UNIVERSITÀ
DEGLI STUDI
FIRENZE

DOCTORAL PROGRAMME in
Sustainable Management of Agricultural
Resources, Forestry and Food

XXX Cycle

Evidences of climate mitigation from Landscape Restoration and Water Harvesting
A Remote Sensing Approach

Settore Scientifico Disciplinare AGR08

PhD Candidate
Ing. Giulio Castelli

Tutor
Prof. Ing. Elena Bresci, PhD.

Coordinator
Prof. Susanna Nocentini, PhD.

Years 2014/2017

Abstract

When changes are made in a landscape, changes are made to the microclimate. When farmers plant trees in or around their field, and when communities dig bunds to improve water retention, they change the local climate around them. In the current global climate debate, adaptation and mitigation are dominant concepts, while no attention has been paid to local solutions that can enhance local climatic resilience of landscapes. In arid to semi-arid areas of the world, measures such as Landscape Restoration and Water Harvesting (LRWH) are implemented to revert land degradation and increase soil moisture, reducing runoff losses. The present work aims to analyse to what extent storing soil moisture, with adequate land and water management practices, can reduce temperatures in the hot months after the rainy season, as a consequence of Soil Moisture-Temperature Coupling. Since it is demonstrated how soil moisture deficit can enhance heatwaves in diverse regions of the world, it is hypothesized that increasing soil moisture availability, during the dry and hot periods, can mitigate hot temperatures. The analysis has been carried out for Enabered catchment, in Tigray Region, Ethiopia, where the rainy season runs from June to August. Here, large scale LRWH implementation ended in 2008. An analysis based on remote sensing data has been carried out to evaluate (1) to what extent LRWH implementation can enhance soil moisture conservation at catchment scale; (2) to what extent LRWH implementation can mitigate temperatures in the dry season at catchment scale; and (3) if SMTC were evident. Results showed an increased capacity of the catchment to retain soil moisture produced in the rainy season until September ($P < 0.01$) and October ($P < 0.1$) and reduced temperatures for September ($P < 0.1$), October ($P < 0.01$) and November ($P < 0.05$), with decreases of Land Surface Temperatures up to 1.74 °C. A simple, parsimonious linear regression model demonstrated that SMTC is evident at catchment scale and that the implementation of LRWH measures provided a climate mitigation effect in the watershed. The present work can reinforce the call for an increased adoption of water harvesting, land restoration and green water management, to increase the resilience of agricultural ecosystem located in arid and semi-arid areas, that represent a key element to achieve global food security.

Keywords: Climate feedbacks, Soil Moisture Temperature Coupling, Transitional soil moisture and evapotranspiration regime, Landsat, MODIS, ERA-INTERIM, CHIRPS, Ethiopia, Tigray Region.

Ringraziamenti

Il principale ringraziamento per questa tesi di dottorato va alla mia famiglia, Gabriele, Carla e Marco, per avermi sopportato e supportato in questi tre anni (e mezzo) di dottorato. Senza di loro nulla sarebbe stato possibile.

Ringrazio la Professoressa Elena Bresci, per il continuo supporto, scientifico e non e per le opportunità messe a disposizone, nonostante le difficoltà dell'Università Italiana, in questi tempi. La ringrazio soprattutto per la costante tenacia nel cercare di superare queste difficoltà e portare elementi nuovi nella nostra istituzione.

Ringrazio Beatrace e Kamar, per i mille momenti, belli e meno belli, passati insieme.

Dal punto di vista accademico ringrazio tutte le persone che hanno contribuito a questo percorso: Frank van Steenbergen, Fabio Salbitano, Federico Preti, Fabio Castelli, Antonio Giacomin, Eyasu Yazew, Guido D'Urso. Ringrazio Yasir Mohamed, per la revisione, negativa e molto giustificata, che ha fatto per la prima versione di questo lavoro. Credo fermamente che qualsiasi revisione negativa debba essere sfruttata per quello che è: un'opportrunità di miglioramento. La sua è stata fondamentale per la riuscita del mio dottorato. Ringrazio il mio amico Tommaso Pacetti. Il suo valore come accademico e ricercatore impone di inserirlo nella lista che qui si conclude.

Come essere umano, e non più come accademico, ringrazio tutte le persone che mi sono state vicine in questi tre anni. Non è mia intenzione fare una lista, dimenticherei sicuramente qualcuno (sono una persona e non un computer). Non voglio invece dimenticare i momenti passati insieme. Spero davvero di avervi fatto sentire parte di questa mia esperienza, e di questa parte della mia vita. Il mio dottorato è stato un viaggio in cui ho visitato posti bellissimi e incontrato persone meravigliose: a tutti voi va il mio ringraziamento.

Inizio del corso di dottorato: 1/11/2014

Difesa della tesi di dottorato: 20/7/2018

Pasei visitati: Burundi, Kenya, Sudan, Etiopia, Bolivia, Ruanda, Guatemala, Emirati Arabi Uniti, Olanda, Svezia, Austria.

Acknowledgements

Thanks to my family, Gabriele, Carla and Marco. Without them, nothing of this would have been possible.

Thanks to Professor Elena Bresci, for the continuous support, academic and not, and for all the opportunities that she made available for me. Most of all, thank to her for her strength in fighting for overcoming the difficulties that so far have been rooted in our system, and for bringing something new in our University.

Thanks to Kamar and Beatrice, for all the good, and less good moments spent together.

As an Academic I thank all the people that have been involved in my thesis: Frank van Steenbergen, Fabio Salbitano, Federico Preti, Fabio Castelli, Antonio Giacomin, Eyasu Yazew, Guido D'Urso. My gratitude goes to Professor Yasir Mohamed. I strongly believe that any negative feedback is nothing but an opportunity to develop. His negative review of the first version of my thesis brought me to develop a better work, giving also good advices and suggestions about theories and tools to be used. Thanks to my friend and colleague Tommaso Pacetti. His value as researcher imposes to insert him within this list.

As a human being, my gratitude goes also to everyone I met in these three and half years. I don't want to make a list, I am sure I will forget someone. I sincerely hope to have shown to all the wonderful people I met in this travel my gratitude to them. It was an honour to share even a small piece of this with you.

Begin of the PhD course: 1/11/2014

PhD dissertation date: 20/7/2018

Countries visited: Burundi, Kenya, Sudan, Ethiopia, Bolivia, Rwanda, Guatemala, UAE, The Netherlands, Sweden, Austria.

Table of Contents

List of figures

List of Tables

List of abbreviations

AL	Agricultural Landscapes
EF	Evaporative Fraction
ES	Ecosystem Services
G	Ground heat flux
L1PT	Level-1 Precision Terrain (Landsat images)
LH	Latent Heat flux
LRWH	Landscape Restoration and Water Harvesting
LST	Land Surface Temperature
NDII	Normalised Difference Infrared Index
NHD	Number of Hot Days
R_{net}	Net incoming Radiation
R_{rs}	Rainfall in the rainy season
SH	Sensible Heat flux
SMTC	Soil Moisture – Temperature Coupling
SPI	Standardised Precipitation Index
SWC	Soil and Water Conservation
V	Soil Volume
T	near-surface air Temperature
T_{850}	Temperature at 850 hPa level
t	normalised temperature index
WCI	Water Conservation Index

1 Introduction

1.1 Societal relevance

Humankind is part of the biosphere. People, communities, economies, societies and cultures shape and are shaped by the Earth as a living system, at local and global scale, being an embedded element of the Planet (Folke et al., 2016).

Social-Ecological System (SES) approach describes humankind as an embedded element of the biosphere (Berkes and Folke, 2000). Societies rely on Ecosystem Services (ES) and can be sustained only by a sustainable and resilient provision of ES from the biosphere (Biggs et al., 2015).

