Utrecht University

Master Water Science and Management

Master's Thesis

An Assessment Tool for Microclimate Management to Enhance Ethiopian Crop Production

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Abstract

Ethiopia's economy heavily depends on traditional rain-fed agriculture. However, the Guba Lafto, Amhara region in Ethiopia is highly susceptible to climate change and has a fragile highland ecosystem threatened by land degradation. This results in crop productivity being about 1/3 of the potential. This yield gap and climate change threats highlight the importance of building climate change resilience and increasing agricultural capacity. Effectively managing the microclimate can help increase a farm's resilience to climate change. For Ethiopian farmers and watershed managers to effectively manage the microclimate, an assessment tool that provides guidance is desired. Therefore, this study aims to create an effective and valid assessment tool that assists Ethiopian watershed managers in guiding land and water management practices to improve microclimate conditions for optimal crop production.

First, a solid scientific knowledge base on the microclimate system and its influence on crop production was created. This was done by an in-depth literature study. Second, human interactions with the system regarding land- and water management interventions were defined. This was done by consulting land- and water management guidelines and experts with field experience. Third, by conducting an in-depth literature study, it was researched how these interventions influence microclimate components and crop production. Finally, this knowledge of microclimate processes and human interactions was translated into questions and decision options for an effective and valid assessment tool in the form of a decision tree. To justify, support and improve the decision tree, farmers and watershed managers operating in Guba Lafto, Amhara, were consulted through interviews and focus groups. The evaluation of the decision tree was an iterative process to improve the validity of the decision options and outcomes. This face validation process involving farmers and watershed managers in the tool creation also touches upon the importance of incorporating end-users in an early stage of tool development.

The results of this research are twofold. First, a scientific knowledge base on the microclimate's workings, its effect on crop production and the effect of human interventions on the microclimate. Second, a valid and effective assessment tool that translated the above-mentioned scientific knowledge base into a directly usable form of knowledge that guides its users in improving the microclimate. Increasing a farms' resilience to climate change and enhancing crop production conditions will strengthen local value chains and lead to a higher-value agricultural sector.

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Chapter 1 – Introduction

Agriculture in Ethiopia is dominated by approximately 7 million small, resource-poor farmers, with average landholdings of about 0.5 to 2 hectares in size (Mati, 2006). The country's economy heavily depends on this traditional rain-fed agriculture. However, the Guba Lafto Amhara region in Ethiopia is highly susceptible to climate change, and its agriculture occurs in a fragile highland ecosystem (Chimdesa, 2016). These threats result in crop productivity being about 1/3 of the potential (Awulachew et al., 2008). This gap in potential highlights the importance of building climate-change resilience and increasing agricultural capacity. Increasing a farm's resilience can be achieved by managing the microclimate (Hadid & Toknok, 2020; Ismangil et al., 2016; Van Wijk, 1963). This highlights the importance of developing an effective and valid microclimate management assessment tool that helps Ethiopian farmers guide their land and water management practices and improve crop production. By understanding the microclimate's dynamic system behaviour, a more integrated intervention approach to this system can be developed, which will guide farmers in more beneficial intervention and improvement of their site's resilience.

The microclimate refers to the meteorological and climatological process that manifests itself at a scale with a horizontal range of centimetres up to a hundred meters and a vertical range of centimetres up to ten meters from the ground (Yoshino, 1987). The vertical range of the microclimate is often also determined by the canopy boundary layer (Rotach & Calanca, 2014). On this scale, plants grow, germinate, and become established (Geiger et al., 2003; Rosenberg, 1983). Microclimates result from multiple climatic components. The scope of this research will include the following components: solar radiation, soil moisture, soil temperature, air temperature, air humidity, and wind direction and speed. Due to the high variability in different soil types, surface slope and orientation, and vegetation cover, the microclimate is the climatic scale with the most extensive diurnal range in air temperature and humidity (Yoshino, 1987). This high variability differentiates the microclimate from the climate just a few meters above, where atmosphere mixing processes are more active, leading to more moderate and stable conditions (Unwin & Corbet, 1991; Rosenberg, 1983). On this higher level, climatic conditions are more challenging to control, and there is only a slight chance for humans to modify the global climate (Gliessman, 2015). However, focusing on a microclimatic scale of a small plot or a single planting mound brings the climate back to more manageable levels (Wilken, 1972). Since changes in a landscape lead to changes in the surrounding microclimate, certain land and water management practices can modify the microclimate (Ismangil et al., 2016). As the microclimate is the scale on which plants grow, modifying the microclimate can improve the plant growth conditions. This way, improving the microclimate on a farm level can increase crop production and land productivity (Hadid & Toknok, 2020; Kingra & Kaur, 2017; Van Wijk, 1963). Microclimates are also essential in understanding how ecosystems respond to macroclimatic change (Zellweger et al., 2020). Microclimates can thus increase crop production by strengthening ecosystem resilience through smoothing out climate change impacts (Ismangil et al., 2016). These properties make microclimates a great opportunity in dealing with the effects of global climate change by increasing resilience and providing a buffer against regional climatic stresses (Falk, 2013). Therefore, the microclimate offers much potential as a third way in dealing with climate change next to adaptation and mitigation (Ismangil et al., 2016). Since climate-induced instability will affect levels of food supply, altering social and economic stability (Altieri et al., 2015), increasing microclimatic resilience to climate change is of high importance.

However, when studying biotic responses to global climate change, microclimates are frequently neglected (Zellweger et al., 2020). This lack of consideration makes microclimatic effects often an unintended by-product of landscape changes (Ismangil et al., 2016). Therefore, a shift in focus to microclimates is fundamental as it regulates and determines the natural conditions for crop production. Also, by narrowing down the scope of a system, its resilience can be enhanced (Matalas & Fiering, 1977). Focusing on the microclimate can therefore uncover methods to increase the resilience of a landscape.

Using microclimates to increase resilience and buffer against climate change to optimize crop production boundaries requires knowledge of the microclimatic system dynamics and how this can be influenced and managed. The various microclimate components are inextricably linked to each other. Changing one factor will affect the other parts as well (Ismangil et al., 2016). Understanding the main characteristics of these components and their mutual relations provides the building blocks for understanding how different land and water management practices can transform the microclimate. In other words, a clear description of the behaviour of the system in response to several land- and water management interventions is needed. Currently, most models fail to account for humans' adaptive responses that influence the microclimate components (Srinivasan, 2015). Khan (2017) and Ray et al. (2019) state a growing recognition among water managers to incorporate human actions on the natural system. Thus, to make microclimate management a well-working instrument in improving crop production, a tool that integrates the relation between microclimate and land and water management is desired (Figure 1).

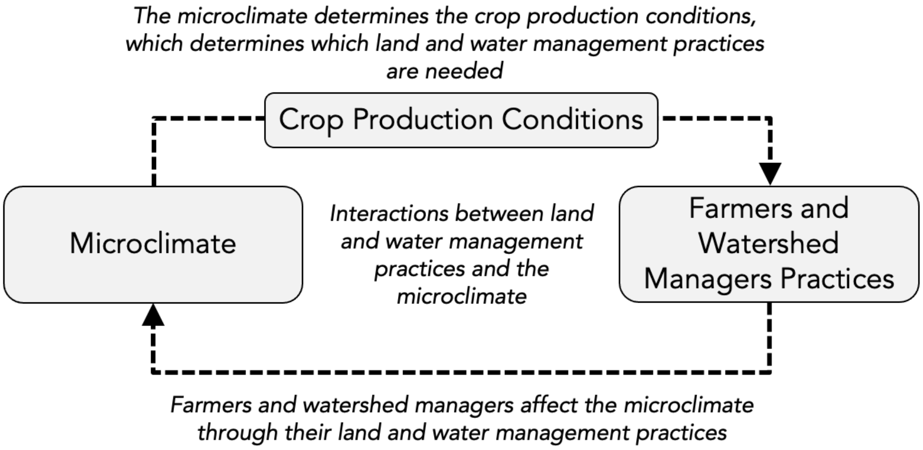

Figure 1 Visual representation of the human-nature interactions between farmers and watershed managers and the microclimate

In this light, the MetaMeta Research Company has expressed its interest in creating an applicable conceptual model for landscape and watershed projects in Ethiopia. This research, therefore, aims to create an assessment tool in the form of a decision tree, which can be used by Ethiopian watershed managers to guide farming practices to improve microclimate conditions for optimal crop production. In other words, this study seeks to determine all the knobs and buttons that watershed managers and farmers have at their disposal to improve the microclimate and translate this knowledge into an assessment tool. Based on a solid scientific knowledge base and local knowledge and expertise on microclimatic processes, such a tool gives guidance in the decision-making processes regarding land and water management practices (Figure 2).

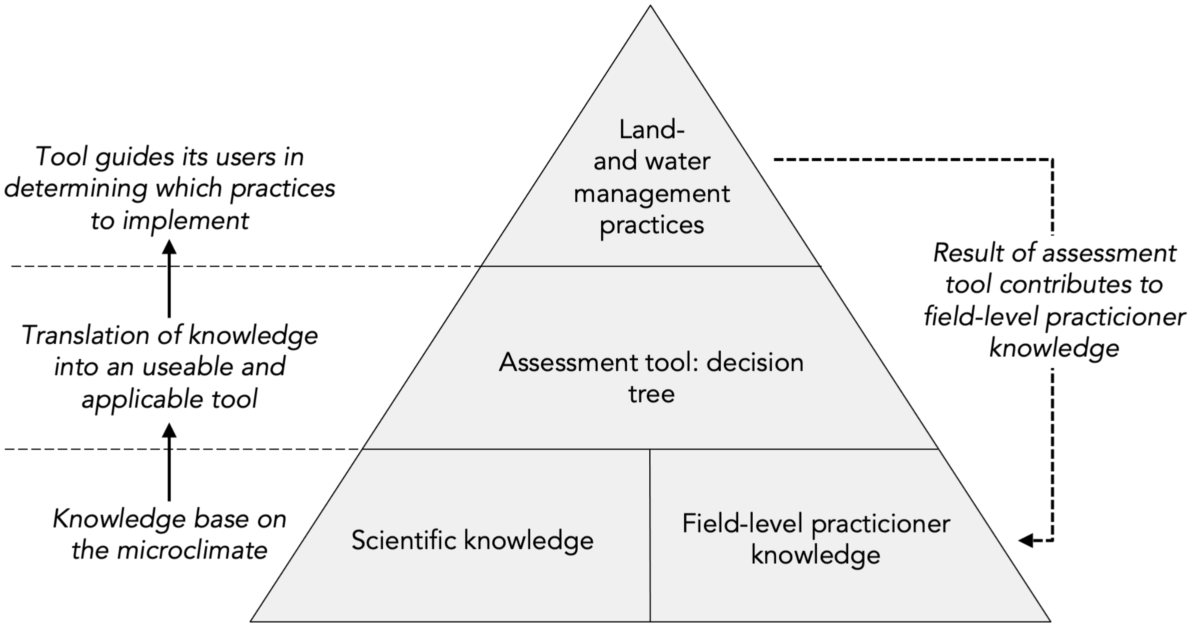

Figure 2 Conceptual model of the microclimate management assessment tool

This results in the following goal of this research:

Create an effective and valid assessment tool that assists Ethiopian watershed managers in guiding agricultural practices to improve microclimate conditions for optimal crop production.

This aim results in the following research questions:

1. How do the microclimate components and their interactions influence crop production?
2. What are the common human interactions with the system in terms of land and water management interventions in Ethiopia?
3. How do these land and water interventions influence the microclimate components and, through that, crop production?
4. How can these farmer-microclimate interactions be translated into questions and decisions for an effective and valid assessment tool to be used in Ethiopia?

By answering these research questions, this research aims to contribute to the scientific knowledge base on how human interventions influence the microclimate and crop production. Simultaneously, focusing on translating this knowledge into directly usable knowledge that watershed managers and farmers can use to enhance their site's resilience and increase crop production. As Ethiopia is considered one of the countries highly susceptible to climate change and crop productivity is about 1/3 of the potential, increasing farm resilience and enhancing crop production will strengthen local value chains and market opportunities, enabling local communities to engage in higher-value agriculture and generate income.

Chapter 2 – Methodology

To achieve the determined research goal, first, a solid scientific knowledge base on the microclimate system and its influence on crop production was created (research question 1). This was done by an in-depth literature study. Second, human interactions with the system regarding land- and water management interventions were determined and defined (research question 2). This was done by consulting Ethiopian land- and water management guidelines and experts with field experience. Third, it was researched how these interventions influence microclimate components and crop production (research question 3). This was also done by an in-depth literature study. Fourth, this knowledge of microclimate processes and human interactions was translated into questions and decisions for an effective and valid assessment tool in the form of a decision tree (research question 4). The prototype decision tree was developed on the knowledge base created by answering research questions 1-3 (bottom-up approach). Since using best practice and knowledge from local experts in developing and verifying the concept model increases a model's reliability (Yin & McKay, 2018), finetuning and evaluation of the prototype decision tree was done through face validation by consulting Ethiopian agricultural workers and watershed managers (top-down approach). Since this was done with people operating in Guba Lafto, Amhara, Ethiopia, the evaluation of the tool is specified for highland agriculture in this context. This face validation was an iterative process to improve the model's accuracy and to represent the real-world system better. Each evaluation cycle provided a new opportunity for refinements (Rounsevell et al., 2012) (Figure 3).

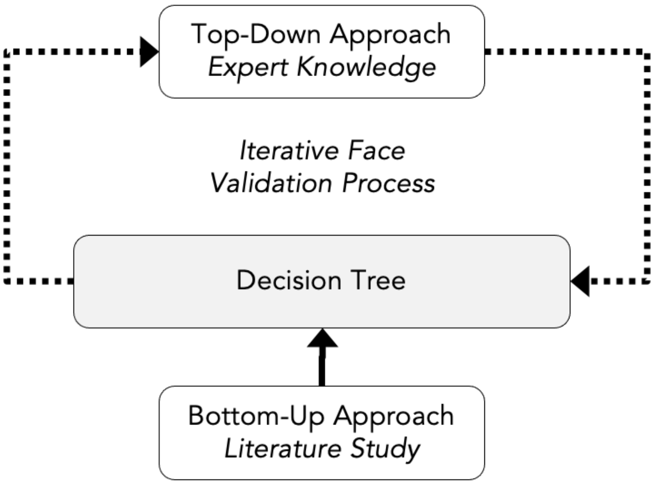

Figure 3 Visual representation of the decision tree creation method. First, the prototype was constructed by a bottom-up approach. Second, this prototype was evaluated and improved through several iterative cycles of face validation by local experts.

Thus, this research consisted of two parts: creating the knowledge base on human-microclimate interactions and translating this knowledge into a practical and valid assessment tool. The research steps and analysis procedures' specific details will be elaborated on in the following two sections (2.1 & 2.2).

2.1 Microclimatic Processes and Human Interactions

Research Question 1: Influence of Microclimate System on Crop Production

The microclimate factors considered are solar radiation, soil moisture, soil temperature, air humidity, air temperature and wind direction and speed. A detailed search strategy was developed and revised appropriately for the following databases: Google Scholar, WorldCat, and Utrecht University library using English only text from established peer-reviewed journals. Relevant academic books and 'grey' literature were also reviewed. A search was conducted for literature providing knowledge of the relationship between microclimate and crop production. As stated in the introduction, the microclimate affects crop production in two ways: direct and indirect through general micrometeorological processes. Therefore, the search was split into two sections for each microclimatic factor: (1) their effect directly on crop production and (2) indirectly by their effect on the microclimate. Keywords and phrases for searches within the databases were based on the research question components (Appendix A – Research Strategy: Key Search Terms). When a search was not successful, the term 'crop production' was replaced by other terms such as 'primary production', 'agricultural production', 'crop growth'. Since this research focuses on the microclimate, every search also included 'microclimate', 'local scale', or 'near ground'. Next, all these findings were documented and formed the knowledge base for the microclimate system part of the tool. For a clearer display of the findings, a conceptual model of the microclimatic system was created.

Research Question 2: Human Interventions

Next, the selection of land- and water management practices (research question 2) was determined by both field experience from MetaMeta co-workers and the Community Based Watershed Management Guideline from the Ministry of Agriculture of Ethiopia (Ministry Agriculture Ethiopia, 2005). Determining the practices was done through an iterative process of consulting the guideline and discussing these findings with MetaMeta co-workers to test if the compounded list aligned with their experience from the field. After two feedback moments, the relevant land- and water management practices for Ethiopia were defined. Next, more background information was searched on each practice to elaborate on them beyond the Community Based Watershed Management Guideline. This gathering of additional information was done by consulting the Google Scholar electronic database, where every practice term was used as a search term consecutively. This was done using the practice term solely and combined with the search terms 'Ethiopia' or 'East-Africa'.

Research Question 3: Human-Nature Interactions

After determining the land and water management practices, the interactions between these interventions and the microclimate (research question 3) were determined by combining the previously generated knowledge on the microclimatic system and an additional literature review on specific practices and their effect on the microclimate. For each practice, a detailed search strategy was developed and revised appropriately for the following (electronic) databases: Google Scholar, WorldCat, and the physical Utrecht University library using English only text from established peer-reviewed journals. This search strategy consisted of a systematic search of each practice term, combined with each microclimate factor. Here the Boolean operator 'AND' was used to find articles that mention both searched topics (e.g., Check Dams AND Soil Moisture). Sometimes this was also combined with terms such as 'effect on' or 'influence on'. Next, all the combinations (e.g., Check Dams and Soil Moisture) were labelled. This labelling was done by consulting the created knowledge base and from this concluding whether an intervention had an increasing (+) or decreasing effect (-) on the separate microclimate components. When there was no significant effect, the label 'not significant' was used.

2.2 Assessment Tool Creation and Evaluation

Research Question 4: Decision Tree Development

Both a bottom-up and top-down approach were conducted to create the heuristic in the form of a decision tree (Figure 3). A bottom-up approach consists of collecting and analysing qualitative data to understand the domain's characteristics. However, this is limited by the qualitative data's scope and richness and the researchers' interpretation (Quiñones & Rusu, 2017; Jaferian et al., 2014). A top-down approach can be used in which theories or existing heuristics are used by experts to improve the heuristics (Jaferian et al., 2014). This approach relies on expert knowledge to modify a theory or existing heuristics, which can be prone to bias. To avoid each approach's limitations, research can combine both a bottom-up and top-down approach to creating heuristics (Quiñones & Rusu, 2017). For this research, this was done by first adopting a bottom-up approach consisting of analysing qualitative data to create the decision tree. Next, a top-down approach was used to justify, support, and combine the identified heuristics into an improved set of heuristics.

