation of *Ralstonia solanacearum* strains indicated Phylotype II. Thus, ameliorating soil acidity needs to be considered as a requirement to manage bacterial wilt under acidic soil conditions effectively.

In Chapter 6, we conducted action research to investigate how seed and ware potato farmers learn to control bacterial wilt. The learning intervention was designed based on the findings in Chapters 2 and 3. Experiential learning and social learning approaches were found to be complementary in enhancing the capacity of smallholder farmers to deal with bacterial wilt.

Farmers learned disease dynamics and how to deal with the problem collectively. They also identified the feasibility of various methods recommended to manage the disease in their context.

In Chapter 7, key social and biophysical factors that spread bacterial wilt were discussed. Social and technical interventions that could enhance the management of the disease were also discussed. In general, this thesis has shed light on social and biophysical conditions that spread bacterial wilt. This thesis argues that an integrated disease management approach is not sufficient to deal with complex diseases like bacterial wilt and late blight. Collective action among the interdependent smallholder farmers and coordination among the actors in the potato innovation system are needed.

Samenvatting

In ontwikkelingslanden neemt de aardappelproductie toe vanwege de aanzienlijke bijdrage die het levert aan de wereldwijde voedselzekerheid. Het levensonderhoud van miljoenen kleinschalige boeren is afhankelijk van dit gewas. Verschillende ziekten, zoals bruinrot (veroorzaakt door *Ralstonia solanacearum*) en fytoftora (veroorzaakt door *Phytophthora infestans*), vormen echter belangrijke beperkingen voor de aardappelproductie. Wetenschappers hebben verschillende managementmethoden ontwikkeld om met deze en andere gewasziekten om te gaan. Maar de doeltreffendheid van de meeste van de aanbevolen geïntegreerde methoden voor ziektebestrijding is beperkt vanwege de specifieke context van kleinschalige boeren. Hoewel het belang van het in ogenschouw nemen van sociale en technische dimensies van gewasziektebeheer in de literatuur wordt erkend, is er een gebrek aan kennis over hoe het samenspel tussen sociale en biofysische condities gewasziekten verergert of verspreidt. Met name de informatie over het beheer van complexe gewasziekten die een collectief risico vormen voor de onderling afhankelijke kleinschalige boeren is beperkt. Effectief beheer van gewasziekten vindt niet geïsoleerd plaats van het bredere systeem en het vereist een beter begrip van de dynamiek van sociale en biofysische omstandigheden en identificatie van innovaties die het beheer van de ziekten verbeteren. Het belangrijkste doel van dit proefschrift was om de sociale en biofysische factoren te onderzoeken die de wijde verbreiding van bruinrot in aardappelen in Ethiopië verklaren en te onderzoeken welke technische en sociale innovaties zouden kunnen helpen bij het bestrijden van de ziekte.

In hoofdstuk 2 identificeerde ik verschillende actoren in het aardappelinnovatiesysteem en bestudeerde ik hoe ze het probleem van bruinrot en fytoftora interpreteerden. De betrokken actoren erkenden hun onderlinge afhankelijkheid voor een effectief beheer van de ziekten niet. Het voorlichtingssysteem volgde voornamelijk een top-down benadering van technologieoverdracht met beperkte resultaten. Bovendien waren alleen de pootaardappeltelers het doelwit, ondanks de sociaal-ecologische afhankelijkheden tussen de pootgoed- en consumptieaardappeltelers. De aanpak van de kwaliteitscontrole van pootaardappelen was ook problematisch omdat er in het land geen formeel systeem voor pootgoedcertificering bestond.