Agricultural ecosystems are the most relevant interface between humans and the biosphere (Díaz et al., 2015), and represent the most important solution space for pursuing environmental sustainability and food security (DeClerck et al., 2016). At the same time, they are one of the major driving forces shaping the Anthropocene, and a major contributor for breaching the so-called “Planetary Boundaries”, as they are responsible of greenhouse gas emissions, freshwater consumption, loss of biodiversity and alteration of Nitrogen and Phosphorous cycles (Rockström et al., 2009). Agricultural yield has been too often quantified as the sole outcome of these systems. In this view, no importance has been given to ES provision service that, however, are vital for the sustainability and the resilience of agricultural ecosystems themselves. Indeed, most of the increase in yields has been obtained by replacing the supporting function of ES with external inputs, that have driven most of agriculture’s negative externalities (DeClerck et al., 2016; Duru et al., 2015).

Agricultural ecosystems offer a myriad of possibilities for the implementation of new practices and management techniques, by using a landscape approach (DeClerck et al., 2016; Garbach et al., 2017; Gordon et al., 2010). Supporting ES provision in Agricultural Landscapes (AL) will maximise their stability and reduce the need external inputs, enhancing their sustainability and resilience (Power, 2010).

Among these services, AL can support a wide range of provisioning, regulating, supporting and cultural services (Table 1 - Power, 2010; Stavi et al., 2016).

A sound Biosphere Stewardship (Folke et al., 2016) is required to maintain AL in the condition of providing ES in a sustainable and resilient way. In this framework Climate Change, regardless if induced by anthropic activities or not, is representing one of the major forces driving the alteration of the biosphere.

Table 1 – ES of Agricultural Landscapes according to Duru et al. (2015) and Stavi et al. (2016)

Provisioning services	• Food • Animal feed • Fibre • Freshwater
Regulating services	• Flood control • Disease control • Climate regulation
Supporting services	• Soil formation • Water and nutrient cycling • Oxygen production • Provision of Habitat
Cultural services	• Spiritual • Recreational • Aesthetic

In the global climate discourse, adaptation and mitigation are the two the dominant concepts in pursuing AL resilience (Ismangil et al., 2016; O'Neill et al., 2014; Wise et al., 2014). A third way of coping with Climate Change is going largely unattended: the possibility of managing microclimates (Brown, 2011; Chen et al., 1999).

When a landscape is modified, its microclimate is modified. When farmers plant trees around their fields, or when communities dig water conservation trenches, they modified the microclimate of the AL around them.

Microclimate is "the suite of climatic conditions measured in localised areas near the earth's surface" (Chen et al., 1999:288). At spatial scale, the term microclimate is often applied to phenomena occurring with a range up to 100 m, followed by *meso-climatic* effects, up to 100 km (Foken, 2008).

Experiences of microclimatic modifications through landscape planning and natural resources management strategies have been carried out for urban landscapes and built environment (Brown, 2011; Evans and De Schiller, 1996; Lin et al., 2018; Tsitoura et al., 2016), and a wide body of knowledge has been produced on microclimatic interactions at forestry level (Chen et al., 1999; De Frenne et al., 2013; Moore et al., 2005).

Microclimate plays a fundamental role in AL (Foken, 2008; Gliessman, 2015) and the management of microclimatic interactions can represent a proactive way of achieving resilience, especially in arid and degraded regions.

Different studies about microclimatic management in AL, scattered around the world and across disciplines, show the potential of appropriate landscape management techniques. Mulching, for instance, can represent a suitable measure for microclimate control, affecting soil temperature, soil moisture, soil physical and chemical properties, soil microbial activities, aerial physical properties, the mechanical impact of rain and weed growth (Stigter, 1984). Trees in AL can provide a considerable shading effect, with positive feedbacks on temperature, evapotranspiration and soil water availability, but they can have also a negative feedback when, in driest periods, they can compete with cultivations for the few water available in the soil (Kuyah et al., 2016). Evidences are also offered by paleo agronomic studies, concerning the role of water in the soil or in AL. Lhomme and Vacher (2003) demonstrated the effectiveness of climate mitigation effect of ancient pre-Columbian water management structures, the so-called *Waru Waru* (*Suka Kollus* in Bolivia). These were canals around the fields located in flood-prone plains of the Andean region (Lombardo et al., 2011). The study of Lhomme and Vacher demonstrated that the diurnal temperature range in the area comprehended between canals ranged between 11.5 and 18 °C, while in the open *pampa* plains it goes from 10.7 to 20 °C. The presence of standing water provided a thermal regulation effect that attenuates temperature extremes.

1.1.1 Microclimate in Agricultural Landscapes: an operative framework

Microclimatic conditions are defined by soil humidity, soil temperature, air temperature, air moisture, wind direction and speed, solar radiation (Chen et al., 1999; Gliessman, 2015), and their mutual interplay.

Soil moisture is one of the most important microclimate determinants. Water in the soil increase soil heat capacity (Seneviratne et al., 2010), allowing a more balanced soil temperature, and affects vegetation growth. Different patterns of soil moisture can also affect major climatic phenomena, such as heat waves generation (Alexander, 2011; Herold et al., 2016) and local rainfall (Mohamed et al., 2005; Seneviratne et al., 2010).

Soil temperature has a direct effect on plant growth: warm soil temperature positively affects seed germination and micro-organisms development, guaranteeing soil fertilization. Extremely high soil temperatures can stall biological soil activities (FAO, 2016). Low soil temperatures can inhibit basic AL ecologic functions, such as plant water uptake and nitrification (Gliessman, 2015).

Air temperature affects crop behaviour in different growth stages. In general, for all crops, development is hindered over a certain temperature limit. Also photosynthesis can be inhibited over high temperature thresholds. Elevated air temperature can also determine a faster spreading of diseases, by affecting plant resistance.

Air humidity can slow down transpiration from plant because of air saturation. In conjunction with wind, air humidity can represent an additional water supply to vegetation in the form of dew (Tomaszkiewicz et al., 2017) or fog (Correggiari et al., 2017; Klemm et al., 2012). These effects can be triggered by inserting in the landscape structural elements for fog and dew collection (such as trees or artificial meshes) and are most effective in arid areas, where due to microclimate effects (such as oceanic evaporation) large air moisture masses move over arid zones.

Wind has a cooling effect by removing the boundary layer around plants. In addition to it, it can have a regulating role on CO_2 levels and on excess humidity in the surrounding of crop (Gliessman, 2015; Ismangil et al., 2016). However, excessive wind can dry the soil due to the effect on evapotranspiration, while high wind velocities can hinder crops development.

Solar radiation has multiple effects in influencing soil and air temperature and as driver of evapotranspiration from vegetation and evaporation from soil. At the scale of AL, the effect of solar radiation can be managed by shading options (such as vegetation cover or mulching) and by altering the colour of surfaces.

Considering the nature of microclimate elements in AL, modification to microclimate can be induced by the morphology of the landscape, by altering the water retention pattern with water harvesting and soil and water conservation, by the pattern of land use and the vegetation, by soil properties and at by the macro – climatic variables.

An operative framework for the evaluation of microclimatic dynamics, considering what described above, is shown in figure 1.