Bottom-Up Approach

The first part of the research (research question 1-3) collected empirical data from which a prototype of the decision tool was created. Decision tools start with the root nodes, or decision nodes, representing a choice that will result in the subdivision of all records into two or more mutually exclusive subsets (Song & Ying, 2015). Thus, this node represents a 'test', and the outcome of that test determines to which internal node the user is directed. This internal node then presents another 'test' from which the user is guided to another internal node. This continues until the user arrives at an end node, also called a leaf node. These represent the final result of a combination of decisions. Each path from the root node through internal nodes to a leaf node represents a classification decision rule. (Song & Ying, 2015). For the creation of the prototype, the following steps were taken:

1. The root node was determined by analysing the outcomes to the research question 1-3
2. From this node, splits were made, and from the subsequent internal nodes, new splits were made according to the 'tests' taken. The 'tests' were determined by analysing the outcomes to the research question 1-3 and the additional information on landscape characteristics requirements provided in Appendix D. These requirements were gained by conducting a literature study.
3. This splitting procedure continued until no further 'tests' needed to be made to determine the outcome (leaf node), the advised land and water management practices.

Top-Down Approach

Next, a top-down approach was used to justify, support, and improve the prototype decision tree. Evaluation and finetuning of the tool were done by consulting agricultural workers and watershed managers operating in Guba Lafto, Amhara, Ethiopia. These consults were done through one-on-one interviews and Focus Group Discussions (FGD). FGD's are group discussions on a particular topic (Gill et al., 2008). The sample size consisted of three people for one-on-one interviews and two focus groups of five participants. Participants for the interviews and focus groups were selected through the network of MetaMeta, whereby a snowball sampling was conducted: participants were recruited based on the recommendations of other participants. The length of the interviews varied between 30 to 60 minutes. The focus groups took up to a maximum of 1,5 hours.

The interviews and focus groups were semi-structured (Appendix B – Interview & Focus Group Outline). Semi-structured interviews helped keep the discussion on track and not missing essential details. It also gave it the flexibility to change the line of questioning depending on the conversation's direction (Gill et al., 2008). Before the actual data collection, the interview schedule was piloted with MetaMeta co-workers. This allowed establishing if the schedule was clear, understandable and capable of answering the research questions. The sessions' outline was designed in line with the two goals of the interviews and focus groups: (1) face validation of the model and (2) incorporating end-users in an early stage of the tool development. For the face validation, participants were asked about the microclimate system and whether the tool behaviour corresponded to their experience in the field. For the incorporation of end-users, participants were asked about the efficacy of the tool. During the focus group discussions assisting visuals were used to avoid any confusion between researcher and farmer regarding the type of intervention (e.g., a picture of 'soil bunds' was shown when farmers were asked about the effect of soil bunds on the microclimate). Next to this, a translator was arranged for communication with farmers during the focus groups. The sessions were held online through the video call platforms *Zoom* or *Skype*. Before every session, respondents were informed about the research details and were given assurance about ethical principles, such as anonymity and confidentiality. Anonymity and confidentiality of the interviewees were protected and the right to withdraw from the research was provided at all times. All respondents also signed an informed consent form before the session. All sessions were recorded as this protects against bias and provides a permanent record of what was said.

Chapter 3 – Results

This chapter presents the results of this study. The first three sections (3.1, 3.2 & 3.3) display the results of the first three research questions regarding microclimatic processes and human interactions. This forms the scientific knowledge base needed to create the tool. Next, section 3.4 presents the final assessment tool.

3.1 – Impact of Microclimate System on Crop Production

This section displays the results to the first research question: '*How do the microclimate components and their interactions influence crop production?'*. First, the influence of each microclimate component on crop production is presented. The microclimate components taken into account in this research are solar radiation, soil moisture, soil temperature, air temperature, air humidity and wind direction and speed. Second, a conceptual model of all microclimate system interactions is presented (Figure 4).

Solar radiation directly influences plant growth through photosynthesis and indirectly since its heat and energy is the driver of all microclimate components (Rosenberg, 1983). Some solar radiation is reflected, and some is absorbed by plants or soil, thereby increasing soil temperature through conduction (Stoutjesdijk & Barkman, 1992). The quantity of solar radiation that the surface receives depends on the sun's position compared to the earth and the atmosphere's transparency (Rosenberg, 1993). The higher the air humidity, the lower the amount of solar radiation that reaches the earth's surface (Abdullahi et al., 2017). The sun's position compared to the earth determines the amount of solar radiation on a surface and can be expressed with Lambert's Cosine Law (Appendix C – Micrometeorological Processes). On a site, two factors influence this: aspect and inclination. As a result of the solar radiation absorption by the earth and plants, large quantities of energy are exchanged in evaporation and condensation (Rosenberg, 1983). This heat and water budget of plants is essential for photosynthesis, making solar radiation essential for plant growth. However, too high irradiances can damage the photosynthetic system, mainly when other stresses such as extreme temperature or water stress occurs (Jones, 2014).

Soil moisture is essential for a crop's metabolic activity (Matlock & Morgan, 2011; Rosenberg, 1983). Water retention and transmission properties of a soil control how much of the incoming water infiltrates and is retained in the soil and available for crops (Gardner, 1999; Tsuji et al., 1998). This storage capacity, in turn, is determined by its texture, structure, depth, organic matter content, and biological activity (Ismangil et al., 2016). When the soil moisture level is too low, the homoiohydric plant's production stagnates due to reduced net photosynthesis (Barry & Blanken, 2016) and reduced seed germination (Etherington, 1982). Too much soil moisture can also be stressful for plants because of the lack of oxygen supply to the roots or other submerged parts (Jones, 2014), resulting in slower microbial activity (Ismangil et al., 2016). Soil moisture also indirectly influences crop production by affecting the microclimate. Soil moisture impacts the evolution of near-surface air temperature and precipitation formation (Schwingshackl et al., 2017). From the soil surface water balance (Appendix C – Micrometeorological Processes), it can be seen that when soil moisture decreases, the evapotranspiration rate reduces (Stoutjesdijk & Barkman, 1992), which results in lower air humidity (Hutjes, 1996). A lower evaporation rate means that less energy goes into the latent heat fluxes. More energy will be available for the sensible heat flux, increasing the near-surface air temperature (Gardner, 1999). Areas with available soil moisture thus have a more balanced microclimate with lower air and soil temperatures. The balancing influence of soil moisture also accounts for low temperatures, and soils stay warm longer than dry soils during frost events (Ismangil et al., 2016). This way, soil moisture can increase a site's resilience by moderating the extremes, which is beneficial for crop production.

A soil's temperature is determined by the incoming radiation, the soil's albedo, thermal conductivity and the soil's heat capacity (Stoutjesdijk & Barkman, 1992). Heat is continually moving into or out of the soil, and thermal energy is continually redistributed in the soil (Rosenberg, 1983). Soil temperature influences crop growth by providing the warmth necessary for seeds, plant roots and microorganisms in the soil. Extreme low temperatures have several effects: it affects the intake of nutrients (Ismangil et al., 2016), it slows down the rate of organic matter decomposition (Gardner, 1999), it inhibits water uptake by plants and nitrification (Etherington, 1982), it reduces soil fertility, and it increases desiccation when simultaneously air temperatures are higher (Gliessman 2015). Too high soil temperatures can also stall the biological processes of micro-organisms (FAO, 2016) and are harmful to roots and cause lesions of the stem (Rosenberg, 1983). Thus, both too high and too low soil temperatures negatively influence crop production, highlighting the importance to moderate the extremes and increase temperature resilience (Ismangil et al., 2016).

The air temperature is determined by the flow of heat between the surface and the air, also known as sensible heat transfer (Rosenberg, 1983). The air temperature directly influences the crop temperature. The most optimal air temperature range for photosynthesis for temperate zone plants tend to be between 20 and 30 degrees Celsius (Jones, 2014). At high temperatures, a decline in the photosynthesis of crops occurs. This decline results partly from the more rapid increase of respiration with temperature and partly from time-dependent photosynthetic inactivation at high temperatures (Jones, 2014). Low-temperature stress is usually met in the form of frost damage, though some tropical plants show an ultrastructural deterioration of tissues at temperatures as much as 10 degrees above freezing. Thus, both low and high temperatures have a limiting effect on crops' photosynthesis, even for many days after the extreme situation has occurred (Jones, 2014). Like soil temperatures, this highlights the importance of using the microclimate to increase resilience on a local scale to buffer against the extremes caused by global climate change.

Air humidity results from evapotranspiration and forms the basis for cloud, fog, dew and precipitation formation (Ismangil et al., 2016). Dew has great importance in agriculture since it can be an essential moisture source for plant growth in semi-arid environments when absorbed by the leaf surface (Ismangil et al., 2016; Rosenberg, 1983). However, most dew, especially in arid regions, is formed from moisture evaporated from the immediate ground surface. Under these conditions, dew is essentially recovered soil moisture and does not represent a new addition of water to the local system (Wilken, 1972). Fog forms when the atmospheric water vapour and fog deposition on plants and trees is a significant contributor to the water balance (Barry & Blanken, 2016). Besides the direct impact of air humidity on crops' primary production through the water balance and influence on fungus and pests, air humidity also plays a vital role in forming the microclimate. First of all, dew formation on the soil surface might impact the albedo rate since it moistens and darkens the soil, lowering its albedo (Ismangil et al., 2016). Next, air humidity plays a significant role in air movement on a microclimatic scale. Damp air is less dense than dry, so when air humidity near the surface increases due to evaporation, it rises (Unwin & Corbet, 1991).

Local winds play an essential role in crop production. By sweeping away a leaf's boundary layer and replacing it with drier air, wind removes the constraint on transpiration (Allaby, 2015). Both evaporation from the soil and transpiration from leaves increases with the increase of wind velocity and decreases sharply in the range of weak wind velocity (Appendix C – Micrometeorological Processes). The rate of evapotranspiration may increase to such an extent that the crop loses moisture faster than rising soil moisture can replace it (Allaby, 2015), resulting in an impaired plant-water status, which directly affects crop production (Yoshino, 1975). Winds can also directly affect crops through asymmetrical air pressure and suspended sediments that hit the crops (Geiger et al., 2003; Etherington, 1982). Wind can additionally lead to soil erosion, resulting in the loss of topsoil and reduced soil fertility (Gardner, 1999). Reduced soil fertility can have a cascading effect on the microclimate by losing vegetation potential and soil moisture capacity (Ismangil et al., 2016). However, sufficient soil moisture can reduce soil susceptibility to wind erosion because of the enhancement of aggregate strength due to surface tension forces within the water-filled pores (Gardner, 1999). Light wind, however, can enhance crop production as it has a cooling effect, and it removes excess humidity, thereby reducing the potential for pests and diseases (Ismangil et al., 2016). Wind between the leaves of a crop canopy is also essential to maintain adequate carbon dioxide levels for photosynthesis (Rosenberg, 1983). Table 1 provides an overview of indicators of the effect of each microclimate component on crop production.

Table 1 Indicators for guidance in determining the effect of each microclimate component on crop production

Microclimate Components		Effect on Crop Production Indicators
Solar Radiation	Too Much	Chlorophyll losses (discolouration of the leaves) and fruit sunburns (Ferrante & Mariani, 2018). Too much solar radiation can, in combination with high temperatures, lead to water stress (Jones, 2014).
	Too Little	Slower plant development, including seed germination, stem elongation, and slower floral initiation (Ferrante & Mariani, 2018).
Soil Moisture	Too Much	Too much soil moisture creates an unfavourable anaerobic environment for the roots. This results in a lack of oxygen supply, slower microbial activity and potential rotting of the roots. When the soil is saturated, it will not absorb any more water, leading to a water layer on top of the soil (Jones, 2014).
	Too Little	Reduced leaf area, reduced number of leaves, slow crop productivity (slow crop growth) and wilting of the crop (Akinci, 2013). Additionally, too little soil moisture can cause cracking of the soil and increase soil erosion (Gardner, 1999).
Soil Temperature	Too High	Dehydration of clay and cracking of sand particles (Earth Observing System, 2021). Too high soil temperatures can cause damage to the roots and lesions of the stem (Rosenberg, 1983).
	Too Low	Lower water and nutrient intake, resulting in reduced crop production (Earth Observing System, 2021).

Table 1 Indicators for guidance in determining the effect of each microclimate component on crop production (Continued)

Microclimate Components		Effect on Crop Production Indicators
Air Temperature	Too High	Reduced yield due to a more rapid transpiration increase leading to water stress of the crops (Jones, 2014).
	Too Low	Damage to the crop, including curled or dropped leaves caused by cell damage (Jones, 2014) and white, yellow or red marks near the veins in the leaves, which are spots of dead cells killed by frost (Grunert, n.d.)
Air Humidity	Too High	Stagnation of the crop's transpiration, which lowers the crop's production and may even cause the plant to rot (Barry & Blanken, 2016)
	Too Low	Increased transpiration rates in a plant, leading to wilting of the crop (Barry & Blanken, 2016).
Wind Speed	Too High	Mechanical effects on the crops, which causes structural damage (Geiger et al., 2003), soil erosion (Gardner, 1999), impaired plant water status (Yoshino, 1975).

The interactions between microclimate components discussed here are shown in figure 4. Soil moisture influences soil temperature since its thermal conductivity and soil heat capacity significantly increase when soil moisture is sufficient (Bonan, 2016). The soil temperature variation ratio (Appendix C – Micrometeorological Processes) shows that in soils containing much air, the soil temperature increases rapidly in the daytime and decreases quickly at night. When soil contains less air and more moisture, the temperature variation will be modified (Yoshino, 1975; Van Wijk, 1963). Soil temperature also influences the soil moisture: increased soil temperatures decrease the water viscosity, allowing more water to percolate through the soil. Increased soil temperatures additionally result in higher evaporation rates, lowering the soil's moisture level (Onwuka & Mang, 2018). The water movement through soil results from soil temperature gradients in that soil: soil moisture flows from areas where its kinetic energy is high to where it is low (Rosenberg, 1983), leading to water movement from warm to cooler parts of the soil. This can be a significant water source in areas under extensive diurnal temperature fluctuation conditions (Gardner, 1999).

Soil moisture and air humidity are both parts of the hydrological cycle, therefore changes in one component will lead to changes in the other (Barry & Blanken, 2016). Dew will form when the surface is cooler than the air's dewpoint temperature around it (Rosenberg, 1983). The air temperature determines the amount of water vapour that air can hold, with warm air being able to hold more water vapour than cold air (Ismangil et al., 2016). With moister air, meaning that dew formation starts at a higher temperature, nocturnal cooling will proceed at a slower rate (e.g., slow cooling off in the tropics) (Stoutjesdijk & Barkman, 1992). Local winds also play an essential role in dew formation. Light winds help dew formation in unsheltered sites. However, too strong winds inhibit dew formation (Ismangil et al., 2016). A visual overview of all these microclimatic processes is given in figure 4 below.

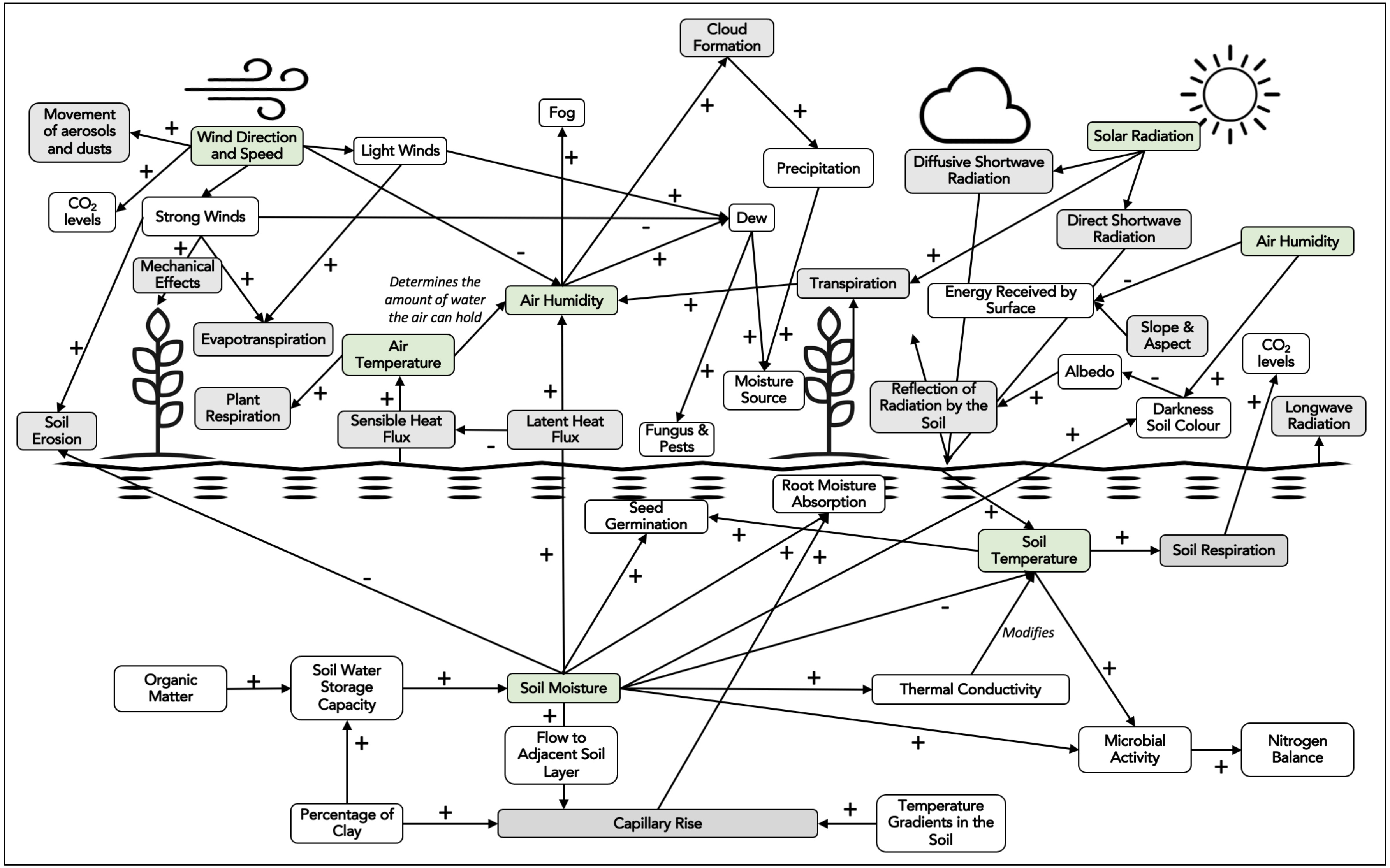

Figure 4 Conceptual model of all microclimate components and interactions. A '+' indicates one component having a positive (increasing) effect on the other components and a '-' indicates one component having a negative (decreasing) effect on the other component.