Geleid door de bevindingen in hoofdstuk 2, richtte hoofdstuk 3 zich op het begrijpen van de kennis en praktijken van boeren met betrekking tot het beheer van bruinrot en fytoftora. Bij boeren bestond er beperkte kennis over de oorzaak, de verspreidingsmechanismen en de beheersmethoden van de ziekten. Ze kenden de oorzaken van bruinrot en fytoftora niet, omdat ze deze ziekten niet in verband brachten met besmettelijke levende micro-organismen. Bovendien verspreidden praktijken zoals selecteren de ziekte verder in plaats van het onder controle te houden, omdat veel boeren geïnfecteerde planten optrokken en aan de kant van het veld weggooiden. Gewasrotatie was ook beperkt en de meerderheid van de boeren werkte met een interval van slechts één seizoen tussen opeenvolgende aardappelgewassen.

Hoofdstuk 4 was bedoeld om te begrijpen hoe pootaardappelcoöperaties het vóórkomen en beheren van bruinrot monitoren. Pootaardappelcoöperaties spelen een cruciale rol in het Ethiopische pootaardappelsysteem. We hebben een nieuw raamwerk ontwikkeld dat bestaat uit elementen van een monitoringsysteem voor het beheersen van een complexe ziekte zoals bruinrot in aardappel. De ontwikkeling van het raamwerk was gebaseerd op 'common-pool resource' literatuur. De bestudeerde pootaardappelcoöperaties hadden een zelfmonitoringsysteem opgezet om het probleem van bruinrot aan te pakken. De coöperaties hadden commissies die verantwoordelijk waren voor het opleggen van sancties aan leden die zich niet aan de regels hielden. De doeltreffendheid van het monitoringsysteem was twijfelachtig daar de commissies aardappelvelden zelden afkeurden op basis van de aanwezigheid van ziekten of vanwege bestaande wanpraktijken. Ze maakten ook enkel gebruik van visuele waarneming om de ziekte te diagnosticeren waardoor latente infectie niet gedetecteerd kon worden. Bovendien vertrouwden veel boeren de commissies niet. Ondanks de onderlinge afhankelijkheid van de boeren was het monitoringsysteem niet gericht op telers van consumptieaardappelen. De studie identificeerde het belang van collectieve actie onder de producenten van pootgoed- en consumptieaardappelen. Pootgoedcoöperaties zullen een belangrijke rol blijven spelen in het pootgoedsysteem van het land. Het versterken van de capaciteit van pootaardappelcoöperaties zou daarom het effectieve beheer van de ziekte kunnen verbeteren door het op de markt brengen van geïnfecteerd pootgoed te verminderen.

Hoofdstuk 5 draagt bij aan het begrip van de biofysische conditie die de aanwezigheid van bruinrot in het land heeft verergerd middels onderzoek naar de relatie tussen verzuring van de bodem en bruinrot. De meeste van de belangrijkste aardappelteeltdistricten werden aangetast door bodemverzuring en dit verergerde op zijn beurt de aanwezigheid van bruinrot. Veldexperimenten om het effect van verhoging van de zuurgraad met kalk te testen, toonden een significante vermindering van bruinrot aan. Bovendien duidden isolatie en karakterisering van *Ralstonia solanacearum*-stammen op Fylotype II. Het verhogen van de zuurgraad van de bodem moet worden beschouwd als een vereiste om bruinrot onder zure bodemomstandigheden effectief te beheersen.

In hoofdstuk 6 hebben we actieonderzoek uitgevoerd om te onderzoeken hoe pootgoed- en consumptieaardappeltelers leren om bruinrot te bestrijden. De leerinterventie was ontworpen op basis van de bevindingen uit hoofdstuk 2 en 3. Er werd vastgesteld dat ervaringsleren en sociale leerbenaderingen complementair zijn in het vergroten van het vermogen van kleinschalige boeren om met bruinrot om te gaan. Boeren leerden de ziektedynamiek kennen en leerden hoe ze collectief met het probleem konden omgaan. Ze stelden ook de haalbaarheid vast van verschillende methoden die worden aanbevolen om de ziekte in hun context te behandelen.