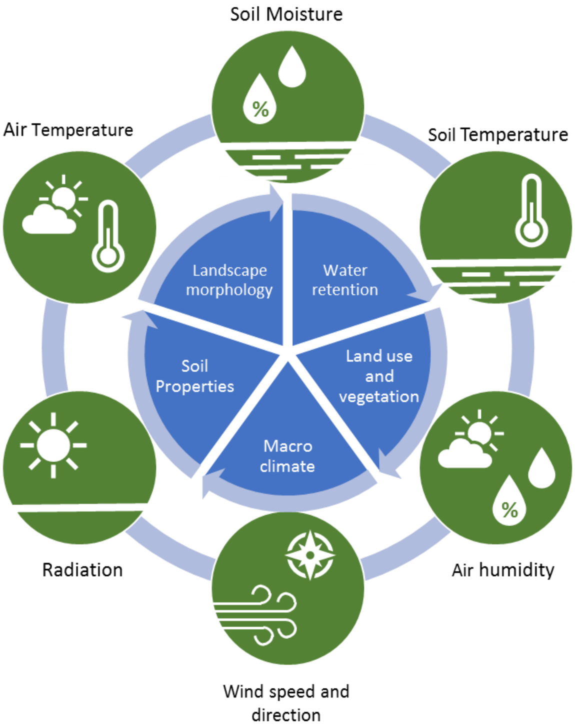

Figure 1 – Operative framework for microclimate management in Agricultural Landscapes, based on Ismangil et al. (2016)

Three clusters of possible interventions can be considered for a proactive management of microclimate in AL (Ismangil et al., 2016):

1. *Water Buffering:* water buffering refers to the whole set of landscape technologies that can contribute to store soil moisture within an AL. Soil moisture is a key determinant of microclimate and, especially in arid areas, may contribute to mitigate climate extremes. Water harvesting namely the collection of rainwater and surface runoff (Rockström et al., 2002), represent the main agricultural technique for enhancing water buffering. Different effects can be obtained, depending on the storage volume in which rainwater is stored, as shown in Table 2.
2. *Re-greening:* Vegetation is a powerful tool to manage microclimate in AL. Trees can shade crops, lowering radiation input, air and soil temperature, and thus reducing evapotranspiration, maintaining soil moisture. In addition to this, trees can act as windbreaks, contributing to crop yields (Gliessman, 2015).
3. *Land Use Planning:* at a larger scale, land use planning represents the main tool for microclimate management (Brown, 2011). Different land use patterns show different microclimatic characteristics, such as green areas in built environments (Zareie et al., 2016). Modifying the structural pattern of the landscape at meso scale can represent a powerful tool of microclimate management (Chen et al., 1999).

Table 2 - Effects of different types of water buffering techniques on microclimate components (Ismangil et al., 2016)

Water buffering	**Techniques in use**	**Soil moisture**	**Soil temperature**	**Air humidity**	**Air temperature**	**Wind direction and speed**
Open storage	Surface ponds and micro-dams	Limited Fringe effects dependent on seepage	Not significant	Significant More rainfall, higher air humidity and more dew	Significant Cooling effect of surface evaporation	Limited Causing local difference in temperature and hence air pressure
Soil moisture	Eyebrows, stone bunds, flood water spreaders, terraces, gully plugging and fog collection	Direct Significant impact on soil moisture	Significant Soil temperature more balanced	Significant More dew and white frost, increased air humidity closer to the ground	Limited Some cooling effect	Not significant
Shallow groundwater	Infiltration trenches, infiltration ponds and wells	Delayed Contribute to soil moisture later in the season	Delayed Moderation effect on soil temperature	Not significant	Not significant	None

1.2 Scientific relevance

While there is consensus in considering microclimate management as a relevant ES in AL, there are still few experiences of direct monitoring, especially in arid areas.

Most of the research is undertaken in the framework of the built environment (Brown, 2011; Evans and De Schiller, 1996; Lin et al., 2018), or in forest areas (Anderson et al., 2007; Chen et al., 1999; De Frenne et al., 2013; Moore et al., 2005).

In addition to this, a more scholarly knowledge is required to collect information, organising experiences and implement new instruments for microclimate research (Brown, 2011).

To organize and frame diverse experiences, a framework involving main microclimatic components and possible drivers of microclimate management has been shown in Figure 1, and suitable clusters of microclimate management tools have been presented in Section 1.1.1.

Different research perspectives are then presented in Table 3 including microclimate measuring, remote sensing analysis, and small-scale and cross-scale modelling. Last, but not least, investigation with participatory techniques can enhance and inform microclimate research.

Table 3 - Examples of different approaches to research on microclimate

Microclimate measuring	J Chen et al. (1999); Lhomme and Vacher (2003); Lin et al. (2018)
Remote sensing analysis	Zareie et al. (2016); Carlson and Traci Arthur (2000)
Small-scale modelling	McCaskill et al. (2016); Shashua-Bar et al. (2010)
Cross-scale modelling	Keys et al. (2017, 2016); Mohamed et al. (2005)
Participatory analysis	Ismangil et al. (2016); Stigter et al. (2005); Tsirogiannis et al. (2015); Valdivia et al. (2010)

Knowledge on microclimate science is wide, but fragmented. In addition to this, even if microclimatic effects at crop level are widely known (Foken, 2008; Gliessman, 2015) few studies have been carried out to demonstrate the action of AL in affecting and modifying microclimate.

In particular, landscape approach has been applied to the study of microclimate in urban areas (cities) and in forests, while no attention has been paid to AL.

1.2.1 Framework of the thesis

The thesis focuses on an advancement of the knowledge on micro- to meso-climatic effects induced in AL by Landscape Restoration and Water Harvesting (LRWH) interventions, investigating if, and how much, they can affect local climate.

When considering the introduced framework, the present work will seek to assess how these land and water management techniques can increase the water retention pattern, and thus their potential of mitigating high temperatures in arid climates, as a consequence of Soil Moisture-Temperature Coupling (SMTC) (Schwingshackl et al., 2017).

Within the framework, LRWH will be considered as a merge of Water Buffering and Re-Greening cluster of intervention, the latter excluding extensive reforestation. This necessity is given by the practical impossibility of finding localities where only Water Buffering interventions have been realised, totally excluding planting of grass and trees in key areas.

The thesis adopts a catchment scale as reference spatial scale for the definition of an AL. This choice is determined by the hydro-climatic topic of the study, and by the common characteristic of LRWH projects to be realised at catchment scale. Considering an ES-based approach, the work examines the relevance of climate regulation ES in AL, and how well-developed LRWH implementation can enhance this latter regulating service.

Remote sensing data have been utilised for testing the research hypothesis of a climate mitigation phenomena triggered by LRWH, and to determine how and which increase in soil moisture can determine a decrease in soil and air temperature. Google Earth Engine (Gorelick et al., 2017), Python, Matlab and Excel have been utilised for data collection and analysis.

1.3 Objectives of the dissertation and research questions

The present PhD dissertation aims to answer the following research questions:

1. To what extent can LRWH enhance soil moisture retention at landscape (catchment) level?
2. To what extent can LRWH modify temperature patterns at landscape (catchment) level?
3. (a) What is the micro-climate effect of modified soil moisture on temperature given by LRWH?

   (b) What is most suitable remote sensing methodology to monitor SMTC at landscape (catchment) level?

2 Literature review

Earth climate is influenced by a large set of surface variables, including geographical position, orography and land cover change. Soil moisture, in particular, can influence near surface air-temperature, formation of precipitation, and the carbon cycle (Schwingshackl et al., 2017, and cited literature).

The effect of soil moisture on heat waves has been largely discussed and documented (Hauser et al., 2016; Hirschi et al., 2010; Miralles et al., 2014), attributing the occurrence of large heat events to soil moisture deficit, evidenced for example by precipitation deficits (Hirschi et al., 2010; Mueller and Seneviratne, 2012).

For instance, Mueller and Seneviratne (2012) showed how hot days tends to be induced by antecedent precipitation deficit in large areas of the world, firstly evidencing that SMTC effects are geographically widespread, larger than how was assumed before their work.

The effect has been also studied for regional cases: one of the most recent work of Hauser et al. (2016) discusses the generation of the 2010 mega heatwave occurred in Russia, driven by both climate change impacts and soil moisture deficit. The authors provided a set of simulation showing that the effect of soil moisture deficit of 2010 alone can be expected to generate an exceptional dry summer, even considering the 1960 climatic conditions.

Soil moisture, in fact, exerts a control on water and energy fluxes, affecting near-surface air temperature SMTC.