3.2 – Human Interventions

This section displays the results of the second research question: '*What are the common human interactions with the system in terms of land and water management interventions in Ethiopia?*'. Table 2 presents an overview of the selection of interventions taken into account in the tool. How all these land and water management practices influence the microclimate, and, through that, crop production will be presented in the next section (Section 3.3).

Table 2 Definition and elaboration on the human interventions in the system

Human interventions in the system	Description of the intervention	The objective of the intervention
Check dams	A check dam is a small dam constructed across a drainage ditch, swale, or channel to lower flow velocity. A check dam may be built from stone, sandbags filled with pea gravel, or logs (Ministry Agriculture Ethiopia, 2005).	Reduce flow velocity (Massachusetts Executive Office for Environmental Affairs, 2003).
Eyebrow terraces	Eyebrow terraces are circular and stone-faced structures, applicable in steep and degraded hillsides and community closures (Farahani et al., 2016).	Harvest moisture (Farahani et al., 2016).
Stone-faced soil bunds	Stone-faced soil bunds are stones arranged in (semi-)permeable bars across the slope to form a strong wall (Farahani et al., 2016).	Harvest moisture & slow down runoff (Mati, 2006).
Soil bunds	Soil bunds are constructed on slopes, and to stabilize the bunds, different types of tree and grass species are planted on their banks (Mekura et al., 2015). In design, the soil bunds are aligned along the contour, with spillways at 20-meter intervals (Mati, 2006).	Harvest moisture & slow down runoff (Mati, 2006).
Semi-circular bunds	Semi-circular bunds are half-circle shaped basins dug in the earth with earth bunds in the shape of a semi-circle with the bunds' tip on the contour (Mati, 2006).	Harvest moisture & slow down runoff (Mati, 2006).
Tie ridging	Tie ridges are a small rectangular series of basins formed within the cultivated fields' furrow (Farahani et al., 2016).	Increase surface storage & infiltration time (Farahani et al., 2016).

Table 2 Definition and elaboration on the human interventions in the system (Continued)

Human interventions in the system	Description of the intervention	The objective of the intervention
Trenches	Trenches are large and deep pits constructed along the contours. (Ministry of Agriculture, Ethiopia, 2005).	Collecting & storing rainfall water (Ministry Agriculture Ethiopia, 2005).
Ridge-furrow planting	This practice consists of the farmer making furrows and ridges in the land on which the crop rows can be planted (El-Halim & El Razek, 2014).	Water harvesting in the furrows & improve drainage (El-Halim & El Razek, 2014).
Terracing	Terraces are earth embankments channels or combinations of embankments and channels constructed across the slope at suitable spacings and acceptable grades. The benches are typically designed with vertical intervals ranging from 1.2 meters to 1.8 meters, the objective is to achieve a level bench whose slope is zero (Mati, 2006).	Create hillside farming systems by reducing the slope gradient, erosion control, runoff reduction, soil water recharge (Mesfin et al., 2019).
Increasing vegetation	This practice is simply the regeneration of natural vegetation on a site or the increase of crops growing on a farm.	Reduce soil erosion, slow downwind, shading (Ismangil et al., 2016)
On-farm agroforestry	Agroforestry uses trees on the same site as crops in some form of spatial arrangement or temporal sequence (FAO, 2015). For this research, the focus will be on alley farming and scattered trees on the farm. Alley farming is crop cultivation between a row of trees (FAO, 2015).	Reduce soil erosion, slow downwind, shade effects (Ismangil et al., 2016).
Vegetative buffers & grass strips	Grass planted in dense strips, about 0.5 to 1 meter wide, along the farm's contour (Mati, 2006).	Reduce soil erosion and runoff (Mati, 2006).
Conservation tillage	Conservation tillage entails reducing soil manipulation, minimizing the energy required for tillage and retaining some crop residues on the soil surface even during seeding operations (Ministry Agriculture Ethiopia, 2005). Conservation tillage consists of minimum or no-tillage and is the practice of tillage just enough to allow the seed into the ground (Critchley et al., 2013).	Improving soil structure and soil conservation (Tulema et al., 2003). Reduce soil nutrient losses (Ministry Agriculture Ethiopia, 2005).

Table 2 Definition and elaboration on the human interventions in the system (Continued)

Human interventions in the system	Description of the intervention	The objective of the intervention
Mulching	Mulching is the application of any cover to the soil. This cover can be created with materials on the site itself (Rosenberg, 1983).	Erosion control, solar radiation protection, weed barrier, modification of the surface reflection capacity, and moisture retention (Gardner, 1999).
Contour farming	Contour farming is the practice of all farming operations (e.g., tillage, planting) performed on the field slope's contour, so around the hill instead of up and down the hill. Contour farming is most effective on slopes between 2 and 10 per cent (Farahani et al., 2016).	Reduce runoff and soil erosion (Farahani et al., 2016).
Row orientation	The decision of farmers in which direction they orient the rows in which they plant their crops.	Modification of the received solar radiation. Reduce unwanted shade (Wilken, 1972).
Row spacing	The decision of farmers on the distance between rows.	Modification of the received solar radiation and reducing unwanted shade (Wilken, 1972).
Shading	This practice is the shielding of crops from solar radiation (Wilken, 1972).	Reduce the amount of solar radiation received by the crop or soil (Wilken, 1972).
Windbreaks	A windbreak is any structure on a site that influences the wind direction and speed on that site. The length, breadth, height and material may vary considerably.	Reduce the wind force in the sheltered zone and control the wind speed (Rosenberg, 1983)

3.3 – Impact of Human Interventions on the Microclimate

This section displays the answer to the third research question: '*How do land and water interventions influence the microclimate components and, through that, crop production?*'. As was shown in figure 4, there are many interactions between the microclimatic elements. These interactions make it impossible to isolate one element. Control over one component may result in unexpected, or even undesirable, changes in another (Wilken, 1972). There is a need to examine the microclimate characteristics at multiple scales and consider cumulative effects, rather than to simply assess the importance of microclimate independently at each scale (Chen et al., 1999). Therefore, this section shows how each intervention influences the microclimate, taking all components into account. Table 3 provides an overview of all the results.

Check Dams

By reducing the water flow velocity, a check dam reduces the ditch's erosion and allows retention of sediments (Massachusetts Executive Office for Environmental Affairs, 2003). A study by Nyssen et al. (2010) on a North Ethiopian water catchment shows that the annual runoff coefficient decreased by 81% due to check dams. This reduction in runoff led to a rapid recharge of the groundwater table after the dry season and a prolonged water supply due to capillary rise. Check dams increase water infiltration and spread runoff in time. This affects the microclimate by enriching the soil moisture levels. A study on a Northern Ethiopian watershed showed that increased soil moisture changed the area's arid conditions (Mekonen & Tesfahunegn, 2011). Castelli et al. (2019) analyzed to what extent storing soil moisture can reduce temperatures in the hot months after the rainy season in a semi-arid climate. Results showed an increased capacity of the catchment to maintain soil moisture in the rainy season, consequently reduced temperatures. As was stated in section 3.1, increased soil moisture increases air humidity and lowers the air temperature. When soil moisture increases, evaporation from the soil is enhanced. More energy will then be used in these latent heat fluxes, meaning less energy is available for sensible heat fluxes. This uptake of latent heat provides an additional daytime cooling effect. Another effect of increased soil moisture is a reduction in soil erosion by wind since the bond between soil particles becomes stronger through capillary and adhesive forces of absorbed water molecules surrounding the soil particles (Figure 5).

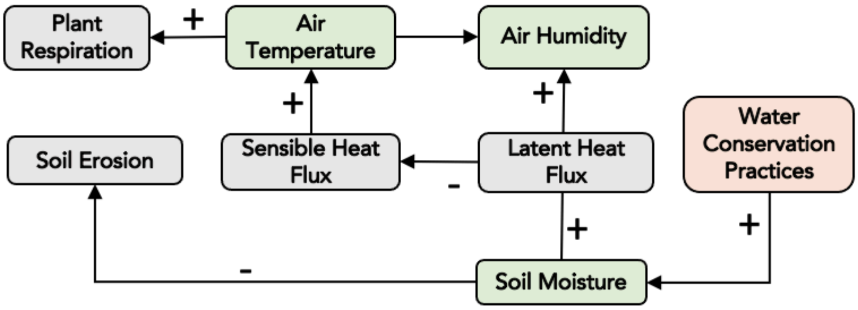

Figure 5 Overview of the influence of check dams on the air temperature, air humidity and soil moisture interactions. A '+' indicates one component having a positive (increasing) effect on the other components and a '-' indicates one component having a negative (decreasing) effect on the other component.

Increased soil moisture also enables groundwater recharge, allowing capillary rise that benefits crop production outside the rainy season. Next, it balances the soil temperature by increasing thermal conductivity, promoting heat diffusion in the soil, thereby offsetting extremes in both daytime heating and nocturnal cooling. Al-Kayssi et al. (1990) also found that an increase in moisture content decreases the soil temperature differences between daytime and night-time, protecting the plant root system against sharp and sudden soil temperature changes. This moderation of soil and air temperatures extremes increases a farm's resilience in light of climate change (Figure 6).

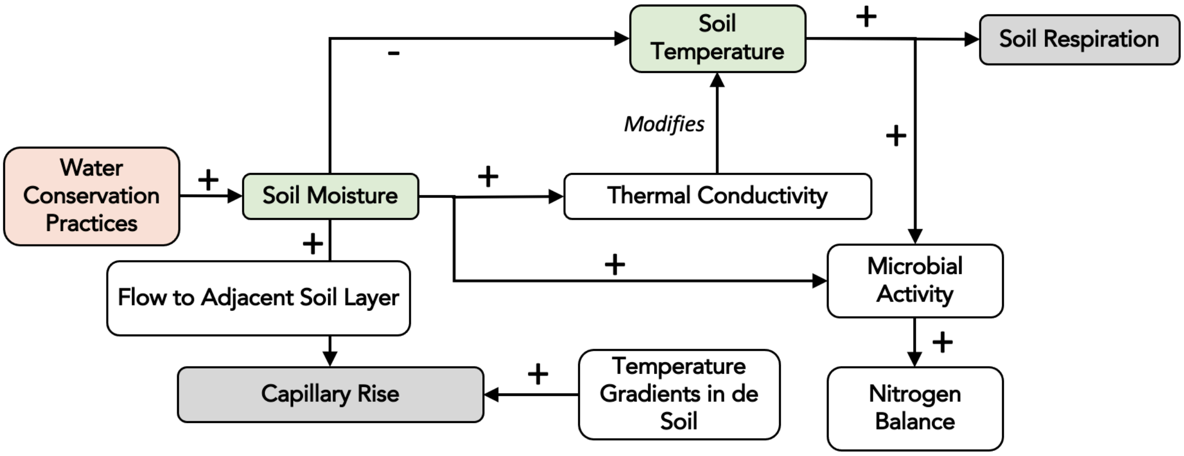

Figure 6 Overview of the influence of water conservation practices on soil moisture and through that on soil temperature and other soil processes. A '+' indicates one component having a positive (increasing) effect on the other components and a '-' indicates one component having a negative (decreasing) effect on the other component.

Stone Faced Soil Bunds & Soil Bunds

To create stone-faced soil bunds, stones are arranged in bars across the slope to form a strong wall. Since the lines are porous, they slow down the runoff rate, spread the water over the field, enhance water infiltration, and reduce soil erosion (Mati, 2006). Due to the capture of moisture, stone-faced soil bunds increase the soil moisture levels and therefore have similar effects to the microclimate as check dams, as described in the previous section. Stone-faced soil bunds balance the soil temperatures due to the soil's higher thermal conductivity, increased air humidity, and moderate air temperature (Figure 5 & Figure 6). Nyssen et al. (2010) investigated changes in the hydrological response of a 200-ha catchment in Northern Ethiopia. From this, it can be concluded that stone-faced soil bunds, together with check dams, led to a decrease in runoff and a rapid recharge of the groundwater table after the dry season. Other studies on stone face soil bunds also showed a reduced runoff (Taye et al., 2013).

Stone-faced soil bunds also impact the microclimate through their high heat capacity: when the incoming energy during the day is high, this warms up the rocks and makes soil bunds a heat source at night, helping prevent nearby crops from night frosts (Oke, 1995). Using light coloured stone walls results in extra short-wave radiation reflection on nearby crops (Oke, 1995). Since stone-faced soil bunds are vertical structures on the site, they can also lower wind speed when placed perpendicular to the prevailing wind direction. As was discussed in section 3.1, too strong winds can have adverse mechanical effects on the crops and lead to soil erosion. Wind can also enhance the evaporation of moisture from the soil. The windbreak section below will elaborate more on the effect of wind reduction on crop production.

Soil bunds work in the same way as stone-faced soil bunds; water is impounded behind the bunds to the contour level, overflowing eventually with water spreading to the next lower tier of bunds, creating a run-on structure for ponding runoff water (Mati, 2006). By reducing runoff, spreading water more evenly, and harvesting moisture, soil bunds increase soil moisture levels and reduce soil erosion.

Eyebrow terraces, Semi-circular bunds and Tie ridging

The objective of eyebrow terraces is to harvest moisture (Farahani et al., 2016). By harvesting moisture, eyebrow basins increase the soil's moisture levels. Increased soil moisture levels decrease soil erosion, making eyebrow basins an important measure in maintaining the soil's quality (Gedamu, 2020). Semi-circular bunds also harvest runoff and infiltrate this into the soil, thereby increasing soil moisture and available water for crop uptake (Mati, 2006). Tie riding also increases the surface's water storage capacity and allows more time for rainfall to infiltrate the soil instead of running off (Mati, 2006). Araya & Stroosnijder (2010) showed runoff reduction and higher soil water content on sites with tied ridges. All three interventions similarly affect the microclimate by increasing the soil moisture levels described in Figure 5 and Figure 6.

Trenches

Trenches collect and store rainfall water and thus harvest precipitation. This rainwater harvesting enhances soil moisture levels (Ministry Agriculture Ethiopia, 2005). Since trenches gather and keep the rain during the rainy season, trenches mainly contribute to soil moisture after the rainy season (Ismangil et al., 2016). By increasing the soil moisture levels, trenches affect the microclimate, as was described previously. By enhancing surface water storage, trenches increase the number of water surfaces on a site. Water surfaces are poor reflectors and therefore serve as an effective sink for solar energy (Stoutjesdijk & Barkman, 1992; Rosenberg, 1983). Many water-filled trenches on a site thus absorb the solar energy during the day and radiate this back by night, buffering the air temperatures.

Ridge-Furrow Planting

Ridge-furrow planting allows excess water to drain off the fields to the lower channels during the rainy season (Ministry Agriculture Ethiopia, 2005), which reduces soil erosion induced by water and spread the water more evenly over a site (Farahani et al., 2016). This intervention increases the efficiency of in situ water utilization and positively affects soil moisture (Gebreegziabher, 2006), this impacts the microclimate likewise as the previously mentioned interventions described in Figure 5 and Figure 6.

By ridging fields, this intervention also impacts the amount of solar radiation received by the surface. As was stated in section 3.1, the slope of a site affects absorbed radiation intensity. Slopes that face the sun receive more energy than slopes that face away from the sun. By manipulating the geometry of receiving surfaces to take advantage of the cosine law of illumination, better use of available short-wave radiation can be accomplished (Gardner, 1995). By making ridges, the sunlit slopes can receive solar radiation at or near their local zenith. Ridge and furrow geometry also provides a radiative 'trap' for solar radiation and the outgoing long-wave radiation (Oke, 1995). This trapping of solar radiation by day tends to increase the maximum soil temperature. The trapping of long-wave radiation tends to reduce surface cooling (Oke, 1995). This is especially useful in spring when heating is critical for germination and when the sun's elevation is still low. However, studies from Burrows (1963) and Buchele et al. (1955) on soil temperatures in furrows, ridges and flat microtopography show that temperatures were generally highest in the ridge planting and lowest in the furrows because of the occurred shading. Thus, this increase in received solar radiation by the surface and increasing soil temperatures might be seasonal until established vegetation shades the ground.

Terracing

By reducing the plot's steepness, terracing can help in erosion control, runoff reduction, and soil water recharge (Mesfin et al., 2019). This runoff reduction and soil water recharge increase the soil moisture levels of a site—the flatter the terrace, the higher the water harvesting capacity. A reverse-slope bench is even more effective in capturing runoff (Mati, 2006). A study from Mesfin et al. (2019) on soil water conservation variations in Ethiopia's Tigray region showed that in terraced areas, the soil water conservation was significantly higher than in nonterraced areas. By increasing the soil moisture, the soil and air temperature get more balanced, and air humidity increases (Figure 5 and Figure 6). A study from Denevan (1995) concluded that agricultural terraces indeed modify the microclimate.

Terracing also affects the level of solar radiation absorption since it alters the slope of a site. The net increase or decrease in solar radiation on the surface differs significantly depending on situational factors such as altitude, latitude, slope aspect, angle and season. In general, it can be stated that the amount of radiation per unit area of the land surface decreases as the slope of the land increases (Elizaberashivili et al., 2007; Evans & Winterhalder, 2000). Terracing will thus increase the soil temperature since more solar radiation is received on the surface (Onwuka & Mang, 2018). However, in combination with increased soil moisture as described above, this effect will be moderate.

Increasing vegetation

Due to the essential role of vegetation in the hydrological cycle, the regeneration and increasing of natural vegetation is a critical approach in increasing the water buffer. Vegetation affects microclimate in several ways. First of all, vegetation impacts the energy balance of a place. It affects how much heat is absorbed and radiated (Ismangil et al., 2016). Closed canopies, so dense vegetation, have a cooling effect, whereas open canopies, due to scarce vegetation, tend to accelerate local heating effects (Zellweger et al., 2020). By absorbing and reflecting the incoming radiation before it reaches the soil, vegetation will hinder the increase of the ground temperature in the daytime and cooling of the temperature at night, resulting in more moderate temperatures (Scott, 2000). Second, vegetation affects air temperature circulation at different layers and the wind's speed and direction (Ismangil et al., 2016). Third, vegetation canopy can retain moisture in the air (Ismangil et al., 2016). Because of the plant's transpiration processes, the temperature on a vegetation canopy will be less than that of bare soil (Stoutjesdijk & Barkman, 1992). Fourth, the roots of vegetation and enhanced soil organic matter levels from litter improve the soil structure and microorganic life, which again determines the porosity and water holding capacity of soils (Wiegant & Van Steenbergen, 2017).