In hoofdstuk 7 werden belangrijke sociale en biofysische factoren besproken die bruinrot verspreiden. Ook werden sociale en technische interventies besproken die de behandeling van de ziekte zouden kunnen verbeteren. Over het algemeen heeft dit proefschrift duidelijk gemaakt hoe sociale en biofysische condities helpen bruinrot te verspreiden. Dit proefschrift stelt dat een geïntegreerde aanpak van ziektebeheersing niet voldoende is om complexe ziekten zoals bruinrot en fytoftora aan te pakken. Collectieve actie onder de onderling afhankelijke kleinschalige boeren en coördinatie tussen de actoren in het aardappelinnovatiesysteem zijn nodig.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Review of literature on an innovation systems approach, and biology and epidemiology of bacterial wilt of potato

Writing of project proposal (4.5 ECTS)
- Explorative design for bacterial wilt management in potato production systems in Ethiopia

Post-graduate courses (11.6 ECTS)
- Tailor-made course for PhD students on INREF-EVOCA project; WUR (2016)
- Research methodology: from topic to proposal; WUR (2016)
- Qualitative data analysis with Atlas.ti; WUR (2016)
- Introduction to R for statistical analysis; WUR (2019)

Laboratory training and working visits (7 ECTS)
- Isolation of *Ralstonia solanacearum* and DNA extraction; Agricultural Biotechnology Research Centre in Holeta, Ethiopia (2019)

Deficiency, refresh, brush-up courses (3 ECTS)
- Research methods microbiology; WUR (2018)

Competence strengthening / skills courses (4.7 ECTS)
- The essentials of scientific writing and presenting; WUR (2016)
- Data management planning; WUR (2016)
- Information literacy for PhD including EndNote introduction; WUR (2016)
- Extreme citizen science; WUR (2016)
- Effective writing strategies; (2019)

Scientific integrity / ethics in science activity (0.4 ECTS)
- Dilemmas in fieldwork and research ethics; WUR (2016)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

PE&RC Workshop carrousel (2016)
PE&RC Weekend first year (2016)

Discussion groups / local seminars / other scientific meetings (9.5 ECTS)
- 1st International EVOCA workshop; oral presentation (2016)
- Centre for Crop System Analysis (CSA) seminars (2016-2019)
- Knowledge, Technology and Innovation (KTI) seminars (2016-2019)
- 2nd International EVOCA workshop (2017)
- 3rd International EVOCA workshop (2018)
- 4th International EVOCA workshop (2019)
- Translational phytopathology meeting (2019)

International symposia, workshops and conferences (3.8 ECTS)
- Plant-soil-microbe interactions for crop and pest management; Wageningen, the Netherlands (2016)
- Workshop on bacterial wilt management in potato production; oral presentation; Addis Ababa, Ethiopia (2017)
- Tropentag: filling gaps and removing traps for sustainable resources development; oral presentation; Kassel, Germany (2019)

Societally relevant exposure (1 ECTS)

- Blog on potato disease management *https://www.rtb.cgiar.org/news/research-recommendations-disease-management-potato-banana/* (2018)

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About the author

Shiferaw Tafesse Gobena was born in Meta Robi district of Oromia regional state, Ethiopia, on May 12, 1981. He grew up in a small village called Buko, where he learned farming activities from his parents and the local community. With the kind support of his elder brother, he moved to Addis Ababa, the capital city, and completed his high school education. He obtained a BSc degree in land resources management and environmental protection from Mekelle University in July 2003. From 2004 to 2008, he worked as a farmer's field school facilitator for Self Help Africa on research for development project focused on potato disease management and soil fertility management. He then joined Addis Ababa University, where he obtained an MSc degree in environmental science in 2010. From 2010 to 2015, he worked for Sasakawa Africa Association, Ethiopian Agricultural Transformation Agency (ATA), ACDI/VOCA, and the International Livestock Research Institute (ILRI) at different capacities. In January 2016, Shiferaw started his PhD study at Wageningen University and Research. He conducted his PhD research on the EVOCA research program, in the Centre for Crop Systems Analysis (CSA), and Knowledge, Technology and Innovation (KTI) groups of Wageningen University and Research.

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