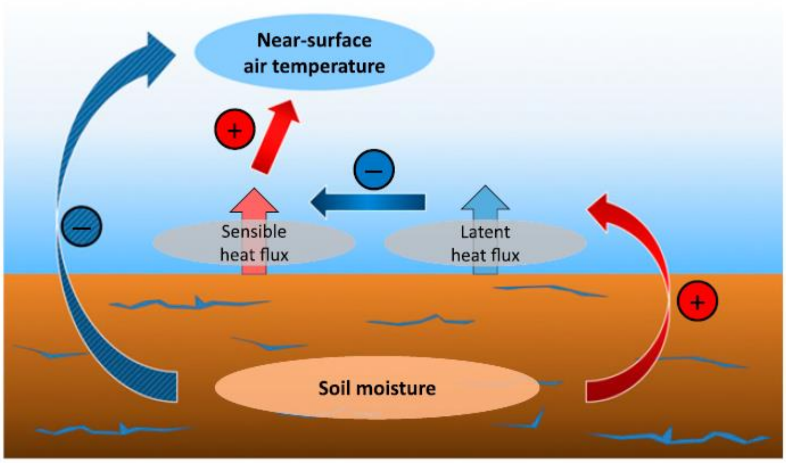

Figure 2 - Overview of SMTC. (+) symbol denotes a positive coupling, (-) symbol denotes a negative coupling [figure taken from Schwingshackl et al (2017)]

SMTC acts as follows (Figure 2): if soil moisture decreases, the soil to atmosphere latent heat flux (LH) decreases, since less water is available for evapotranspiration. According to the energy balance equation of land surface (1, and reorganised in 2), this decrease causes an increase of the fraction of net incoming radiation (R_{net}) that goes in sensible heat flux (SH) and ground heat flux (G), causing an increase of near-air surface temperature, related to the higher transfer of heat in the atmosphere.

$$LH + SH + G = R_{net} \tag{1}$$

$$\frac{LH}{R_{net}} + \frac{SH}{R_{net}} = 1 - \frac{G}{R_{net}} \tag{2}$$

A negative coupling is thus evident between soil moisture and temperature, since increases of soil moisture can lead to decreases of temperature, while decreases in soil moisture can lead to increases in temperature (Schwingshackl et al., 2017; Seneviratne et al., 2010).

The nature of SMTC is also dependant by soil moisture regime, with reference to evapotranspiration, namely soil moisture and evapotranspiration regime. The classical hydrological framework, introduced by Budyko (Budyko, 1974, 1956), and utilised in recent works (e.g. Schwingshackl et al., 2017; Seneviratne et al., 2010) describes the soil moisture regime as a fraction of Evaporative Fraction (EF), namely the fraction of R_{net} that contributes for LH, expressed as:

$$EF = \frac{LH}{R_{net}} \tag{3}$$

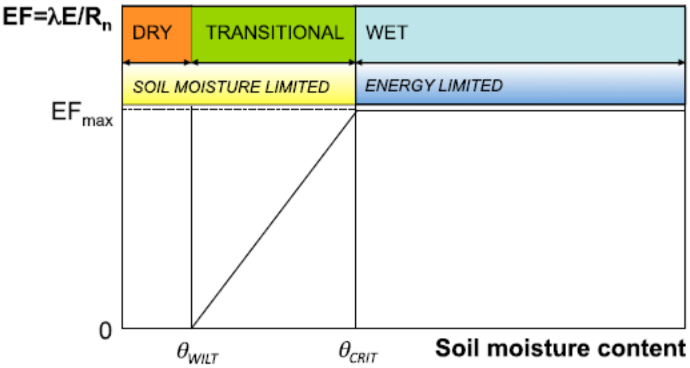

Figure 3 – Framework for the dependence of EF by soil moisture content and definition of different soil moisture and evapotranspiration regime [figure taken from Seneviratne et al.,(2010)]

The framework (Figure 3) defines three main soil moisture and evapotranspiration regimes, as a function of soil moisture content (θ), defined as volumetric soil moisture:

$$\theta = \frac{volume\ of\ water\ in\ V}{V} \tag{4}$$

Where the unit of θ is $[m^3_{water}/m^3_{soil}]$, and the definition is given for a soil volume V.

- The *Dry* regime is characterized by $\theta < \theta_{\text{wilt}}$, namely lower than the soil moisture at the wilting point, where low or no evapotranspiration occurs. The regime is typical of deserts and hyper arid locations.
- The *Transitional* regime, identified by the interval $\theta_{\text{wilt}} < \theta < \theta_{\text{crit}}$, where θ_{crit} is the critical soil moisture value over which evapotranspiration is no longer limited by θ (Seneviratne et al., 2010 and cited literature). θ_{crit} can vary between the 50% and the 80% of θ at field capacity (Shuttleworth, 1993), and it is dependent on location (Schwingshackl et al., 2017). Regions that exhibit a transitional regime are characterised by a strong SMTC, including Sahelian areas and Mediterranean climates.
- The *Wet* regime, for $\theta > \theta_{\text{crit}}$, where soil moisture does not represent a limiting factor for evapotranspiration, while this latter is mostly controlled by the available energy. This regime is mostly evident in tropical areas and high latitudes.

The framework can be expressed according to the following function (Schwingshackl et al., 2017):

$$EF(\theta) = \begin{cases} 0, & if\ \theta < \theta_{\text{wilt}} \\ EF_{max} \cdot \dfrac{\theta - \theta_{\text{wilt}}}{\theta_{\text{crit}} - \theta_{\text{wilt}}}, & if\ \theta_{\text{wilt}} < \theta < \theta_{\text{crit}} \\ EF_{max}, & if\ \theta > \theta_{\text{crit}} \end{cases} \tag{5}$$

Strong SMTC is thus expected in areas characterised by a transitional regime.

The paper of Schwingshackl et al. (2017) represents a first quantification of the phenomenon of SMTC, both in terms of variations of strength of the coupling and spatiotemporal distribution of soil moisture and evapotranspiration regimes, at a global scale.

The work combines the analyses of temperature, soil moisture and EF values. Since EF and soil moisture data at global level are available only for a limited time, the analysis includes the use of reanalysis- and model- based values, to obtain data for a time series going from 1980 to 2009. Authors, thus, considered values obtained from ERA-Interim/Land (Balsamo et al., 2015), MERRA-2 (Gelaro et al., 2017) and a combined reanalysis dataset.

The study of the EF-θ relationship has been based on how analysed data fitted the framework for soil moisture and evapotranspiration regime, and results evidenced that a fraction ranging from the 30% and 60% of global land surface is in the transitional regime for at least half of the year. In these regions, changes in soil moisture can have an impact on near-surface air temperature (T). Global distribution of the occurrence of transitional regime is shown in Figure 4 (the figure refers to the previously mentioned combined dataset, details on the spatial and temporal distribution for ERA-Interim/Land and MERRA-2 are available in Schwingshackl et al. (2017) supplementary material – figures S1 and S2).