Wiegant & Van Steenbergen (2017) state that an increase in vegetation cover can increase rainfall reliability. More vegetation allows more soil moisture, more evapotranspiration and a decrease in land surface temperature. An increase in soil moisture enhances evaporation and root moisture absorption and, therefore, transpiration through plants. Both processes contribute to the hydrological cycle and enhance precipitation (Figure 7) (Shi & Wag, 2002).

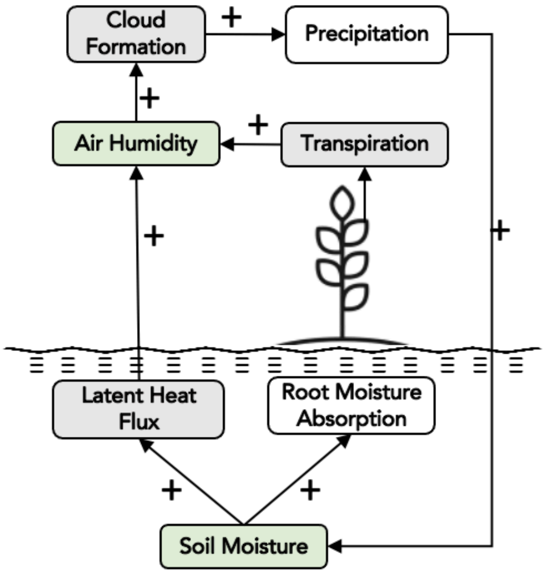

Figure 7 Overview of the hydrological cycle as a result of evaporation and transpiration processes. A '+' indicates one component having a positive (increasing) effect on the other components and a '-' indicates one component having a negative (decreasing) effect on the other component.

A study from Mekonen & Tesfahunegn (2011) on the Medogo watershed in Northern Ethiopia stated that an increasing vegetation cover improved its local climate. This study's respondents confirmed that the hot and dry air that previously dominated the watershed had been replaced by moist and cooler air. Next to the production of crops, which is also a form of vegetation, farmers could increase their site's overall vegetation. However, whilst growing regular vegetation next to the crops, it should be taken into account that the benefits have to balance against the possible competition for water and nutrients between the vegetation and the crops (Gardner, 1999).

On-farm agroforestry

Planting single trees on a site has the same effects as described above (Figure 7). Trees also affect the solar radiation on a site. When a dense canopy forms an active surface above the crop zone, this intercepts much solar radiation (Wilken, 1972). In tree rows, this shading effect is much less on North-South oriented rows of trees than on East-West oriented rows (Geiger et al., 2003). During the night, however, the crops can receive some long-wave radiation from the tree rows. With decreasing distance from the tree row, this influence diminishes rapidly (Stoutjesdijk & Barkman, 1992). Planting trees on a site also affects the wind speed and direction of that site. The trunks, branches and leaves of the trees reduce the wind speed by friction. However, when the paths open for airflow are narrowed, the wind speed increases and the rows of single trees then produce a 'funnel' effect (Geiger et al., 2003). The protective effect of trees is a function of distance from the row of trees. The denser the obstruction, the more significant the wind reduction immediately behind it, but the downward effect diminishes more rapidly (Geiger et al., 2003).

When considering the agroforestry impact on crop production, the crop yield directly next to the trees might be reduced due to competition for moisture and nutrients with the trees. Also, the land occupied by the trees is unavailable for crop production (Geiger et al., 2003). However, most research shows that, overall, agroforestry increases yield due to reduced wind erosion, improved microclimate and increased soil moisture (Jones, 2014; Geiger et al., 2003). A study from Hengsdijk et al. (2005) on soil and water conservation practices in Tigray, Ethiopia, also showed that reforestation practices resulted in 15% less erosion since trees improve water infiltration and reduce runoff. Tree roots also anchor the soil, especially on sloping terrains (Critchley et al., 2013). Lin (2007) found that using an agroforestry system is an economically feasible way to protect crop plants from extremes in microclimate and soil moisture. De Frenne et al. (2013) also showed that microclimatic effects brought about by forest canopy closure can buffer biotic responses to macroclimatic warming.

Vegetative buffers & Grass strips

Vegetative buffers and grass strips create a (semi-)permeable barrier that minimizes soil erosion and runoff through a water filtering process (Critchley et al., 2013). With this, the vegetative buffer and grass strips increase the soil moisture (Mati, 2006). Since this intervention includes adding vegetation to a site, it has the same effects on the microclimate as was described in the previous section.

Conservation Tillage

Conservation tillage is another term for minimum or no-tillage and is the practice of just enough tillage to allow the seed into the ground (Critchley et al., 2013). Studies have shown that conservation tillage practices can decrease soil disturbance and improve soil aggregate stability. This improves water infiltration and thus increases soil moisture and reduces runoff and soil erosion, which benefits soil sediments and nutrients (Adimassu, 2019; Busari, 2015; Chai et al., 2014; Chen et al., 2011). A study from Johnson & Lowery (1985) on conservation tillage practices and soil temperature found that conservation tillage led to reduced soil temperatures compared with conventional tillage. This was attributed to thermal admittance differences, heat flux to a deeper depth, and total heat inputs to the soil profile. This leads to more moderate upper profile soil temperature.

However, currently, most smallholder farmers in Ethiopia practice traditional tillage systems using a Maresha plough. This deep ploughing has caused land degradation and poor utilization of rainwater that led to low crop productivity. As stated above, conservation tillage systems have shown to improve the utilization of rainwater through increased infiltration. However, the implements used for conservation tillage in other countries were too heavy and too expensive for smallholder farms in Ethiopia. On the other hand, lighter and low-cost implements have been developed in Ethiopia as modifications to the Maresha plough. These implements are the subsoiler, tie-ridger, and the sweep. A study from Temesgen et al. (2009) on reduced tillage system tested on Tef indeed showed higher grain yields than conventional tillage. Thus, it can be concluded that conservation tillage for soils positively affects the soil moisture, which also positively influences the microclimate (Figure 5, Figure 6 & Figure 7). It should be taken into account that no-tillage is not an option in high clay content soils (Lai, 1989) and that in the case of smallholder farmers in Ethiopia, low-cost implements should be used.

Mulching

Mulches form a barrier to the heat and vapour flow from the soil and inhibit heat and moisture exchanges with the atmosphere (Rosenberg, 1983; Wilken, 1972). By blocking the transport of vapour out of the soil, mulch reduces the energy available for evaporation processes (Davies, 1975; Waggoner et al., 1960). Mulching thus decreases the evaporation rate, enhances infiltration and thus increases moisture conservation (Stigter, 1984a).

A study from Hopkins (1954) showed that the moisture infiltration over two hours was 183% greater for mulched sites than for un-mulched areas. Dhaliwal et al. (2019) also showed that soil moisture was 4.2 per cent higher in mulched crops than in un-mulched crops. Kader et al. (2017) state that mulching buffered extreme soil moisture and temperature fluctuations. Fang et al. (2009) researched the effects of straw mulching on the microclimate, and the results showed that straw mulching had dramatic effects on surface temperature and soil temperature. Straw mulch increased surface sensible heat flux but decreased latent heat flux and soil heat flux, so water evaporation from the soil was restricted, and moisture accumulation was increased accordingly. A study from Dvorak et al. (2010) on the cultivation of organic potatoes with mulching materials showed that the relative humidity on the site without mulch was 92,5%. The relative humidity on the site with grass mulch was 90,4%.

Increased soil moisture, as was explained in the previous sections, also leads to soil temperature moderation. Next to soil moisture, the soil temperature is also affected by the amount of absorbed solar radiation, which is influenced by mulching directly (Stigter, 1984a). Mulches reduce the incoming radiation on the soil surface, and, by acting as a thermal insulator, mulches moderate the soil temperature (Gardner, 1999). It reduces the soil temperature during the day and increases the soil temperature during the night (Kingra & Kaur, 2017). Mulching avoids the fluctuations in temperature in the first 20–30 centimetre depth of the soil. This favours root development, and the soil temperature in the planting bed is raised, promoting faster crop development (Moreno & Moreno, 2008). A study from Dhaliwal et al. (2019) showed that the mean soil temperature for mulched sites compared to un-mulched sites was 1 degree Celsius higher during the day and the night.

So, in general, it can be said that by blocking the transport of vapour out of the soil, the water availability for crops is enhanced by lowering the evaporation rate. Another effect is that the soil temperature becomes more moderate. However, the impact of mulching on the microclimate depends on the type of mulch that is used. Its effects will rely upon its colour and whether it is impervious to water or not (Davies, 1975). Surface application of pale materials, such as kaolin or ash, increases soil surface's albedo and can decrease soil temperatures by reflecting more solar radiation. Dark material such as coal dust or charcoal can have the opposite impact and increase soil temperatures (Gardner, 1999; Davies, 1975; Suzuki & Maruyama, 1957).

Mulching also affects wind and water erosion; it reduces the rate at which soil erosion occurs from rain, hail, runoff, and wind because of a mulch layer's protective properties (Stigter, 1984a; Rosenberg, 1983). Araya and Stroosnijder (2010) compared mulched and un-mulched sites and showed that runoff was reduced by 69.49% for the mulched area.

Contour farming

By slowing down the runoff from the slope, contour farming reduces soil erosion. Contour farming also promotes positive row drainage. Results showed that contour cultivation reduced the annual runoff by 10% compared with cultivation perpendicular to the slope. It reduces soil losses by 49.5% and reduces water losses by 32% (Farahani et al., 2016). By reducing water losses, contour farming also contributes to the soil moisture levels and consequently the same contribution to the microclimate as explained in the previous sections.

Row orientation

Modification of solar radiation can be accomplished by adopting an appropriate row direction. Directing the crop rows at a near right angle to the sunlight direction can influence the light interception and avoid crops shading each other. The farm's location determines the best direction for the crop rows as row orientation's effect depends on a site's latitude. The right angle to sunlight direction may increase crop production due to the increased light interception by crops and the shading of weeds in the interrow spaces (Borger et al., 2010). In the Northern hemisphere, when the orientation is North-South, crops intercept more solar radiation than the soil, leading to reduced soil temperature. In the case of an East-West orientation, the soil intercepts more solar radiation, leading to an increase in soil temperature (Yildiz & Rattan, 1996), which can also lead to increased water evaporation (Gegner et al., 2008). Row orientation can also reduce wind erosion when the rows are oriented perpendicular to the prevailing wind direction (Funk & Engel, 2015).

Row spacing

Crop row spacing can maximize or minimize light penetration and the trapping of short- and long-wave radiation; this influences the microclimate. A study from Yang et al. (2008) found that with increased row spacing, the relative humidity decreased, and the canopy temperature increased. They also stated that crop yield could be improved by reduced row spacing. Stickler & Laude (1960) found that the soil temperature, light intensity and evaporation from the soil surface decreased with decreasing row width. So, the smaller the rows, the lower the soil temperature and evaporation rates. Denmead et al. (1962) estimated that photosynthesis in corn might be increased by 15-20% if closer row spacings were used to eliminate ground illumination and increase energy capture by the crop. By smaller row spacings, soil moisture can be conserved by reducing evaporation through denser canopy cover with close spacing (Dhaliwal et al., 2019). A study from Sandhu and Dhaliwal (2016) on row spacing and relative humidity profiles within crops found that the smaller the row spacing, the higher the air humidity on crop level. Any yield advantage to growing crops in narrow rows may result from establishing a more uniform root and leaf distribution that aids in exploiting soil water and light resources and reducing soil temperatures and evaporation compared with crop production in conventional rows (Sharratt & McWilliams, 2005). However, Aubertin & Peters (1961) showed that when narrow crop row spacing was conducted under moisture shortage conditions, radiant energy's efficient capture may lead to significantly increased transpiration and, hence, to severe wilting.

Shading

Shading modifies the energy balance at the soil surface and crop canopy. Shading can thus control crop production by moderating the light intensity. Shading also modifies other environmental conditions; it affects the amounts of energy available for heating and evaporation and may lower soil temperatures and reduce water evapotranspiration (Mahmood, 2018). The lower evaporative demand under shade allows plants to increase stomatal conductance and CO_2 assimilation (Mahmood, 2018). Shade nets modify the temperature since long-wave (or thermal) radiation in the open can easily escape. Shade nets then protect against frosts and chilling effects by capturing the long-wave radiation (Stigter, 1984b). Shading also increases the absolute air humidity, decreasing the evaporative demand (Mahmood, 2018). Several studies also showed that shading screens could help reduce the vulnerability of hail and wind damage (Ilic et al., 2015). Tanny & Cohen (2003) found that a shade net reduced the wind speed by about 40% compared to an unshaded site. It should be considered that too little light intensity can decrease crops' production if the crop is not getting enough light for the photosynthesis process (Rosenberg, 1983). Shading is thus helpful to facilitate the growth of shade-tolerant crops.

Windbreaks

Some examples of windbreaks are trees with and without undergrowth, hedges and rows of bushes, tall plants (e.g., sunflowers), straw matting, wire netting with small mesh, stone walls, board fences and fences of woven reeds (Geiger et al., 2003). Windbreaks vary in effectiveness, depending upon their height, porosity and length (Wilken, 1972). The longer the windbreak, the more constant its influence. If a barrier is too short, jetting effects may increase rather than reduce wind speed (Allaby, 2015). The higher the windbreak, the greater the distance of its downwind and upwind influence (Rosenberg, 1983). A barrier should allow just enough air to penetrate to prevent eddying on the lee side and affect a large part of the area behind the break, but still reduce the wind speed enough (Allaby, 2015). The windbreak should be placed perpendicular to the prevailing wind direction; otherwise, it might funnel the wind and increase wind speed (Allaby, 2015).

Windbreaks impact the microclimate and crops in several ways. One benefit of windbreaks is the mechanical protection of the crops (Rosenberg, 1983) and reduced soil erosion (Jensen, 1954). The decreased transport and mixing of air results in steeper vertical profiles of air temperature and water vapour in shelter compared to open fields. Diminished turbulent activity decreases the interaction between the layers right above the surface. During the day, when the sensible heat output from the surface is positive, near-surface air temperatures in the sheltered zone are higher than outside the sheltered zone because of this diminished turbulent activity (Cleugh, 1988). At night, when the sensible heat flux is typically negative, this effect would lead to cooler near-surface air temperatures in the sheltered zone (Cleugh, 1988). Outside the sheltered zone, the surface radiative heat losses get replenished faster due to the wind, and air temperatures are higher during the night (Oke, 1995). Windbreaks thus result in higher daytime and lower night-time temperatures due to less mixing of the inversion layer (Rosenberg, 1983). The higher air temperatures in the shelter may extend to the soil, resulting in soil temperatures being substantially higher in sheltered areas (Geiger et al., 2003). Higher soil temperature will result in more rapid root respiration and organic matter decomposition and cause a more significant release of carbon dioxide from the soil (Rosenberg, 1983). The higher soil temperatures may also result in rapid seed germination (Rosenberg, 1983). Wind speed reduction also lowers evaporation processes, as was explained earlier; this improves the water use efficiency (Cleugh, 1988).

Windbreaks also influence the air humidity of a site. Humidity and vapour pressure gradients are increased in the shelter. The higher daytime relative humidity results from reduced water vapour transport and vertical mixing (Geiger et al., 2003). Vapour pressure remains higher in shelter throughout the night since the surface usually remains the vapour source, except during periods of dew deposition. The relative humidity in shelter is generally greater during the day, despite the contrary influences of the increased temperature and absolute humidity. At night relative humidity in a shelter is more remarkable because of the low air temperatures (Rosenberg, 1983). Dew is also enhanced in sheltered areas due to greater humidity and colder night-time temperatures (Oke, 1995).

As stated in section 3.1, the wind is essential in replenishing CO_2 levels needed for photosynthetic activity. However, Brown and Rosenberg (1972) found that the daytime reductions in CO_2 in shelter were not significant and certainly would not affect photosynthetic activity. Lower wind speeds and higher humidity can also lead to increased fungal diseases (Rosenberg, 1983). Placing windbreaks on a site can also cause shading and reduce the solar radiation received on a site. Despite these considerations, many studies show that windbreaks increase crop yield in nearly all cases where it has been tried in a wide range of climatic regimes (Geiger et al., 2003; Grace, 1988). An overview of the daytime effect of windbreaks on the microclimate is given in figure 8 below.

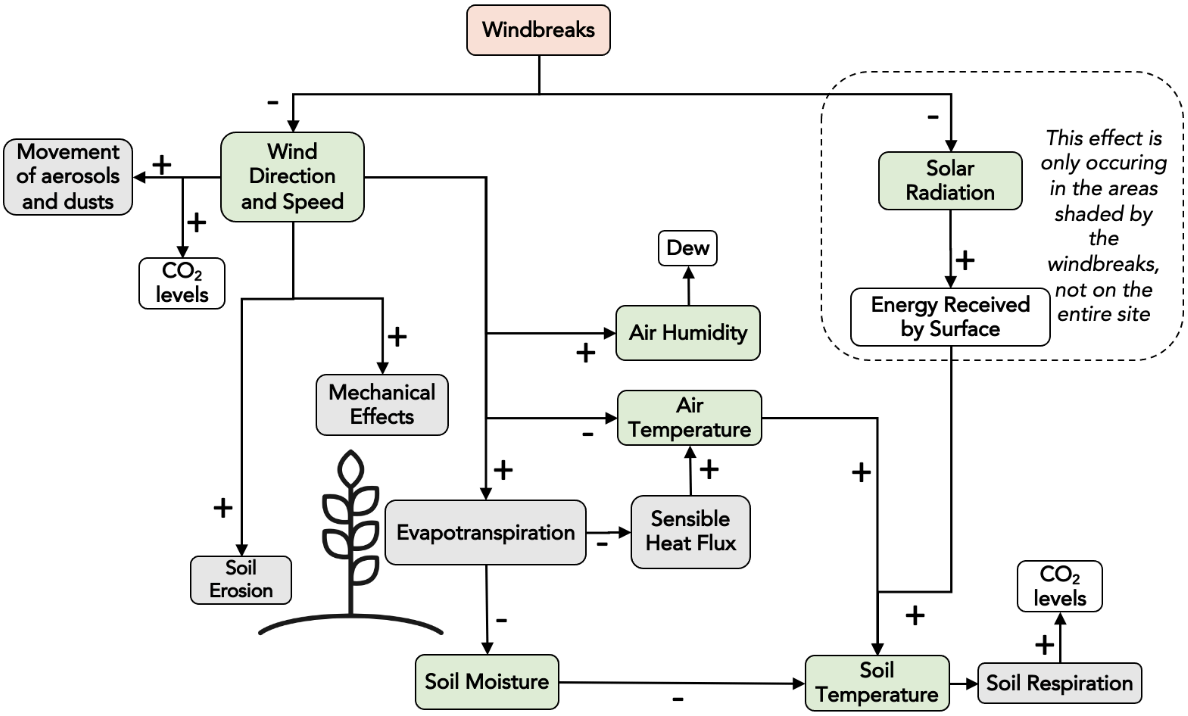

Figure 8 Overview of the day-time effect of windbreaks on wind direction and speed and crop production relation. A '+' indicates one component having a positive (increasing) effect on the other components and a '-' indicates one component having a negative (decreasing) effect on the other component.

Table 3 provides an overview of the findings.

Table 3 Overview of impact on interactions between human interventions and the microclimate. Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A '+' indicates an increase, and a '-' indicates a decrease in that specific microclimate component. 'Not significant' indicates no direct effect of that intervention on that specific microclimate component.

Human interventions in the system	Microclimate components							
	Solar radiation received and absorbed	Soil moisture	Soil temperature		Air temperature		Air humidity	Wind direction & speed
			Day	*Night*	*Day*	*Night*		
Check dams	Not significant	+	-	+	-	+	+	Not significant
Stone-faced soil bunds	+	+	-	+	-	+	+	-
Soil bunds	Not significant	+	-	+	-	+	+	-
Eyebrow terraces	Not significant	+	-	+	-	+	+	Not significant
Semi-circular bunds	Not significant	+	-	+	-	+	+	Not significant
Tie ridging	Not significant	+	-	+	-	+	+	Not significant
Trenches	+	+	-	+	-	+	+	Not significant

Table 3 Overview of impact on interactions between human interventions and the microclimate. Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A '+' indicates an increase, and a '-' indicates a decrease in that specific microclimate component. 'Not significant' indicates no direct effect of that intervention on that specific microclimate component (Continued).

Human interventions in the system		Microclimate components							
		Solar radiation received and absorbed	Soil moisture	Soil temperature		Air temperature		Air humidity	Wind direction & speed
				Day	*Night*	*Day*	*Night*		
Ridge-furrow planting		Ridges: + Furrows: -	+	Ridges: + Furrows: -	+	-	+	+	Not significant
Terracing		+ or – (Depending on the location of the site)	+	-	+	-	+	+	Not significant
Increasing vegetation		-	+	-	+	-	+	+	-
On-farm agroforestry	Tree planting	-	+	-	+	-	+	+	- (or + when there is a funnel effect)
	Alley farming	-	+	-	+	-	+	+	
Vegetative buffers & grass strips		-	+	-	+	-	+	+	-
Conservation tillage		Not significant	+	-	+	-	+	+	Not significant

Table 3 Overview of impact on interactions between human interventions and the microclimate. Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A '+' indicates an increase, and a '-' indicates a decrease in that specific microclimate component. 'Not significant' indicates no direct effect of that intervention on that specific microclimate component (Continued).

Human interventions in the system		Microclimate components							
		Solar radiation received and absorbed	Soil moisture	Soil temperature		Air temperature		Air humidity	Wind direction & speed
				Day	*Night*	*Day*	*Night*		
Mulching	Impervious mulch	Not significant	+	+	+	Not significant	Not significant	-	Not significant
	Light colour mulch	Soil: - Crop: +	+	-	-	-	-	+	Not significant
	Dark colour mulch	+	+	+	+	+	+	+	Not significant
Contour farming		Not significant	+	-	+	-	+	+	Not significant
Row orientation	North-south orientation	+	Not significant	-	Not significant	Not significant	Not significant	Not significant	+/- (depending on the site specifics)
	East-west orientation	Soil: + Crop: -	-	+	Not significant	+	+	Not significant	

Table 3 Overview of impact on interactions between human interventions and the microclimate. Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A '+' indicates an increase, and a '-' indicates a decrease in that specific microclimate component. 'Not significant' indicates no direct effect of that intervention on that specific microclimate component (Continued).

Human interventions in the system		Microclimate components							
		Solar radiation received and absorbed	Soil moisture	Soil temperature		Air temperature		Air humidity	Wind direction & speed
				Day	*Night*	*Day*	*Night*		
Row spacing	Conventional row spacing	Soil: + Crop: -	Not significant	Not significant	Not significant	Not significant	Not significant	Not significant	Not significant
	Narrow row spacing	Crop: + (or – when too narrow and crops shade each other)	+	-	-	-	+	+	-
Shading		-	+	-	+	-	+	+	-
Windbreaks		- (this effect is more substantial with east-west oriented rows)	+	+	-	+	-	+	- (or + when there is a funnel effect)

3.4 – Assessment Tool

This section is the final part of the results and presents the assessment tool. It provides an answer to the fourth research question: "*How can these farmer-microclimate interactions be translated into questions and decisions for an effective and valid assessment tool to be used in Ethiopia?*".

Face Validation of Assessment Tool

The face validation process of the tool prototype with participants of the FGD's and interviews indicate that the effects of particular interventions determined in this study correspond with their experience in the field. Some aspects, however, were questioned, such as the effect of structures on a site on wind direction and speed. It was said that physical structures do not affect the speed and direction; instead, they cause turbulence and variance. Participants also did not see significant differences between the ridges and furrows in ridge-furrow planting practices, as found in the literature (Interview notes can be found in Appendix E).

Efficacy of Assessment Tool

After testing the efficacy of the prototype with participants of the FGD's and interviews, the following points could be indicated: potential end users are convinced the tool will be helpful for extension workers and development agents to talk to farmers about how to manage their land. Participants liked the simplicity of the model and think it will be easy to use. Participants also stressed their enthusiasm for making a digital application out of the tool. However, the participants were hesitant about the solar radiation aspect of the tool since they stated that solar radiation management is not something typically considered in Ethiopian agriculture. It was also indicated that the windbreak practice is not very common among Ethiopian farmers. Next, it was stressed that the more the model is shaped to a specific local context, the better the outcome would be. Another suggestion was to add compost as an intervention. It is experienced that compost increases the water holding capacity and soil moisture levels, and soil temperature levels by darkening the surface. Next, it was suggested to add an extra response column to let the user know what they can expect after they adopted a particular action. It was also highlighted that if a tool is not providing tangible benefits or if a farmer does not perceive a benefit, it is not likely to be used. Finally, it was indicated that row orientation practices depend highly on the slope. At all times, it is more important to follow the contour lines of a slope. A final recommendation to foster implementation was to incorporate such a tool in national agricultural guidelines and to gradually implement the tool since it might take some time for farmers to adapt to such tools (Interview notes can be found in Appendix E).

Final Decision Tree

The results from the FGD's and interviews have been taken into account, and the prototype has been updated accordingly. For clear display purposes, the final version of the decision tree has been divided into six separate sections and presented in this section. The complete decision tree can be found in Appendix F.

The user starts with the first section (S1), solar radiation (Figure 9), and then tries to determine the main problem, *i.e.*, whether there is too much or too little solar radiation. When the user answers 'no' two times, the solar radiation on the site is sufficient (not too high nor too low), and the user is guided to section two (S2). Suppose there is a problem regarding solar radiation. In that case, the user is guided to the best suitable intervention for the particular site by answering questions regarding the rainfall in the area, the slope of the site, and the site's soil. After the advice for the best suitable intervention is given, the user is guided to the following section. There is also an option to obtain more information on the microclimatic response of this intervention in the final column.

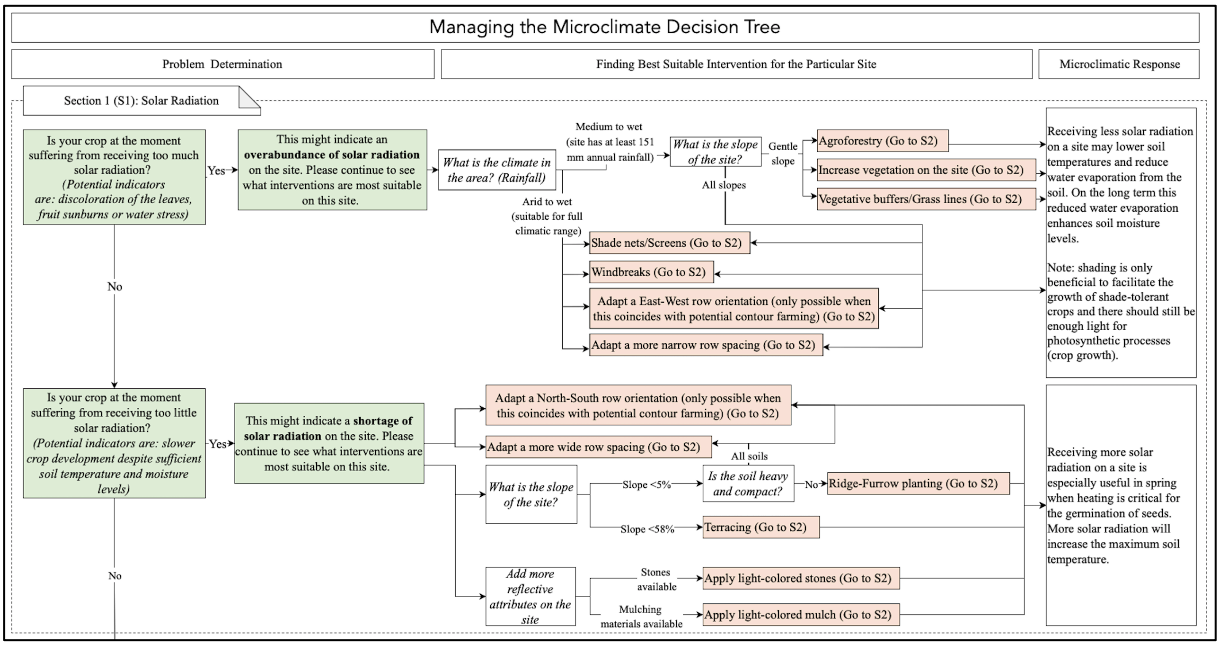

Figure 9 Decision tree section one: Solar radiation

The same structure is obtained for soil moisture interventions: first, determining if there is a soil moisture shortage; if yes, the user is guided towards the best suitable interventions for the specific site (Figure 10).

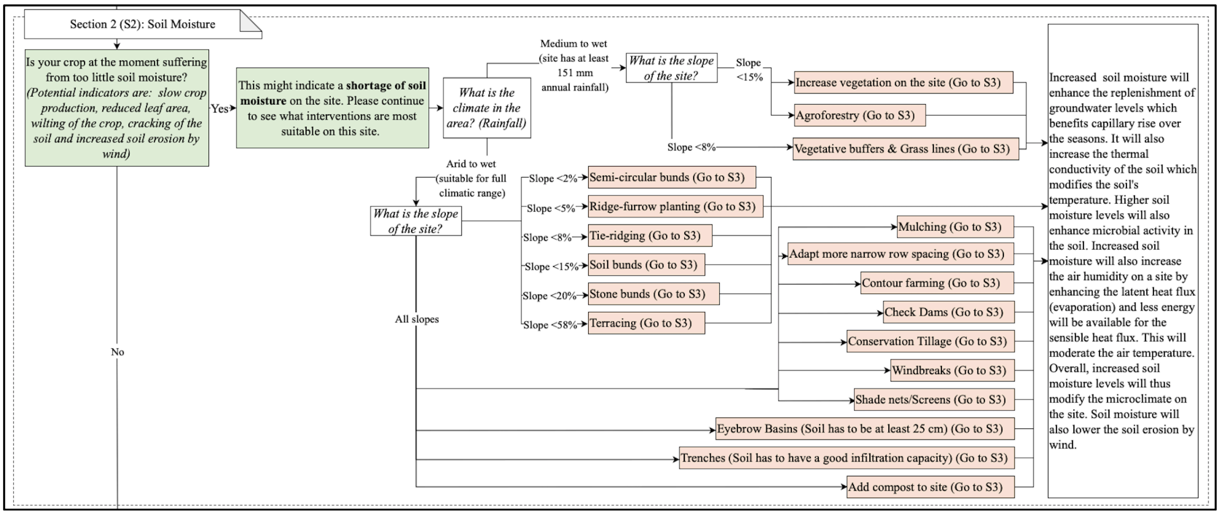

Figure 10 Decision tree section two: Soil moisture

If the soil moisture is already sufficient or after an intervention recommendation is given, the user is guided to section 3: soil temperature (Figure 11).

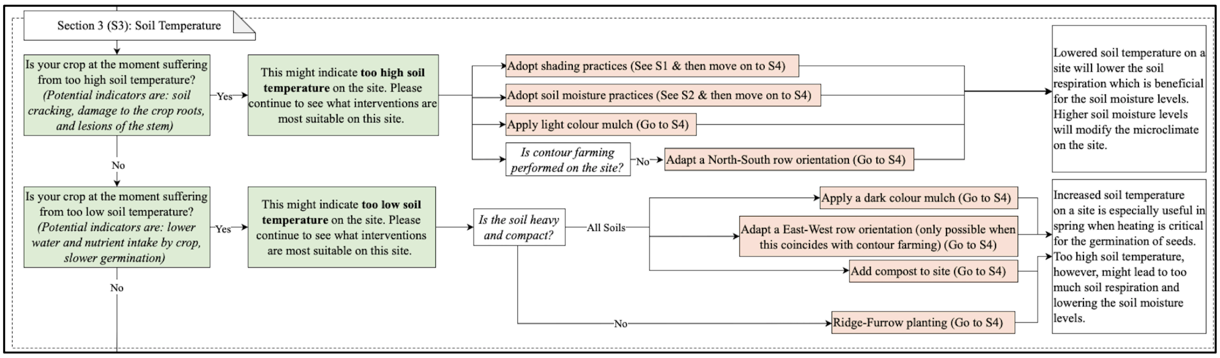

Figure 11 Decision tree section three: Soil temperature

If the soil temperature is already sufficient or after an intervention recommendation to either higher or lower the temperature is given, the user is guided to section 4: air temperature (Figure 12).

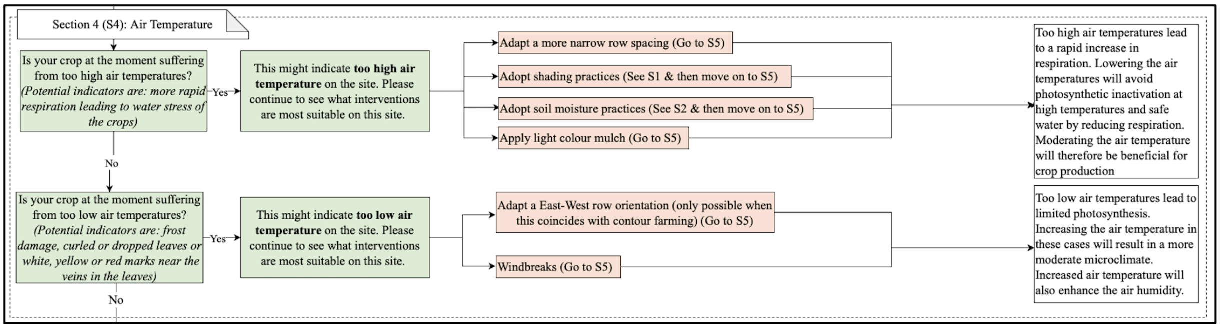

Figure 12 Decision tree section four: Air temperature

If the air temperature is already sufficient or after an intervention recommendation to either higher or lower the temperature is given, the user is guided to section 5: air humidity (Figure 13).

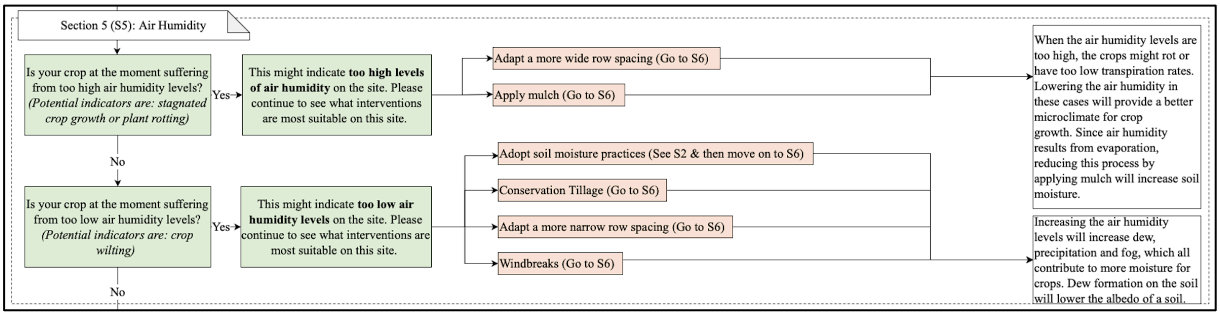

Figure 13 Decision tree section five: Air humidity

If the air humidity is already sufficient or after an intervention recommendation to either higher or lower the temperature is given, the user is guided to the last section: wind speed (Figure 14).