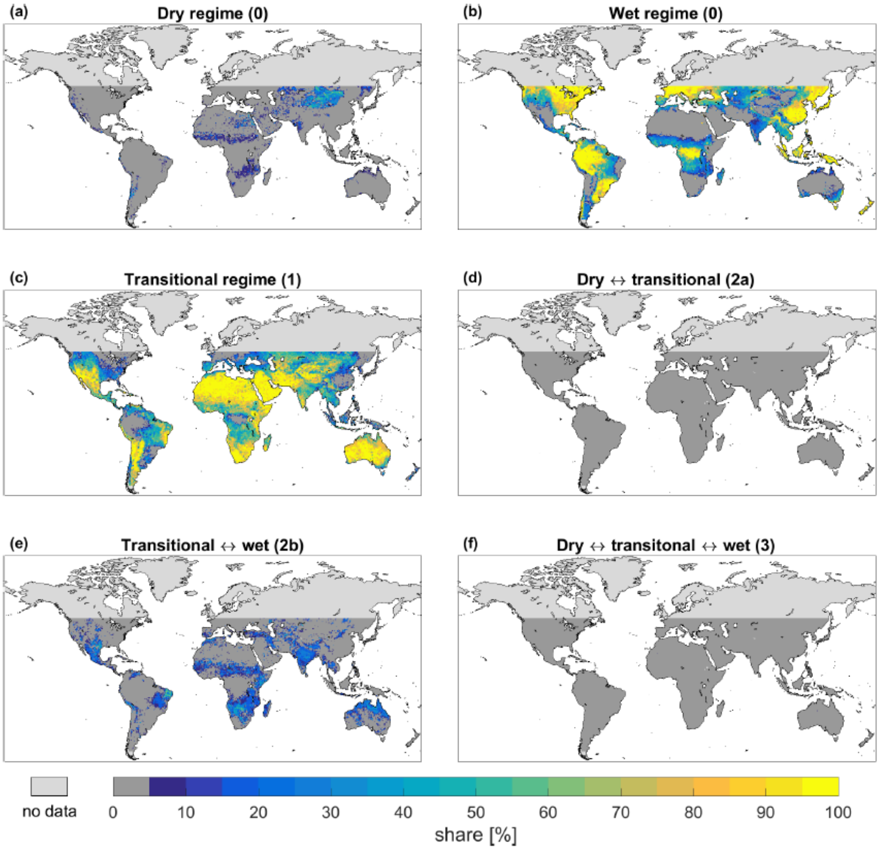

Figure 4 - Share of single soil moisture and evapotranspiration regimes for the Combined dataset used by Schwingshackl et al. (2017). Share of (a) dry regime, (b) wet regime, (c) transitional regime, (d) passage between dry and transitional regime, (e) passage between transitional and wet regime and (f) passage between all three regimes. Taken from Schwingshackl et al. (2017) – supplementary materials, figure S1.

The framework adopted in the work for the analysis of SMTC is based on the following equation:

$$\frac{\partial T}{\partial \theta} = \frac{\partial T}{\partial EF}\frac{\partial EF}{\partial \theta} \tag{6}$$

Where the slope ∂EF/∂θ is obtained from a best fitting of the values calculated from the data, while ∂T/∂EF slopes have been calculated using temperature anomalies (Schwingshackl et al., 2017). The work concludes that impacts on T ranging from 1.1 to 1.3 K can be induced by typical soil moisture variations, while a change in soil moisture over the full range of transitional regime can impact T up to 6-7 K. Results in terms of ∂T/∂θ are variable, but they show consistent negative values in the area characterised by transitional regime, as in Figure 5.

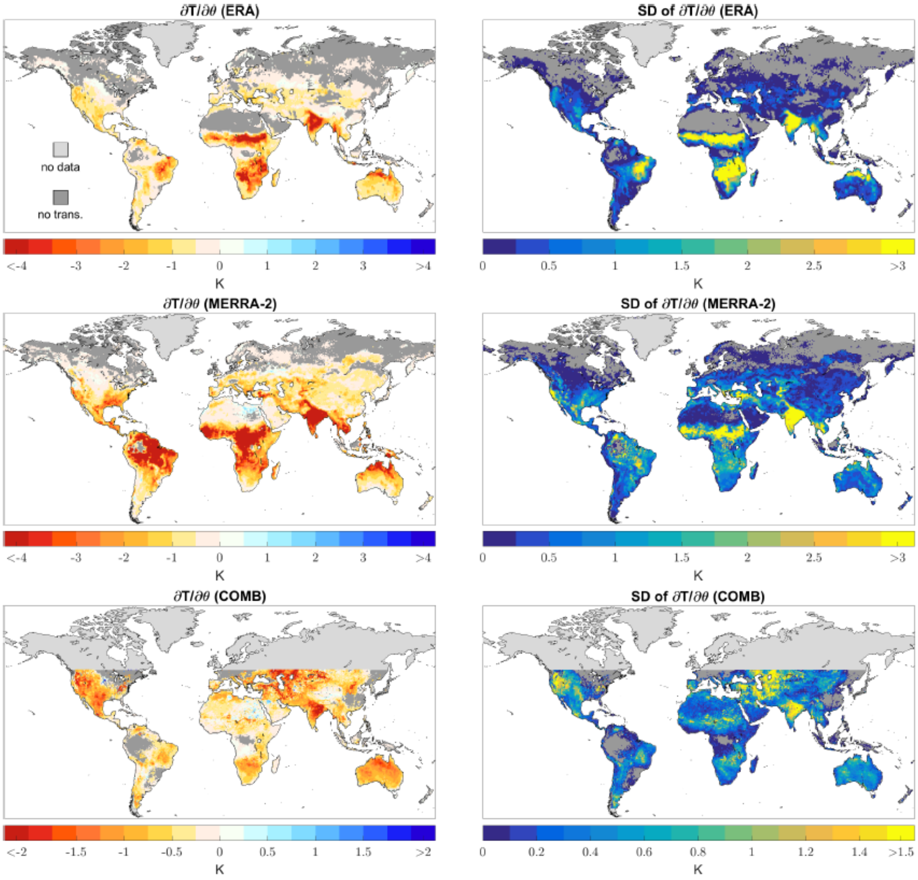

Figure 5 – Annual means and standard deviations for ∂T/∂θ, Taken from Schwingshackl et al. (2017) – supplementary materials, figure S7.

Hirschi et al. (2014) evaluated SMTC by considering the ratio between the Number of Hot Days (NHD) and the antecedent soil moisture status, for each given location. In their global-scale analysis, the first one was evaluated as the NHD for the hottest month for each location, while the second one was evaluated in the three months before the hottest one, with two alternative techniques: as an anomaly of soil moisture content, evaluated with remote sensing analysis of soil moisture, and as 3-months Standardised Precipitation Index (SPI). Their results evidenced stronger SMTC for the NHD-SPI analysis rather than the NHD-remote sensed one. According to the authors, this effect is linked with a decoupling effect between surface soil moisture and root-zone soil moisture: while, during dry periods, surface soil is completely dry, root zone can still store residual moisture been effective as a source of LH. In this way, pronounced dry anomalies (the ones that dry up to the root-zone) results underestimated, leading to an apparently weaker coupling (Figure 6). Given this, author suggests including techniques capable of evaluating also root-zone soil moisture dynamics for a proper evaluation of SMTC.

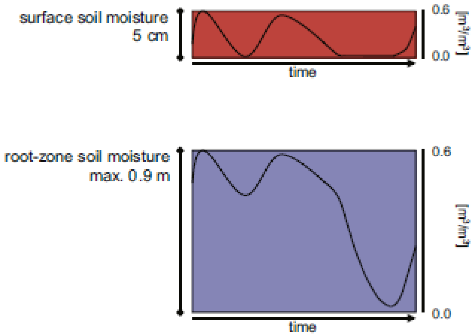

Figure 6 – Schematic representation of surface and root-zone moisture decoupling. Taken from Hirschi et al. (2014)

2.1 Landscape Restoration and Water Harvesting (LRWH)

In arid and semi-arid regions, increasing soil water availability and retaining soil quality is vital to increase food production and meeting global needs (Rockstrom and Falkenmark, 2015; Wolka et al., 2018).

As discussed by different scholars, practitioners, regional and international institutions, water harvesting, namely the process of concentrating precipitation through runoff and storing it for beneficial use (Critchley et al., 1991), represent a key to cope with water scarcity for both sustaining agricultural production (Motsi et al., 2004; Rockström et al., 2002; Wolka et al., 2018) and restore degraded landscapes (García-ávalos et al., 2018; Hishe et al., 2017; Li et al., 2014; Oweis, 2016).

Ouessar et al. (2012) define water harvesting as: "*The collective term for a wide variety of low-cost interventions which are primarily or secondarily intended to collect natural water resources which otherwise would have escaped from human reach, and buffer them through storage and/or recharge on or below the soil surface. The effect is increased retention of water in the landscape, enabling management and use of water for multiple purposes. Water harvesting technologies can operate either as independent units, or require embedding in a larger system of environmental management interventions, or require specific natural conditions*".