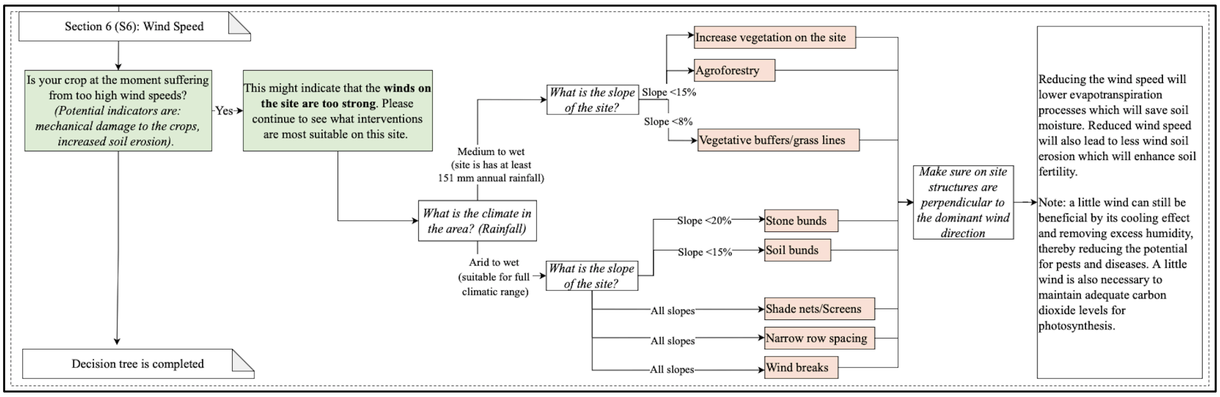

Figure 14 Decision tree section six: Wind speed

If the wind speed on a site is not too high or a recommendation to lower the wind speed is provided, the user has completed the decision tree and collected all the intervention recommendations to improve the microclimate on the specific site.

Chapter 4 – Discussion

The tool created in this research guides its user in selecting land and water management practices, suitable for a particular site, that improve the microclimate. Improving the microclimatic conditions on a farm will strengthen the farm's resilience to larger-scale climate change trends, which will enhance crop production. This research provides insights into the workings of the microclimate and the effects of human interventions on this system, and how to turn this into useable knowledge in the form of a practical guidance tool. By giving shape to managing the microclimate in the form of a practical tool, the results of this research fit into the discourse of agroecology. Agroecology understands agriculture as an ecological system based on cyclic and symbiotic relationships and seeks to maximize sustainable productivity for the long term (Peterson et al., 2018; Hathaway, 2016). A study from Antle et al. (2017) also stated that agricultural system models should focus on a holistic system instead of emphasizing vertical fluxes. This importance of a holistic view corresponds with the approach of this research by researching the microclimate as a system (Figure 4) instead of merely single relationships.

By researching the moderating effects of certain land and water management practices on the microclimate, the results of this research show how these interventions can increase local resilience and modify the effects of global climate change. This relates to other studies such as that of Altieri et al. (2015), which also stresses the resilience of small farming systems. Peterson et al. (2018) also state that by incorporating ecological resilience into agroecosystems research, more valuable insights are gained into the agroecosystem performance under stresses such as climate change. By focusing on the very local scale, this tool distinguishes itself from other agricultural tools such as AquaCrop (Steduto et al., 2009) and CERES (Popova & Kercheva, 2005), which are built upon more uniform assumptions and make use of larger-scale weather data. By focusing on the farm's microclimate and aiming to take local differences into account, the results of this study relate to the study of McNamara & Buggy (2017). They stated that initial top-down approaches to adaptation were often determined based on global and regional climate change scenarios, which did not reflect local nuances. Utset (2009) states that the most reliable climate-change mitigation options depend on each specific situation. This is why crop-model simulations based on global or regional climate scenarios are not yet used for agricultural decision-making (Utset, 2009). A study from Wright et al. (2014) also highlights the importance of tailoring adaptation technologies to the local context. Srivisvasan et al. (2011) additionally state that seasonal climate information is prepared for a broad geographic area and has minimal relevance to the community level concerns. Roncoli et al. (2011) conducted an example of Uganda, where farmers received seasonal climate forecasts, but they were unlikely to utilize that information and adopt alternative farming strategies. This research, therefore, attempted to create an alternative tool that focuses on the microclimate and individual farm-scale.

The next step after the creation of a tool is the implementation process. Problematically, literature shows that the use of agricultural decision support systems by managers of farms has been low (Rose et al., 2016; Giupponi & Sgobbi, 2013; Utset, 2009; McCown, 2002; Tsuji et al., 1998). Studies have found several reasons for this, such as unawareness of available tools (Utset, 2009), limited access due to financial issues (Utset, 2009) or lack of user-friendly design (Utset, 2009; Tsuji et al., 1998). Literature also suggests a way out of this lack of implementation issue: involving end-users in the tool design (McKey & Johnson, 2017; Clark et al., 2016; Rose et al., 2016; Utset, 2009). Even though many theoretical discourses have highlighted this vital need for active involvement of local stakeholders, local communities are still not mandatorily involved before implementing development initiatives (Schindler et al., 2016). This study, therefore, attempted to develop a participatory methodology design by involving end-users in the model design (Figure 3). By doing so, this research contributed to the search for ways in which local knowledge can be incorporated into tools to assist users in making farm management decisions. This inclusion of local expert knowledge corresponds with the increased recognition in the literature that local knowledge should be better integrated as a component for dealing with climate change (McNamara & Buggy, 2017). Rojas Blanco (2006) also states a need to bridge the gap between scientific and local knowledge to create projects that increase local resilience against climate change effects. This fits into the broader discourse of moving away from top-down techno-centric approaches and recognizing local expertise and is, therefore, part of the current approaches that strive for what have been called co-design and co-innovation processes in agricultural systems (Ditzler et al., 2018).

Some limitations to the participatory methodology of this research have been identified. This research included three in-depth interviews with experts and two focus groups with ten agricultural extension workers in total. During the feedback sessions with the focus group participants, a translator had to be used, which might have caused biases in the results. Next, more iterative cycles of improvement with local expert knowledge would have made the tool more adapted to the local context in which it might be used. Bele et al. (2013) also stress the importance of understanding the particularities of a location to determine potential solutions that can be undertaken at the local level. Rose et al. (2016) also found that when decision support tools are insufficiently flexible to allow farmers and advisers to account for local variations, the end-user will consider it to be unsuitable for their situation. In particular, the ability of a decision support tool to be tweaked according to the individual farm variation. This was also shown in the results of the focus group discussions and interviews. The tool that resulted from this research includes several farm-level specifications such as slope and soil requirements (Appendix D – Landscape Characteristics Requirements). Thus, more agro-ecological landscape specification, powered by local expert knowledge, will improve its relevance to its users and make the tool less generic.

Another essential next step in improving the tool is to test the tool with quantitative data and field measurements. Rose et al. (2016) found that an influential factor in convincing farmers and advisers to use decision support tools is performance expectancy. McKey & Johnson (2017) also found that local interest increases local adaptiveness. Spires et al. (2014) found that among the barriers to implementing new agricultural technologies, local communities' scepticism and inflexibility towards these innovations was significant. This scepticism was underpinned by the considerable risk to poor communities if new agricultural practices fail. Unsurprisingly, these communities tend only to continue to do what they know and trust (D'Agostino & Sovacool, 2011). These findings also correspond to the interview findings that if a tool is not providing tangible benefits or if a farmer does not perceive a benefit, it is likely not to be used. Thus, next to the face validation conducted in this research, it is, therefore, important to test the model on a test farm to prove its working and spark local interests by showing its contribution to improved crop production. This testing is also an important step in proving the positive effects of interventions that are not yet mainstream in an area, such as windbreaks and solar radiation management, as the FGD's and interviews indicated. Schindler et al. (2016) also highlight that an ex-ante impact assessment that includes both researcher and farmer's and local experts before actual implementation would help adapt solutions to the locality. Testing the tool and gathering quantitative data can also help determine which aspects of the microclimate should be improved. This is currently only determined by answering questions in the decision tree. Further improvement of the tool should be integrated with complementary innovation processes involving adjustment to fit local context and field testing, whereby local expert knowledge on the working of the tool is used as well. This corresponds with McCown (2002), who highlights the opportunities for co-creating information systems that utilize the comparative advantages of both practical and scientific knowledge.

To specify the intervention recommendations given by the tool, the following topics are recommended for further research: the relationship between the intervention and potential characteristics of a site such as latitude and longitude, significant obstructions to the sun (e.g., nearby mountain) and soil type. Currently, the tool only considers the slope, the annual rainfall, the depth of the soil and whether a soil is heavy and compact or not: more landscape characterization is therefore recommended. Next to the landscape characterization, the microclimatic system components taken into account in this research are also based on a specific scope consisting of six microclimatic components: solar radiation, soil moisture, soil temperature, air temperature, air humidity and wind direction and speed. For a more holistic view of the microclimatic system, it is recommended to study the effects of the interventions on the soil system in more detail. For example, the soil texture and (bedrock) type, which affects water movement through the soil. Another research recommendation is the effect of the interventions on biological and chemical activity in the soil. A final recommendation is long term monitoring to research the iterative impact of the interventions.

Despite these considerations, the tool can guide its users to improve microclimatic conditions since it considers six significant components of the microclimate. Also, the tool can act as a learning opportunity about the workings of the microclimate by contributing back information on the microclimate to its users (Figure 2). The learning feature is central to enhance farmer's professional vision and use the tool more effectively (Lundström & Lindblom, 2018). Mysiak et al. (2004) also stated that a requirement for a successful decision support system, especially in environmental applications, is the facility to explore the problem dealt with, to derive possible solutions, and to discover and analyze the underlying cause-effect relationships. It fits the intervention emphasis shift from prescribing action to facilitating learning in actions (McCown, 2002). The main implication of this research is that it demonstrates a practical application of agroecology and microclimate management, thereby contributing to moving towards a more local scale in dealing with climate change effects with closing the agricultural yield gap as a result. This holistic and microclimatic focus in agriculture seems to be missing in the central agricultural tools. The tools for microclimate management are limited to the urban area (Pijpers-van Esch, 2015), which highlights the importance of further developing this or other microclimate management tools. Next to the research recommendations to improve this tool mentioned earlier, further research could focus on how this tool fits in existing procedures: will this tool fit with or replace them? This builds upon the suggestion from the interviews to incorporate the tool in national agricultural guidelines to foster implementation. Further research could additionally be done on how co-innovative coalitions can be set up in which local people can collaborate and commit to monitoring and helping design, assemble and use feedback on how the system responds. With future climate disruptions inherent, there is an urgent need to get these kinds of projects past the project life cycle and help create resilient and sustainable agricultural systems.

Chapter 5 – Conclusion

This research aimed to create an effective and valid assessment tool that assists Ethiopian watershed managers in guiding agricultural practices to improve microclimate conditions for optimal crop production. This was done by first creating a scientific knowledge base of the workings of the microclimatic system and how human interventions influence this. From this research, it can be concluded that all six microclimate components taken into account in this research (solar radiation, soil moisture, soil temperature, air temperature, air humidity and wind direction and speed) have a direct and indirect effect on crop production. Human interactions with this system, consisting of land and water management practices, intervene in this microclimate dynamic and indirectly influence crop production. This research found 19 most common human interventions in Ethiopia, which all impact the microclimate. In general, the water conservation practices found reduce runoff and increase soil moisture levels on a site. Higher soil moisture levels increase the thermal conductivity and lower or modifies the soil temperature. By enabling latent heat fluxes over sensible heat fluxes, this also increases the air humidity and lowers the air temperature of the microclimate. Increasing soil moisture also reduces soil erosion. Other practices such as increasing vegetation or agroforestry on a site were found to increase local air humidity levels and through that precipitation and thus soil moisture. In other words, these practices can restore the hydrological cycle. Practices that influence the soil were also found to increase soil moisture levels which moderates soil temperatures and reduces wind erosion. Row orientation, row spacing, and shading practices were found to influence the solar radiation that is being received on the site and, through that, other microclimatic factors as well. Wind speed was also found to be affected by any practice that includes adding structures to the site. An alteration in wind speed, in turn, influences other microclimatic factors such as soil moisture. All these human-microclimate system relationships were translated into a decision tree that guides in determining the problem and finding the right solution for a specific site, and finally, provides information about the microclimate responses to this alternation. This tool thus determines the knobs and buttons that farmers have at their disposal to improve the microclimate. Doing so demonstrates a practical application of microclimate management that helps increase the farm's resilience and crop production. Field testing is recommended to specify the tool for a specific agro-ecological zone and convince its users of its efficacy.

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Appendix A – Research Strategy: Key Search Terms

Microclimate factors	Key Search Terms	
	Direct Effect on Crop Production	Indirect Effect on Crop Production through the Microclimate
Solar Radiation	'Effect solar radiation on crop production', 'solar radiation photosynthesis', 'shading crop production'. + 'microclimate'/'local scale'/'near ground'.	'Effect solar radiation on microclimate', 'solar radiation local scale', 'solar radiation and soil moisture', 'solar radiation and soil temperature', solar radiation and air temperature', solar radiation and air humidity', 'solar radiation and wind'.
Soil Moisture	'Effect soil moisture on crop production local scale', 'soil moisture agriculture', 'soil moisture deficit crop production'+ 'microclimate'/'local scale'/'near ground'.	'Effect soil moisture on microclimate', 'soil moisture local scale', 'soil moisture and solar radiation', 'soil moisture and soil temperature', soil moisture and air temperature', soil moisture and air humidity', 'soil moisture and wind'.
Soil Temperature	'Effect soil temperature on crop production local scale', 'Soil temperature too high effect on crop production', 'Soil temperature too low effect on crop production'+ 'microclimate'/'local scale'/'near ground'.	'Effect soil temperature on microclimate', 'solar radiation and soil temperature, 'soil moisture and soil temperature', soil temperature and air temperature', soil temperature and air humidity', 'soil temperature and wind'
Air Temperature	'Effect air temperature on crop production local scale', 'Too high/low air temperature effect crop production', + 'microclimate'/'local scale'/'near ground'.	'Effect soil temperature on microclimate', 'solar radiation and air temperature, 'soil moisture and air temperature', soil temperature and air temperature', air temperature 'and air humidity', 'air temperature 'and wind'
Air Humidity	'Effect air humidity local scale on crop production', 'too high/low air humidity effect crop production' 'Air humidity effect evaporation crops', 'Air humidity effect photosynthesis'+ 'microclimate'/'local scale'/'near ground'.	'Effect soil temperature on microclimate', 'solar radiation and air humidity, 'soil moisture and air humidity', air humidity and air temperature', soil temperature and air humidity', 'air humidity and wind'
Wind Direction and Speed	'Effect wind speed on crop production', 'Effect wind on evapotranspiration', 'effect wind on CO2 supply', 'wind and agriculture'+ 'microclimate'/'local scale'/'near ground'.	'Effect soil temperature on microclimate', 'solar radiation and wind direction and speed' , 'soil moisture and 'wind direction and speed, 'wind direction and speed, and air temperature', 'wind direction and speed and air humidity', 'soil temperature and wind'

Appendix B – Interview & Focus Group Outline

Interview/Focus Group Questions

Part 1 - Face validation of the model

Question 1 What are the most significant climatic issues you are facing on your farms?

Question 2 Which interventions have you adapted on your site, or do you have experience in? (Experience on other sites, e.g., neighbours)

- See visuals of the interventions on the PowerPoint slide –

Question 3 Ask for every intervention mentioned in Q2: Did you see any effects of this intervention on (1) Solar radiation, (2) soil moisture, (3) soil temperature, (4) air temperature, (5) air humidity and (6) wind direction and speed?

- See table for guidance on the PowerPoint slide –

Question 4 Is there anything you would like to add to the discussion? (E.g., essential practices that are not included, other side effects on a site not mentioned currently, general thoughts on this project?)

Part 2 – Incorporation of end-users

- Show participants the prototype of the decision tree -

Question 1 Discuss the order of sequence of the prototype discussion tree

Question 2 Discuss the questions in the prototype discussion tree (e.g., are the questions specific enough)

Question 3 Do you have any thoughts on how to make the decision tree more practical and valuable to you?

Appendix C – Micrometeorological Processes

Lambert's Cosine Law

The equation of Lambert's Cosine Law is as follows:

$$I = I_o \cos\theta = I_o \sin\beta \qquad \textit{(Jones, 2014)}$$

Here 'I' is the flux density at the surface, 'I_0' is the flux density normal to the beam, 'θ' is the angle between the beam and the normal to the surface (known as the zenith angle), and 'β' is the complement of 'θ' and is known as the beam elevation (Jones, 2014) (Figure 1).

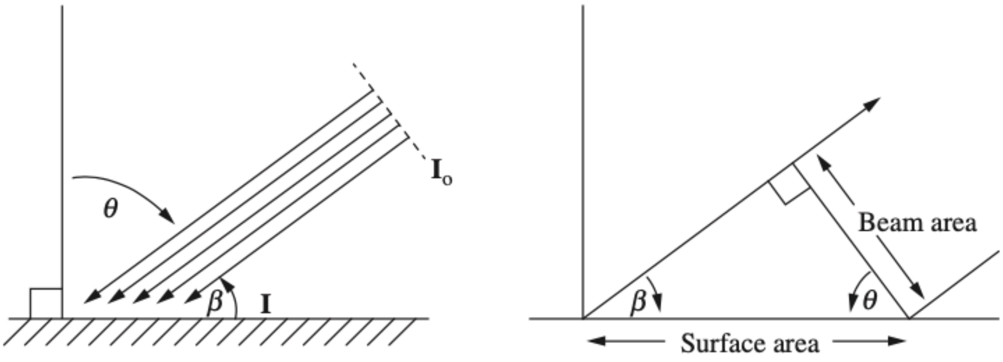


Figure 1: Visual representation of Lambert's Cosine Law (Jones, 2014).

Soil Temperature Variation Ratio

The ratio of the soil temperature variation is proportional to the following equation:

$$\frac{1}{\sqrt{ks}} \qquad \text{(Yoshino, 1975)}$$

where k is the thermal conductivity and s is the heat capacity of the soil. Thermal conductivity is the rate at which a soil transfers heat; a higher thermal conductivity means that radiation flows in and out of the heat at a higher rate. Soil is composed of particles and spaces filled with air or water. Consequently, 'k' and 's' values depend on whether space is occupied by air or by water. Since air has little thermal conductivity and heat capacity, soil containing much air has a large value of $1/\sqrt{ks}$.

Evapotranspiration Rate Equation

$$E = (0.44 + 0.118u)\,(e_0 - e_a) \qquad \text{(Rosenberg, 1983).}$$

Whereby 'E' is the evapotranspiration and 'u' is the wind speed. Less wind thus means less evaporation (Rosenberg, 1983).

Water Balance

A simple balance of the atmosphere's water and energy content is given by Gardner (1999):

$$P + I - Q = ET + D + \Delta W \qquad \text{(Gardner, 1999)}$$

Here 'P' is the amount of precipitation, 'I' is the amount of any irrigation that might be applied, 'Q' is the runoff, 'ET' is the evapotranspiration, which is the evaporation from the soil surface and the transpiration of plants combined (Rosenberg, 1983), D is the drainage to the soil below the depth of profile and 'ΔW' is the change in the water content of the soil profile above that depth (Gardner, 1999).

Appendix D – Landscape Characteristics Requirements

Table 1: Landscape Characteristics Requirements

Human Interventions	Landscape Characteristics Required				
	Average Annual Rain	*The slope of the Land*	*Mulching Material in the region*	*Stones in the region*	*Soil requirements*
Check dams	*Additional information required*	All slopes, however, gullies are more prone after the foot slopes and down lying areas (Knoop et al., 2012)	Not needed	They are only required for stone check dams—otherwise, gabion check dam, brushwood or live check dam.	All soils (Knoop et al., 2012).
Stone-faced soil bunds	It is primarily suitable in semi-arid and arid parts of the country and medium rainfall areas with deep and well-drained soils (Ministry Agriculture Ethiopia, 2005).	Maximum of 20% (Knoop et al., 2012)	Not needed	Stones or boulders required	All soils (Knoop et al., 2012)
Soil bunds	Suitable mostly in semi-arid and arid parts of the country and in medium rainfall areas with well-drained soils (Ministry Agriculture Ethiopia, 2005).	Maximum of 20%. The steeper the slope, the closer the interval between bunds. Above 15% slope, it is better to use stone bunds (Knoop et al., 2012)	Not needed	Not needed	All soils. However, not common on heavy black cotton soils (due to swelling on wetting and cracking on drying) (Knoop et al., 2012)
Eyebrow basins	200-600 mm of annual rainfall (arid to wet areas) (Greener Land, n.d.)	Applicable in steep and degraded hillsides: maximum of 100% slope (Ministry Agriculture	Not needed	Not needed	Depth of soil minimum of 25 cm (Ministry Agriculture Ethiopia, 2005).

		Ethiopia, 2005). The steeper the slope, the more the bunds have to be reinforced with stones (Greener Land, n.d.)			
Semi-circular bunds	200-750 mm of annual rainfall (arid to wet areas) (Critchley et al., 1991)	Below 2% (Critchley et al., 1991)	Not needed	Not needed	*Additional information required*
Tie ridging	Suitable mostly in semi-arid and arid parts of the country and in medium rainfall areas with deep and well-drained soils (Ministry Agriculture Ethiopia, 2005).	Gentle slopes (Knoop et al., 2012; Ministry Agriculture Ethiopia, 2005)	Not needed	Not needed	Loamy soils with good water holding capacity. Not suitable for sandy soils or poor infiltration soils (Knoop et al., 2012)
Trenches	*Additional information required*	Maximum of 100 % (Knoop et al., 2012)	Not needed	Not needed	Soils of good infiltration: otherwise, the water could be lost to evaporation (Knoop et al., 2012)
Ridge-furrow planting	Contour ridges: 350-750 mm (high rainfall as the amount of harvested runoff is comparatively small due to the small catchment area) (Critchley et al., 1991).	Contour ridges: from flat up to 5.0%. (Critchley et al., 1991)	Not needed	Not needed	Heavy and compacted soils may be a constraint to the construction of ridges (Critchley et al., 1991)
Terracing	Arid to wet regions (Greener Land, n.d.)	On average, 12-58% considering the various land use types (Knoop et al., 2012)	Not needed	Not necessary: could be used to reinforce. Otherwise, it could be stabilized with vegetation (Knoop et al., 2012)	Deep soils (Knoop et al., 2012)

Increasing vegetation	Medium (151-600 mm) to Wet (600 mm) areas (Greener Land, n.d)	0% - >15% (Greener Land, n.d.)	Not needed	Not needed	*Additional information required*
On-farm agroforestry	Medium (151-600 mm) to Wet (600 mm) areas (Greener Land, n.d)	0% - >15% (Greener Land, n.d.)	Not needed	Not needed	*Additional information required*
Vegetative buffers & grass strips	Medium (151-600 mm) to Wet (600 mm) areas. In the case of drier environmental condition, vegetative lines with cactus could be used instead (Greener Land, n.d)	Gentle slopes up to 8% (Knoop et al., 2012)	Not needed	Not needed	All soils (Knoop et al., 2012)
Conservation tillage	*Additional information required*	*Additional information required*	Not needed	Not needed	All soils
Mulching	*Additional information required*	*Additional information required*	Mulching materials required	Not needed	All soils
Contour farming	Contour ridges: 350-750 mm (high rainfall as the amount of harvested runoff is comparatively small due to the small catchment area) (Critchley et al., 1991).	From flat up to 5.0% (Critchley et al., 1991)	Not needed	Not needed	All soils
Row orientation	*Additional information required*	*Additional information required*	Not needed	Not needed	All soils
Row spacing	*Additional information required*	*Additional information required*	Not needed	Not needed	All soils
Shading	*Additional information required*	*Additional information required*	Not needed	Not needed	All soils

Windbreaks	*Additional information required*	*Additional information required*	Not needed	Only needed in case of stone made windbreaks. Other materials can be used as well.	All soils

Appendix E – Focus Group Discussion and Interview Notes

In this appendix, all the notes of the FGD's and one-on-one interviews are displayed. The recordings of each session are available upon request. The main goal of these sessions was to validate the research results, in other words, validating the found effects of each human intervention on the microclimate. Next to this validation, the interviews and FGDs focused on the decision tree itself and how this can be improved to be better workable for the potential end-users. As stated in the methodology section, participants were selected through snowball sampling as MetaMeta hosted a five-day workshop with development agents. Ten of these agricultural extension workers agreed to participate in the study.

Focus Group Discussion 1 (8th of April 2021)

This FGD was held in Bahir Dar, Ethiopia. The participants were **five male agricultural extension workers** from the Guba Lafto Woreda and surrounding areas (Figure 2). These workers work directly with farmers in providing advice on how to manage their farms. A summary of the results from this discussion is presented below according to the questions asked (Appendix B – Interview & Focus Group Outline).

Figure 2: Focus Group Discussion with the five male agricultural extension workers (Photograph from Jean Marc Pace)

Question 1 - Major climatic issues that the participants are noticing:

- Big decrease in available soil moisture.
- Increased occurrence of high-intensity rainfall leads to more flooding, landslides and natural disasters.
- Decrease of soil water retention capacity.
- Decreasing size of the wetland areas.
- Less available groundwater.
- Deforestation is a significant issue.

- Soil erosion is a significant issue.
- A relatively new phenomenon in the highland areas is hail, which is very damaging to the crops.
- The rainfall patterns are becoming erratic and unpredictable (particularly in the short/spring rain season '*Tseday*').

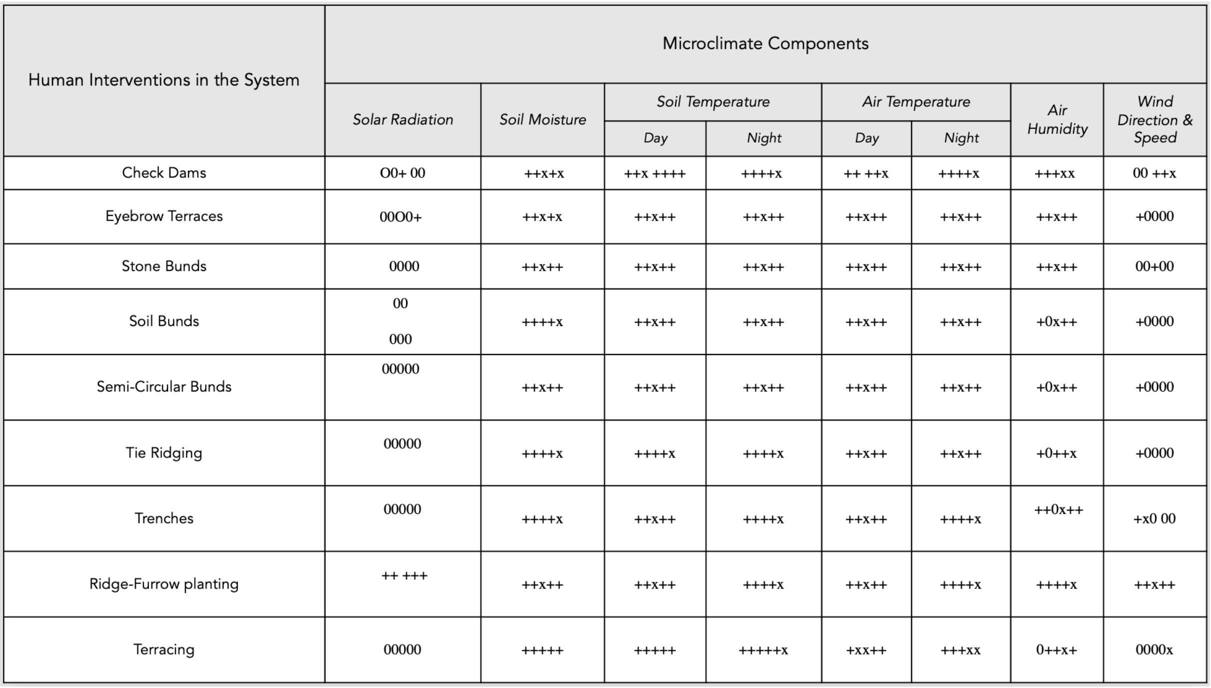
Question 2 – Recognition and prevalence of interventions:

- All interventions incorporated in the tool prototype are commonly practised except for the following:
- Semi-circular bunds are rarely used.
- Ridge and furrow planting are very rare in highlands. However, in the lowlands, this is sometimes practised where there is too much moisture.
- Vegetative buffers and grass strips are not very common but are practised especially at higher elevations.
- Conservation tillage is extremely rare; this contradicts advice given through agricultural extension services.
- Mulching is only practised around young fruit trees. A lack of mulching material and stone mulch is not considered.
- Row orientation is not considered on the farms, but East-West orientation is typical in tree nurseries.
- Row spacing is dependent on crop type and not changed for microclimate reasons. For example, Teff has tiny seeds and is broadcasted, then formed into rows through tillage in parallel lines, forming small ridges with narrow spacing. For larger-seeded crops, they are planted in rows without much attention given to spacing.
- Shading is not practised except in the early stages of growth in plant nurseries (typically locally sourced grass/reeds/sticks).
- Windbreaks – trees are planted on field boundaries, but the intention is not to break the wind; it is more for boundary demarcation and an anti-erosion measure.
- The recommendation of adding 'composting/increasing organic matter in topsoil' as a measure is widespread practices and influences the microclimate (the water holding capacity, moisture levels, humidity, darkening of the surface).

Question 3 – Microclimatic effect of all interventions

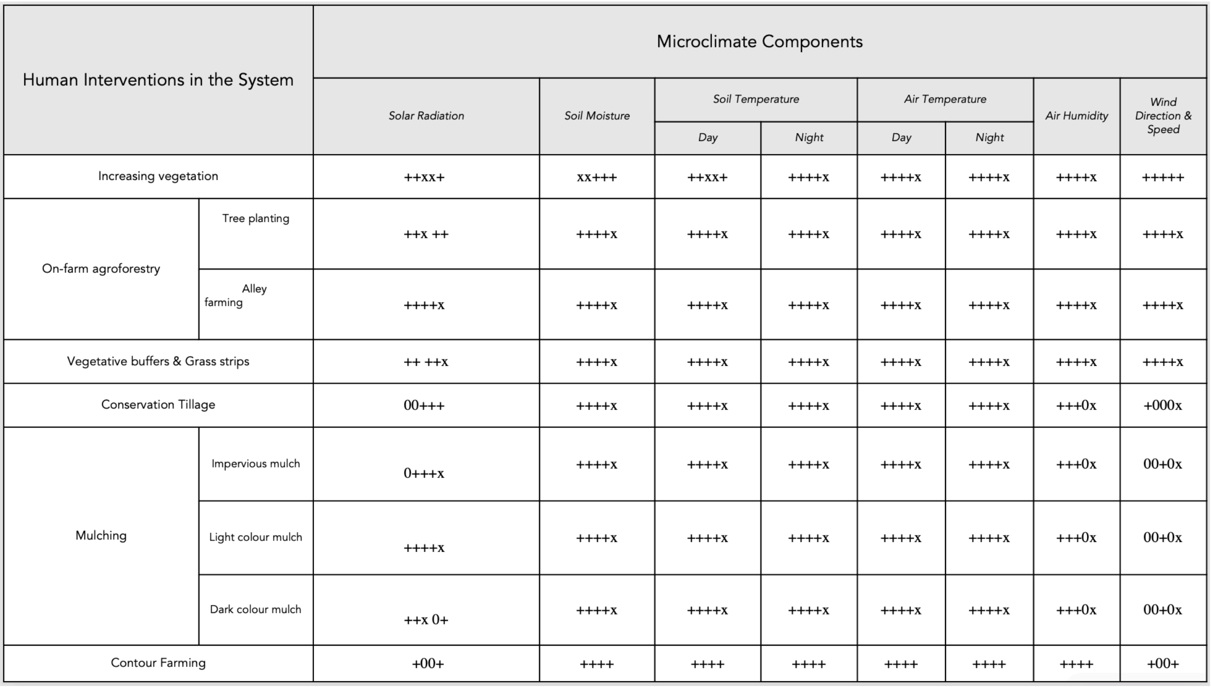
For this section of the research, participants were asked to discuss and mark on a flip chart with a '+' (improved), a '0' (neutral), or an 'x' (makes worse). The results were sometimes conflicting, and some answers may have been a bit rushed due to the lengthy process. However, a general impression can still be taken (Table 2).

Table 2: Results from FGD Question 3 (Part 1): Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A ‘+’ indicates an increase, and a ‘x’ indicates a decrease in that specific microclimate component. ‘0’ indicates no direct effect of that intervention on that specific microclimate component (neutral).



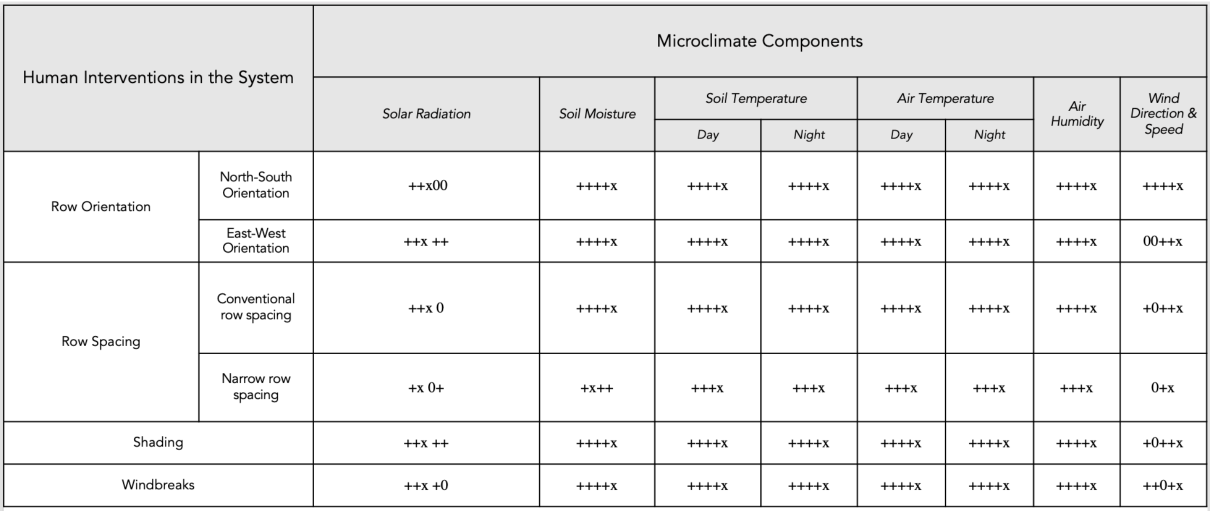
Human Interventions in the System	Microclimate Components							
	Solar Radiation	*Soil Moisture*	*Soil Temperature*		*Air Temperature*		*Air Humidity*	*Wind Direction & Speed*
			Day	*Night*	*Day*	*Night*		
Check Dams	O0+ 00	++x+x	++x ++++	++++x	++ ++x	++++x	+++xx	00 ++x
Eyebrow Terraces	00O0+	++x+x	++x++	++x++	++x++	++x++	++x++	+0000
Stone Bunds	0000	++x++	++x++	++x++	++x++	++x++	++x++	00+00
Soil Bunds	00 000	++++x	++x++	++x++	++x++	++x++	+0x++	+0000
Semi-Circular Bunds	00000	++x++	++x++	++x++	++x++	++x++	+0x++	+0000
Tie Ridging	00000	++++x	++++x	++++x	++x++	++x++	+0++x	+0000
Trenches	00000	++++x	++x++	++++x	++x++	++++x	++0x++	+x0 00
Ridge-Furrow planting	++ +++	++x++	++x++	++++x	++x++	++++x	++++x	++x++
Terracing	00000	+++++	+++++	+++++x	+xx++	+++xx	0++x+	0000x

Table 2: Results from FGD Question 3 (Part 2): Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A ‘+’ indicates an increase, and a ‘x’ indicates a decrease in that specific microclimate component. ‘0’ indicates no direct effect of that intervention on that specific microclimate component (neutral).



Human Interventions in the System		Microclimate Components							
		Solar Radiation	*Soil Moisture*	*Soil Temperature*		*Air Temperature*		*Air Humidity*	*Wind Direction & Speed*
				Day	*Night*	*Day*	*Night*		
Increasing vegetation		++xx+	xx+++	++xx+	++++x	++++x	++++x	++++x	+++++
On-farm agroforestry	Tree planting	++x ++	++++x	++++x	++++x	++++x	++++x	++++x	++++x
	Alley farming	++++x	++++x	++++x	++++x	++++x	++++x	++++x	++++x
Vegetative buffers & Grass strips		++ ++x	++++x	++++x	++++x	++++x	++++x	++++x	++++x
Conservation Tillage		00+++	++++x	++++x	++++x	++++x	++++x	+++0x	+000x
Mulching	Impervious mulch	0+++x	++++x	++++x	++++x	++++x	++++x	+++0x	00+0x
	Light colour mulch	++++x	++++x	++++x	++++x	++++x	++++x	+++0x	00+0x
	Dark colour mulch	++x 0+	++++x	++++x	++++x	++++x	++++x	+++0x	00+0x
Contour Farming		+00+	++++	++++	++++	++++	++++	++++	+00+

Table 2: Results from FGD Question 3 (Part 3): Each column presents a microclimate component, and for every intervention, the effect of that specific microclimate component is given. A '+' indicates an increase, and a 'x' indicates a decrease in that specific microclimate component. '0' indicates no direct effect of that intervention on that specific microclimate component (neutral).