A schematic representation of a water harvesting system can be based on four elements: a catchment, or collection, area; a runoff conveyance system; a storage component and an application area. The components can be adjacent to each other, or they can be connected by a conveyance system. Storage and application areas may also be overlapped, typically where water is concentrated in the soil for direct use by plants. Rain is harvested in the form of runoff in the catchment area. The catchment may range from few square meters to several square kilometres, varying from a rooftop, a paved road, to compacted surfaces, rocky areas or open rangelands, cultivated or uncultivated land and natural slopes. The conveyance system transports the collected runoff to the area of application. It can consist of gutters, pipes (in case of rooftop water harvesting) or overland, rill, gully or channel flow. The flow can either be diverted on cultivated fields or into storage structures. According to Oweis (2016) water harvesting techniques include only those ones that involve the transformation of rainfall in runoff, or the direct harvesting of runoff. Structures such as terraces are then not considered as water harvesting, since allow soil moisture storage after rainfall infiltration, but not runoff. Similarly, structures like Qanats, that harvest groundwater cannot be considered as water harvesting structures.

The storage component is used to store harvested runoff until it is used by people, animals or plants. Water can be stored in the soil as soil moisture, above ground level (jars, ponds or reservoirs), underground (cisterns), or as groundwater (Oweis et al., 2012). The application area, or target, is where the harvested water is used, either for domestic consumption (drinking and other household uses), for livestock consumption, or agricultural use (including supplementary irrigation) (Mekdaschi Studer and Liniger, 2013). If runoff is directly diverted to fields, the application area is the same of the storage area, as plants can directly uptake the accumulated water in the soil.

Starting from this framework, water harvesting structures can be classified as a function of the catchment type and size, and of the method of water storage. The classification of water harvesting based on catchment type (Table 4) considers four groups: floodwater harvesting, macro catchment water harvesting, micro catchment water harvesting, and rooftop water harvesting (Mekdaschi Studer and Liniger, 2013)

Table 4 - Overview of water harvesting systems, modified from Mekdaschi Studer and Liniger (2013)

	Floodwater harvesting	Macro catchment water harvesting	Micro catchment water harvesting	Rooftop water harvesting
Catchment : application area ratio	100:1 to 10,000:1	10:1 to 100:1	1:1 to 10:1	-
Catchment area	2 to 50 km^2	0.1 to 200 ha	10 to 1000 m^2	-
Catchment type	Ephemeral river catchment	Hillsides, pasture land, forests or roads and settlements	Generally bare, with sealed, crusted and compacted soils	Rooftop
Source type	Temporary channel flow	Overland flow or rill flow	Sheet and rill flow	Sheet flow

A large body of literature shows how water harvesting technique can improve soil moisture, with direct measurements (Oweis, 2017; Previati et al., 2010; Rango and Havstad, 2009; Suleman et al., 1995; Tubeileh et al., 2016).

Different water harvesting techniques can increase soil moisture at different levels. Singh (2009), for instance, demonstrated how box trenches and V-ditches can increase surface soil water, while contour trenches can facilitate deep soil water storage. Similarly, Al-Seekh and Mohammad (2009) showed how the implementation of water harvesting structures, as Jessour, and stone terraces can produce a shift in water partitioning, allowing a reduction of surface runoff (and soil erosion) and an increase of soil moisture, measured at 30 cm below terrain surface. If purposely implemented, water harvesting structures can also be used to increase the inflow towards aquifer, as shown for the Ethiopian aquifer of Mendae Plain by Walraevens et al. (2015), where infiltration occurring in water harvesting ponds and trenches is responsible for 30-50 % of the aquifer recharge, with peaks in driest years.

If we consider LRWH approaches, namely approaches integrating water harvesting and a different mix of measures for ecological land restoration, such as reforestation and/or terracing, effects on soil moisture are also evident. Tianjiao et al.(2018) showed how a LRWH approach integrating water harvesting techniques (level ditches, fish-scale pits) with terraces and tree planting can increase soil moisture. Their study, realised in the arid Loess Plateau (China) shows how water harvesting and terraces are more effective in increasing the soil moisture for the first 80 cm of soil, while tree plantation affects soil moisture in soil layer located between 80 and

180 cm under from the surface. Terraces, as a soil conservation measures, are also widely recognised as a mean for increasing soil moisture in arid areas (Wei et al., 2016, and cited literature).

In Tigray region, northern Ethiopia, soil moisture is the main limiting factor to agricultural development (Gebreegziabher et al., 2009). The region is characterized by arid to semi-arid climate, while large-scale deforestation and agriculture have been practiced for 2500 years (Nyssen et al., 2000). Given this, Tigray has been targeted with a large scale effort in developing LRWH measures since 1970s (Gebremeskel et al., 2017; Nyssen et al., 2014; Woldearegay et al., 2018), including ponds, trenches, check dams (Grum et al., 2017), contour measures (Gebreegziabher et al., 2009), reforestation (Gebremeskel et al., 2017) and terraces (Amsalu and de Graaff, 2007; Nyssen et al., 2007) (from Figure 7 to Figure 9).

Historically, indigenous land and water management practices in the region have been dated since 400 BCE (Ciampalini et al., 2012). Driven by early World Food Program aids, massive implementation started in 1970s. After that, the Tigray People’s Liberation Front started to implement those techniques in liberated areas, and also the new government, active since 1991, continued the adoption of land restoration measures (Gebremeskel et al., 2017).

Figure 7 - Bench terraces system in Endemehoni Wereda, Tigray, photo of the author

Figure 8 - Percolation pond in Ofla Wereda, Tigray, photo of the author

Figure 9 - trenches, Ofla Wereda, Tigray, photo of the author

The recent study of Nyssen et al. (2014) considered an integrated comparison of historical images for analysing the latest 145 years of landscape evolution in Tigray region. Results highlights how the minimum woody vegetation cover of the region was reached in 1930s., and historical series show how the implementation of LRWH, also defined as Soil and Water Conservation (SWC), has reversed this trend (Figure 10).

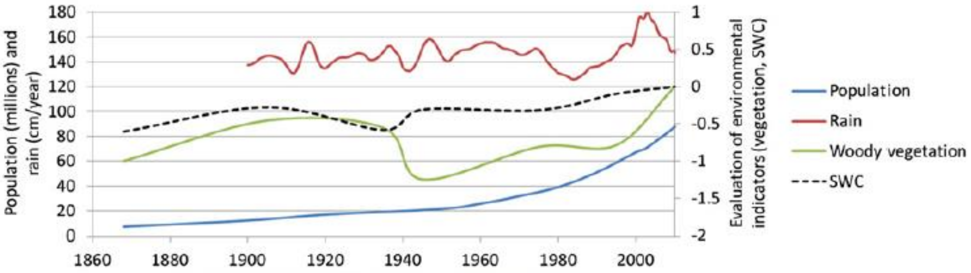

Figure 10 – Trends of rainfall, environmental and anthropic parameters for the latest 145 years in Tigray region. Taken from Nyssen et al. (2014) *– Graphical abstract.*

Despite some pitfalls of the approach, linked with the mismanagement of fertilisers, low survival of planted trees and low income obtained from exclosures, the SWC implementation in Tigray represents a successful case, achieving environmental, agricultural and economic improvements (Gebremeskel et al., 2017). In achieving these results, an important step has been represented by the shift to a catchment approach (Gebremeskel et al., 2017), introduced in Gira Kahsu, southern Tigray, since the mid-1980s (Asfaha et al., 2016). The comprehensive study of Asfaha et al. (2016), showed how the catchment level LRWH approach led to a stabilisation in 30 watersheds of northern Ethiopia, reversing the degradation trends and contributing to local resilience.

In the framework of the analysis of positive effects of LRWH at catchment level, the present PhD dissertation aims at analysing and discussing the possibility of an additional hydro-climatic effect, induced by local SMTC dynamics, given by the increased soil moisture availability at catchment scale. Considering the spatialization of coupling effects as presented by (Schwingshackl et al., 2017), northern Ethiopia fully lies in the area characterised by a transitional soil moisture and evapotranspiration regime, and changes in SMTC could be expected. Results can be meaningful for the discussion of ES provided by LRWH and may encourage its adoption in other arid and semi-arid areas of the world.

The analysis has been carried out for Enabered catchment, in Adwa Wereda (Haregeweyn et al., 2012), where LRWH techniques have been recently implemented, allowing a full detection of their impacts, comparing the situation before, during and after their implementation.

3 Materials and Methods

3.1 Study Area

The study area of Enabered catchment is located in Adwa woreda. The catchment is between 38°53’ to 38°57’E and 14°08’ to 14°11’N, elevations range from 1,850 to 2,540 m above sea level (Figure 11).

The wereda of Adwa has a tropical summer-rain climate influenced by the Inter Tropical Convergence Zone, and it is characterised by high spatial and temporal rainfall variability. The average annual precipitation and daily temperature for the period between 1998 and 2008 were 742 mm and 19.8 °C, respectively. Around the 85 % of the annual rain falls in the rainy season, ranging from June to September, with a monthly precipitation concentration index (Oliver, 1980) equal to 26.5, that indicates an high rainfall variability between months.

According to local elderly residents, around 30–40 years ago the catchment was covered by different vegetation types. After that, however, the area has been deforested, given the demand for cultivated land, construction material and firewood, triggered by the increase of population (Haregeweyn et al., 2012).

To revert the degradation trends in the area, LRWH interventions have been implemented between 2004 and 2008, including soil bunds, trenches, terraces, check dams, reforestation and regreening. For the particular case of Enabered catchment, Haregeweyn et al. (2012) reported the full list of the techniques implemented in the area, retrieved thanks to their cooperation with the Bureau of Agriculture and Rural Development. The full list is showed in Table 5. The study showed also that, as a consequence of the LRWH implementation, runoff decrease by 27% and soil loss by 89 %, while a large number of gully areas were reclaimed and used for agricultural purposes.

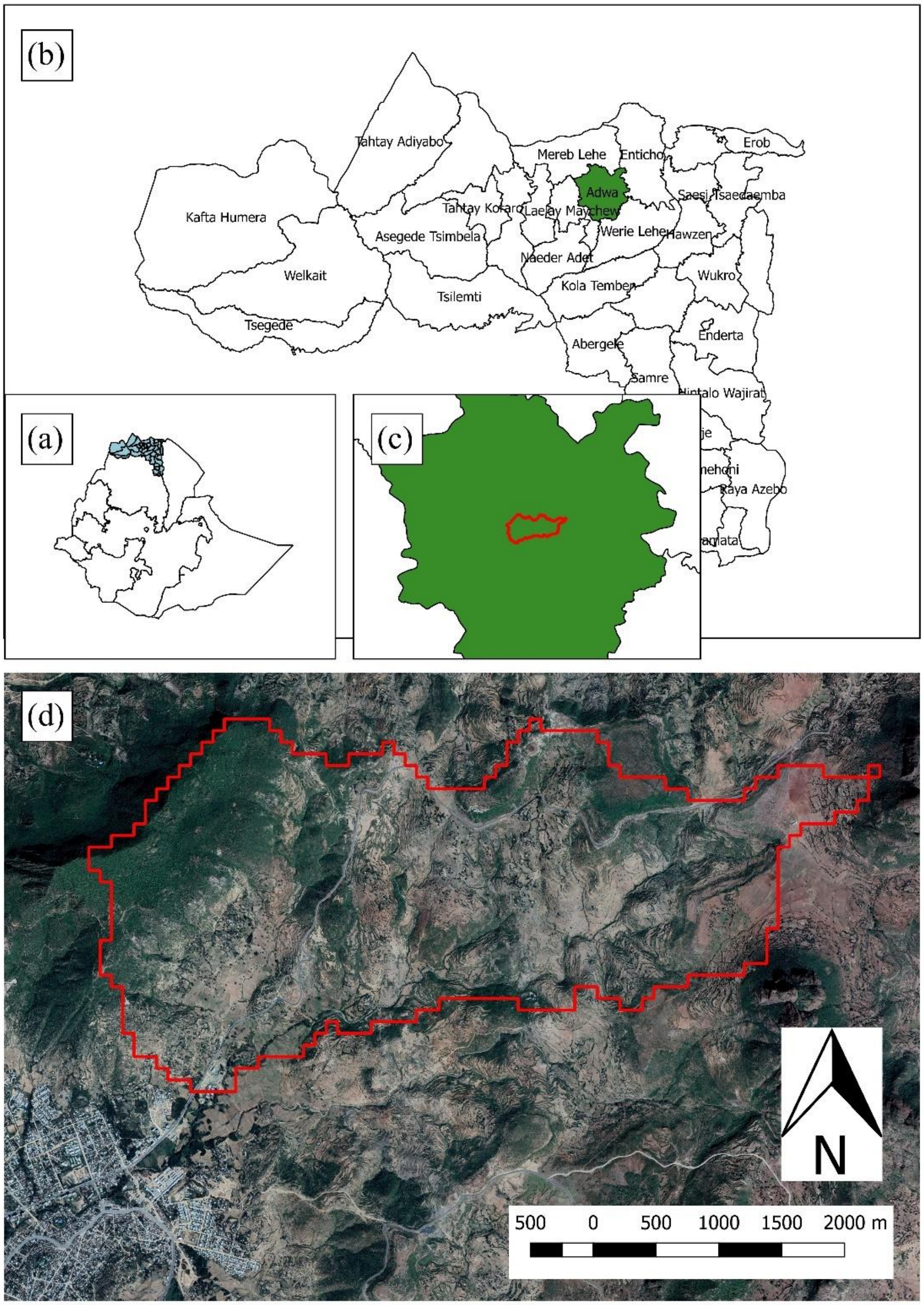

Figure 11 - Enabered watershed location: (a) Tigray region in Ethiopia; (b) Location of Adwa Wereda in Tigray region; (c) Location of Enabered watershed in Adwa wereda; (d) Enabered wtareshed

Table 5 – List of LRWH techniques implemented in Enabered watershed from 2004 to 2008. Taken from Bureau of Agriculture and Rural Development (2008) as cited in Haregeweyn et al. (2012)

Type of LRWH	**unit**	**Extent of LRWH**			**Total**
		Hillside	**Gully**	**Cultivated and grazing land**	
Physical measures	ha	1,108	8	1,036	2,152
Stone-faced bunds with trench	km	135			135
Stone and soil bunds	km	472		205	677
Deep trenches	km	1,592			1,592
Trenches	km			555	555
Loose-stone check dams	m^3	38,999	23,150		62,149
Gabion check dams	m^3		20,231		20,231
Retention walls	km		0.5		0.5
Sediment storage dams	m^3		498		498
Microbasins	no.	50,629			50,629
Gully reshaping	m^3		90,788		90,788
Pond construction	no.			10	10
Bund stabilization	km			516	516
Biological measures	ha	1,201	28	635	1,931
Exclosures	ha	601			601
Grass/split planting	ha		8		8
Grass sowing	ha	545	5	308	850
Enrichment plantations	ha	55	8		63
Fruit trees	ha		2	7	9
Forage trees	ha		8	320	400

3.2 Research Framework

The framework adopted in this study is based on the approach developed by Schwingshackl et al. (2017) described by equation (6). More in detail, the analysis aims to evaluate the value of SMTC comparing the inter-annual variations of the average soil moisture and near-surface temperature in the target catchment.

The approach is conceived to test the hypothesis of an increased level of soil moisture, and a coupled decrease of near surface air temperature, after the implementation of LRWH interventions. The first analysis is functional to answer to research question 1, while the second one will be functional to answer to research question 2.

By analysing the variation of T as a function of θ, the thesis will aim also to test the occurrence of SMTC phenomena in the watershed, by analysing the value of ∂T/∂θ, answering question 3a.

3.2.1 Evaluation of soil moisture conservation at catchment scale

To evaluate the degree to which Enabered catchment is capable to retain soil moisture after the rainy season, a normalised Water Conservation Index (WCI) has been defined, starting from the definition of the Normalised Difference Infrared Index (NDII) defined by (Hardisky et al., 1983).