Human Interventions in the System		Microclimate Components							
		Solar Radiation	*Soil Moisture*	*Soil Temperature*		*Air Temperature*		*Air Humidity*	*Wind Direction & Speed*
				Day	*Night*	*Day*	*Night*		
Row Orientation	North-South Orientation	++x00	++++x	++++x	++++x	++++x	++++x	++++x	++++x
	East-West Orientation	++x ++	++++x	++++x	++++x	++++x	++++x	++++x	00++x
Row Spacing	Conventional row spacing	++x 0	++++x	++++x	++++x	++++x	++++x	++++x	+0++x
	Narrow row spacing	+x 0+	+x++	+++x	+++x	+++x	+++x	+++x	0+x
Shading		++x ++	++++x	++++x	++++x	++++x	++++x	++++x	+0++x
Windbreaks		++x +0	++++x	++++x	++++x	++++x	++++x	++++x	++0+x

Question 4 – Extra additions to the discussion

- Add composting as an intervention
- Many interventions have indirect effects also: short term, medium term, long term effects.

Part 2 – Incorporation of end-users in tool creation

- Solar radiation management is not something typically considered in Ethiopian agriculture
- Questions should be problem-oriented, and the effect on the crop should come first, followed by its climatic cause.
- Consider agro-ecological zonation and use this to shape the model differently based on local context.
- Consider major livelihood options and the climatic issues associated with them too.
- Very enthusiastic about the decision tool. Participants believe it will be a beneficial tool for extension workers and development agents to talk to farmers about managing their land.
- Participants liked the simplicity of the model and think it will be easy to use.
- Participants like the idea of making a digital application out of the tool.
- The order of questions is fine other than solar radiation.

Focus Group Discussion 2 (9th of April 2021)

This FGD was held in Bahir Dar, Ethiopia. This group consisted of **five female participants with expertise mainly in livestock and socio-economic development**.

This FGD was, unfortunately, less fruitful as the participants were not very knowledgeable since their expertise mainly was in livestock and socio-economic development; only the agricultural practices they are familiar with have been discussed.

One-on-One Interview 1 (13th of April 2021)

The interviewee of this one-on-one interview was **Bantamlak Wondmnow**. Bantamlak is a CRG (climate-resilient green economy) projects coordinator at the Ethiopian Bureau of Agriculture.

- The decision tree should start with identifying the problems that farmers or experts are noticing. First, identify the root cause, then move on to the solutions. For farmers, it should be clear that: first, I am working in this microclimatic area, and the main problems to this farming system are this, and this and the leading cause of these problems are, for example, the lack of soil moisture or the lack of air temperature.
- Include what climate or weather-related problems the watershed faces to determine some of the critical problems and before moving to a solution.
- Maybe add a question like in which climatic zone are you working.
- Add some basic parameters to classify certain agricultural areas: average temperature, elevation above sea level, major crops grown, common trees in the area. This will help identify the climatic areas that the practitioners work in.
- Solar radiation intervention: for most farmers, the crop row orientation depends on the aspect of the land: you need to keep your slope position most dominant: contour farming is more important than the row direction.
- Include compost as an intervention that affects the microclimate.
- Shift happening to digital and mobile phones. Everyone will prefer to use such applications instead of books.
- Some of the recommendations are packages of different technologies: more elaboration on the interventions in the end.

One-on-One Interview 2 (16th of April 2021)

The interviewee of this one-on-one interview was **Dr Taye Alemayehu**, the country director of MetaMeta Research Ethiopia.

- Intervention should be customized to the local situation; the greater number of factors taken into account, the better. Since there are many agricultural zones: recommendations should be explicitly given for a specific agricultural zone.
- Geology and bedrock structures are also important to take into account.
- To recommend interventions to the whole of Ethiopia, more specifications should be made.
- Microclimate components are challenging to measure and difficult to quantify for local practitioners.
- A response column would be helpful to let farmers know what they can expect after they did a particular action (action, process, response).
- Diurnal temperature variation is very important, and temperature change is a very important factor in the microclimate.
- The main limitation of the tool right now is that it is not specified for each agricultural zone.
- Farmers are mostly interested in enhancing moisture: more rainfall. Their overall goal is more water security, and they do not care about the microclimate.

- Implementing new interventions: sometimes, it takes time for new technology to take up. Things that might speed up this process are demonstration sites and piloting phases. The implementation should be gradual; otherwise, it might fail.
- How to improve the tree and make it more valuable to farmers:
  - Specify agricultural zones: soil foundation/rocks/dominant wind directions. This will define the geographic area more.
  - Include a response column to show the effect of an intervention on the microclimate in general. Specify this in short- and long-term response.
- Thoughts on a mobile application: first, the tool should get acceptance and people need to demand for it. Farmers are not sophisticated to use such applications, but development agents can use them to guide farmers.
- Implementation process: one cannot directly approach farmers with this decision tree; this should be a step-by-step approach. Being part of a government guideline could be beneficial. Once the tool is accepted, it can be adopted in development programs.
- It is very important to follow the right implementation processes; otherwise, it might be a waste of the tool.

Interview 3 (19th of April 2021)

The interviewees interviewed during this session were **Bantamlak Wondmnow** and **Yismaw Wuletaw**. As stated above, Bantamlak is a CRG (climate-resilient green economy) projects coordinator at the Ethiopian Bureau of Agriculture. Yismaw is a natural resource management expert for the Amhara region at the Ethiopian Bureau of Agriculture.

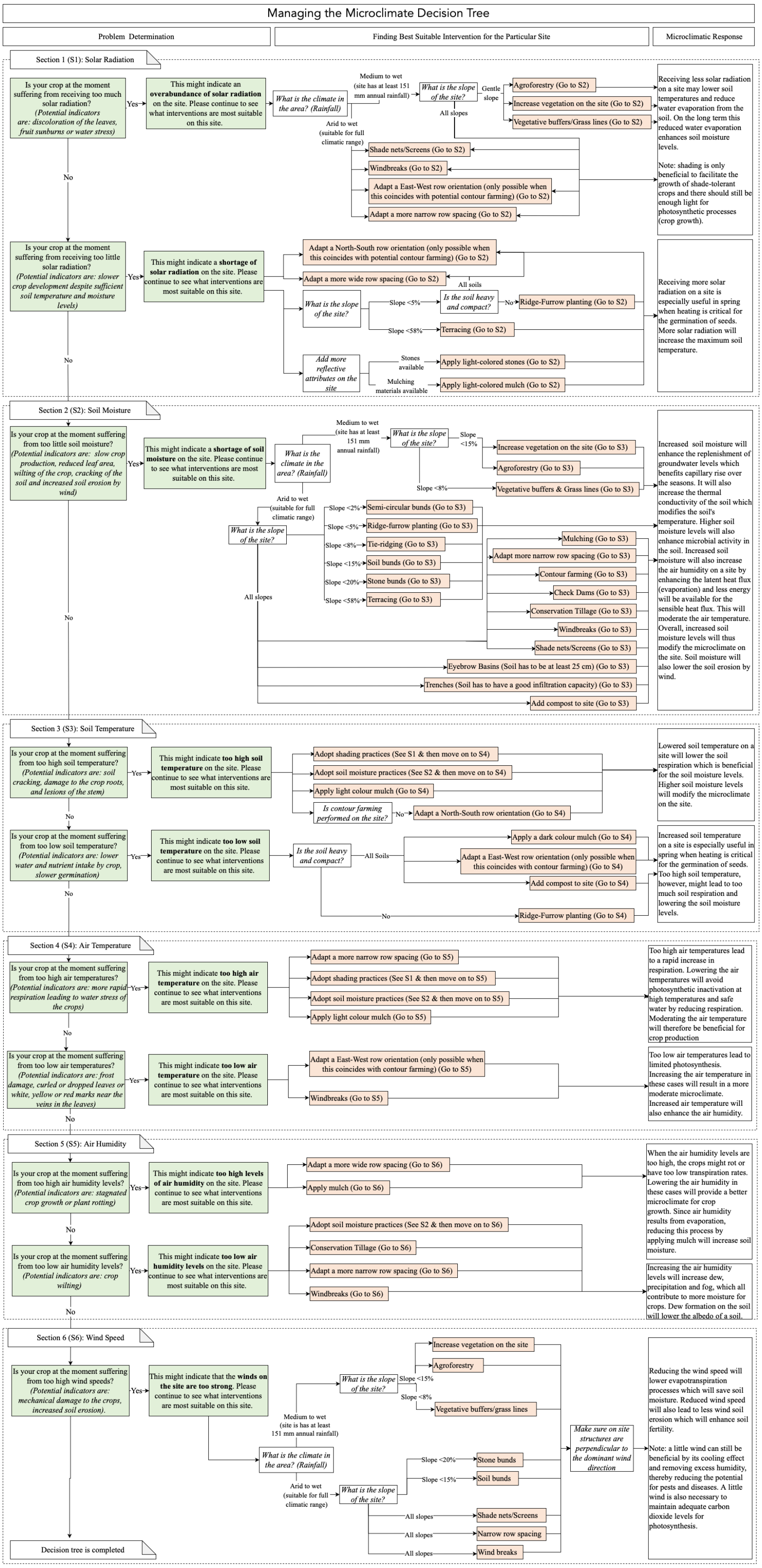
- Validation of Table 3:
  - All structures have a significant effect on solar radiation by reflecting and absorbing the solar radiation, however, this effect is very local. The effects of how these objects transfer to their surroundings are very local (B).
  - Tie ridges significantly affect the soil moisture because it retains the moisture and provides more time for the moisture to percolate down in the soil (Y).
  - It is seen that trenches have the same effect as tie ridging (Y).
  - Soil bunds are also used to establish the vegetation, and in areas with more rocks, farmers use stone-faced soil bunds (B).
  - The effect of all these structures on reducing the daytime temperature (moderating effect) is quite clear. In the night, they will emit the absorbed temperature to the very local area—same effect for air and soil temperature (B).
  - This is also correlated to air humidity. Usually, an increased soil temperature and soil moisture and increased radiation absorption lead to increased air humidity (B).
  - Wind direction and speed: These structures have no significant effect on the wind speed and direction on a side (Y). Reduction effect on wind speed by physical structures because they act as a barrier on the field (B). Physical structures have no more effect regarding the wind direction and speed; they only cause turbulence and variance (Y).
  - Ridge-Furrow planting: Furrows are where the irrigation goes and where the seeds are planted. Honestly, I did not notice any effect in that change of region between the ridge and furrows (B). Ridge-Furrow planting does not affect wind direction. Ridge furrow planting will create a better moisture zone, affecting the absorption of solar radiation. By increased moisture levels, the area will absorb more heat than the dryer parts (Y).

  - Terracing: Increased moisture and solar radiation absorption. Increased moisture leads to more moderate microclimate. However, this effect depends on the local situation (Y).
  - Increasing vegetation/Agroforestry/Vegetative buffers & Grass strips: The effect of increasing vegetation is straightforward; it will decrease the amount of solar radiation coming in. It increases the soil moisture, and it decreases the air temperature during the daytime (B). I agree (Y).
  - Conservation tillage: Conservation tillage includes important parameters as crop protection, crop residue management and reduced number of tillage at the same time. Usually, an increased effect on the amount of solar radiation absorbed is found and a decreasing effect on soil temperature (B). Good soil cover with crop residue management will also be a barrier to the wind, positively affecting the land (B). Crop residue management has its own significant effect because it covers the white area uniformly. By covering the white area, there is more solar radiation absorption and more soil moisture. Conservation tillage absorbs moisture like a sponge (Y).
  - Mulching: Increase soil cover with crop materials has the same effect as we mentioned on conservation tillage. There are also differences between the types of mulch; the amount of solar radiation reflected depends on the colour of the material used. I know some fields where they used dark colour plastic sheets and stone mulching practices, and these areas will have a greater amount of radiation being absorbed. And the lighter ones, like crop residue types of mulching, will have some limited amount of radiation being absorbed (B).
  - Row orientation & Row spacing: Row orientation is not only N-S and E-W. It depends on the slope as well, and it is more important to follow the contour lines (Y). Row spacing practice is done by the recommendation of the package of that specific crop to maximize production. I did not realize the difference in spacing; it is primarily implemented to increase production. Remaining other things constant. I am indifferent in this regard (B). Both conventional and narrow row spacing have their own advantages. Conventional row spacing has its own advantage because it allows more space to percolate the moisture into the soil. The narrow spacing will also have its own advantage regarding the shading effects (Y).
  - Shading: Soil moisture is quite related to incoming radiation. If reducing the amount of solar radiation, the daytime evaporation rate will decrease, which will increase the soil moisture (B). I agree (Y).
  - Windbreaks: This practice is not very common among our farmers (Y). Not a common practice (B).

- General comments:
  - The effect of all the physical structures depends on orientation and the aspect and characteristics of the land (B).
  - If an effect is significant depends on the area and the number of structures to treat the specific area. The horizontal distance between two structures is also very important: the narrower the distance between the structures, the stronger its effect (Y).
  - Adding more variables to characterize the landscape + agricultural zone of the area will improve the model. Some variables could be land-use type, average slope, erosion history of the area, soil characteristics. If the user is able to identify where he or she is working on, then the different interventions will be more specific for that landscape (B).
  - Add the impacts on the microclimate to the decision tree as well. Any impact from the practice will have to be seen on the decision tree (B).

    - Very helpful tool (B).

Appendix F – Decision Tree



Managing the Microclimate Decision Tree

Problem Determination

Finding Best Suitable Intervention for the Particular Site

Microclimatic Response

Section 1 (S1): Solar Radiation

Is your crop at the moment suffering from receiving too much solar radiation? *(Potential indicators are: discoloration of the leaves, fruit sunburns or water stress)*

This might indicate an **overabundance of solar radiation** on the site. Please continue to see what interventions are most suitable on this site.

Receiving less solar radiation on a site may lower soil temperatures and reduce water evaporation from the soil. On the long term this reduced water evaporation enhances soil moisture levels.

Note: shading is only beneficial to facilitate the growth of shade-tolerant crops and there should still be enough light for photosynthetic processes (crop growth).

Is your crop at the moment suffering from receiving too little solar radiation? *(Potential indicators are: slower crop development despite sufficient soil temperature and moisture levels)*

This might indicate a **shortage of solar radiation** on the site. Please continue to see what interventions are most suitable on this site.

Receiving more solar radiation on a site is especially useful in spring when heating is critical for the germination of seeds. More solar radiation will increase the maximum soil temperature.

Section 2 (S2): Soil Moisture

Is your crop at the moment suffering from too little soil moisture? *(Potential indicators are: slow crop production, reduced leaf area, wilting of the crop, cracking of the soil and increased soil erosion by wind)*

This might indicate a **shortage of soil moisture** on the site. Please continue to see what interventions are most suitable on this site.

Increased soil moisture will enhance the replenishment of groundwater levels which benefits capillary rise over the seasons. It will also increase the thermal conductivity of the soil which modifies the soil's temperature. Higher soil moisture levels will also enhance microbial activity in the soil. Increased soil moisture will also increase the air humidity on a site by enhancing the latent heat flux (evaporation) and less energy will be available for the sensible heat flux. This will moderate the air temperature. Overall, increased soil moisture levels will thus modify the microclimate on the site. Soil moisture will also lower the soil erosion by wind.

Section 3 (S3): Soil Temperature

Is your crop at the moment suffering from too high soil temperature? *(Potential indicators are: soil cracking, damage to the crop roots, and lesions of the stem)*

This might indicate **too high soil temperature** on the site. Please continue to see what interventions are most suitable on this site.

Lowered soil temperature on a site will lower the soil respiration which is beneficial for the soil moisture levels. Higher soil moisture levels will modify the microclimate on the site.

Is your crop at the moment suffering from too low soil temperature? *(Potential indicators are: lower water and nutrient intake by crop, slower germination)*

This might indicate **too low soil temperature** on the site. Please continue to see what interventions are most suitable on this site.

Increased soil temperature on a site is especially useful in spring when heating is critical for the germination of seeds. Too high soil temperature, however, might lead to too much soil respiration and lowering the soil moisture levels.

Section 4 (S4): Air Temperature

Is your crop at the moment suffering from too high air temperatures? *(Potential indicators are: more rapid respiration leading to water stress of the crops)*

This might indicate **too high air temperature** on the site. Please continue to see what interventions are most suitable on this site.

Too high air temperatures lead to a rapid increase in respiration. Lowering the air temperatures will avoid photosynthetic inactivation at high temperatures and safe water by reducing respiration. Moderating the air temperature will therefore be beneficial for crop production

Is your crop at the moment suffering from too low air temperatures? *(Potential indicators are: frost damage, curled or dropped leaves or white, yellow or red marks near the veins in the leaves)*

This might indicate **too low air temperature** on the site. Please continue to see what interventions are most suitable on this site.

Too low air temperatures lead to limited photosynthesis. Increasing the air temperature in these cases will result in a more moderate microclimate. Increased air temperature will also enhance the air humidity.

Section 5 (S5): Air Humidity

Is your crop at the moment suffering from too high air humidity levels? *(Potential indicators are: stagnated crop growth or plant rotting)*

This might indicate **too high levels of air humidity** on the site. Please continue to see what interventions are most suitable on this site.

When the air humidity levels are too high, the crops might rot or have too low transpiration rates. Lowering the air humidity in these cases will provide a better microclimate for crop growth. Since air humidity results from evaporation, reducing this process by applying mulch will increase soil moisture.

Is your crop at the moment suffering from too low air humidity levels? *(Potential indicators are: crop wilting)*

This might indicate **too low air humidity levels** on the site. Please continue to see what interventions are most suitable on this site.

Increasing the air humidity levels will increase dew, precipitation and fog, which all contribute to more moisture for crops. Dew formation on the soil will lower the albedo of a soil.

Section 6 (S6): Wind Speed

Is your crop at the moment suffering from too high wind speeds? *(Potential indicators are: mechanical damage to the crops, increased soil erosion).*

This might indicate that the **winds on the site are too strong**. Please continue to see what interventions are most suitable on this site.

Make sure on site structures are perpendicular to the dominant wind direction

Reducing the wind speed will lower evapotranspiration processes which will save soil moisture. Reduced wind speed will also lead to less wind soil erosion which will enhance soil fertility.

Note: a little wind can still be beneficial by its cooling effect and removing excess humidity, thereby reducing the potential for pests and diseases. A little wind is also necessary to maintain adequate carbon dioxide levels for photosynthesis.