The NDII is calculated as:

$$NDII = \frac{\rho_{0.85} - \rho_{1.65}}{\rho_{0.85} + \rho_{1.65}} \tag{7}$$

Where:

- $\rho_{0.85}$ is the reflectance at a wavelength of 0.85 μm
- $\rho_{1.65}$ is the reflectance at a wavelength of 1.65 μm

NDII is a simple parameter that can be derived from freely available satellite data (e.g. MODIS or Landsat). It was found to have a good accordance with the root-zone soil moisture at a catchment scale. In particular, an average R^2 equals to 0.87 was found for values of NDII and root-zone soil moisture during the dry season (Sriwongsitanon et al., 2016), by using 8-days NDII composites scenes obtained from MODIS sensor.

Considering that the analysis should be carried out to evaluate soil moisture conservation in the dry season, and that, according to Hirschi et al. (2014), SMTC dynamics are more evident when considering root-zone soil moisture, the parameter appears adequate as a proxy of θ for the present study.

NDII data were obtained from the ‘Landsat 7 Collection 1 Tier 1 8-Day NDWI Composite’ available on Google Earth Engine (Gorelick et al., 2017). Despite the data source name, Landsat 7 NDWI data is calculated as:

$$NDII = \frac{\rho_{B4} - \rho_{B5}}{\rho_{B4} + \rho_{B5}} \tag{8}$$

Where

- ρ_{B4} is the reflectance in Landsat 7 ETM+ sensor Band 4
- ρ_{B5} is the reflectance in Landsat 7 ETM+ sensor Band 5

Considering the wavelength range of ETM+ sensor (Table 6) it can be observed how the released data corresponds to NDII.

*Table 6 – Landsat 7 ETM+ sensor wavelength and resolution. * ETM+ Band 6 is acquired at 60-meter resolution, but products are resampled to 30-meter pixels.*

Bands	**Wavelength (µm)**	**Resolution (m)**
Band 1 - Blue	0.45-0.52	30
Band 2 - Green	0.52-0.60	30
Band 3 - Red	0.63-0.69	30
Band 4 - Near Infrared (NIR)	0.77-0.90	30
Band 5 - Shortwave Infrared (SWIR) 1	1.55-1.75	30
Band 6 - Thermal	10.40-12.50	60 * (30)
Band 7 - Shortwave Infrared (SWIR) 2	2.09-2.35	30
Band 8 - Panchromatic	0.52-0.90	15

Landsat Tier-1 scenes, used for the analysis, are the ones characterised by the highest quality. The processing level of Tier 1 includes the Level-1 Precision Terrain (L1TP), including the LEDAPS algorithm (Masek et al., 2013). Tier 1 data is distributed with a georegistration precision characterised by a <=12 m RMSE at ground level.

The calculation of NDII time series has been carried out in Google Earth Engine platform. For each Landsat 8-days composite, the catchment value has been calculated as an average of the values of the pixels overlapping the catchment area, weighted by the percent of a pixel area that is effectively fully within the catchment edges.

For each year, WCI has been then defined as a fraction of the average monthly NDII after the rainy season, considering separately September, October and November, and the rainfall of the rainy season, running from June to August.

$$WCI_i(y) = 1000\frac{NDII_i(y)}{R_{rs}(y)} \tag{9}$$

Where:

- $WCI_i(y)$ is the WCI for the i-th month of the year y (considering the months after the rainy season, we obtain i =9,10,11);
- 1000 is a scale factor, inserted to obtain values close to the unit;
- R_{rs} (y) is the rainfall occurring in the rainy season in the catchment in the year y, calculated as a sum of monthly values taken by CHIRPS dataset (Funk et al., 2015);
- $NDII_i$ (y) is the Normalised Difference Infrared Index for the i-th month of the year y, calculated as an average of the value of NDII from Landsat 7 scenes available in the given month.

The index has been calculated diving NDII values by the rainy season rainfall amount to evaluate an information independent from the inter-annual rainfall variability. The choice of CHIRPS dataset is based on the work of Gebremicael et al.(2018), that indicates CHIRPS as a suitable database for hydrological modelling in the Tekeze-Atbara river basin. The dataset was extracted by the Google Earth Engine platform.

With the presented methodology, we obtained three time series of WCI, respectively for the months of September (WCI_9), October (WCI_{10}) and November (WCI_{11}), ranging from 2000 to 2017.

3.2.2 Evaluation of temperature

The evaluation of the evolution of near-surface air temperature for Enabered watershed was carried out by considering the average of Land Surface Temperature (LST) in the catchment as a proxy, given the lack of available data for a sufficiently long time series.

MODIS MYD11A2.006 Aqua Land Surface Temperature and Emissivity 8-Day Global at 1 km were used for the analysis (NASA LP DAAC, 2018).

Average LSTs, for different months after the rainy season, were calculated as $LST_i(y)$ being the average LST for the i-th month of the year y. Considering the months after the rainy season, we obtain i =9,10,11,12);

To establish a temperature parameter independent by the macroclimatic forcing from the atmosphere outside the planetary boundary layer, $LST_i(y)$ was normalised by a homologous average value, calculated as average of the temperature at 850 hPa at 12:00 a.m. (T_{850}). This latter parameter was obtained from ERA-INTERIM climatic reanalysis dataset (Balsamo et al., 2015). The average value of T_{850} was calculated as $T_{850,i}(y)$, being is the average T_{850} for the i-th month of the year y. Considering the months after the rainy season, we obtain i =9,10,11,12).

Considering those two parameters, time series of a normalised temperature index (t) were obtained by normalising LST (in °C) by T_{850} (in °C) with the following formula:

$$t_i(y) = {LST_i(y)} \big/ {T_{850,i}(y)} \tag{12}$$

For the temperature analysis, MODIS MYD11A2.006 were obtained from Google Earth Engine dataset, while ERA-INTERIM data were downloaded through an ECMWF Web-API python script and elaborated with Matlab.

Time series for September (t_9), October (t_{10}), November (t_{11}), and September-December (t_{12}) averages were calculated from 2002 to 2017, forced by MODIS data availability. In the framework of t analysis, the month of December was considered in order to detect possible lag effects of SMTC.

4 Results

4.1 Water Conservation Index (WCI)

WCI analysis has been carried by comparing the temporal evolution of WCI_9, WCI_{10} and WCI_{11} time series with the implementation record of LRWH measures in the catchment. The evolution of NDII and rainfall data is shown in Figure 12. The results of the analysis of WCI are shown in Figure 13.

The approach followed by the dissertation defined water conservation as a fraction of NDII, as a proxy of soil moisture content in the root zone, and rainfall available during the rainy season, considered as the total amount of rainwater that can potentially be harvested in the catchment with LRWH interventions

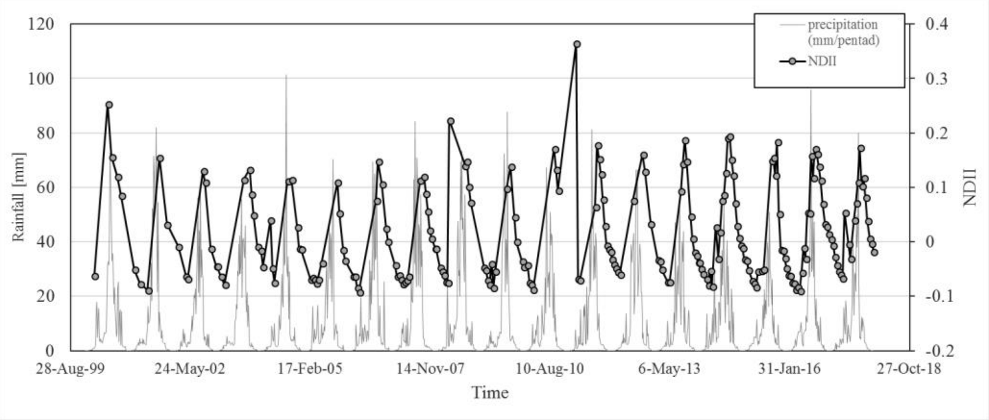

Figure 12 – Time series of average NDII and CHIRPS values for Enabered catchment. NDII series are dated for the day of 8-days Landsat 7 composite scenes interval, CHIRPS data are based on the pentadecadal interval of the data.

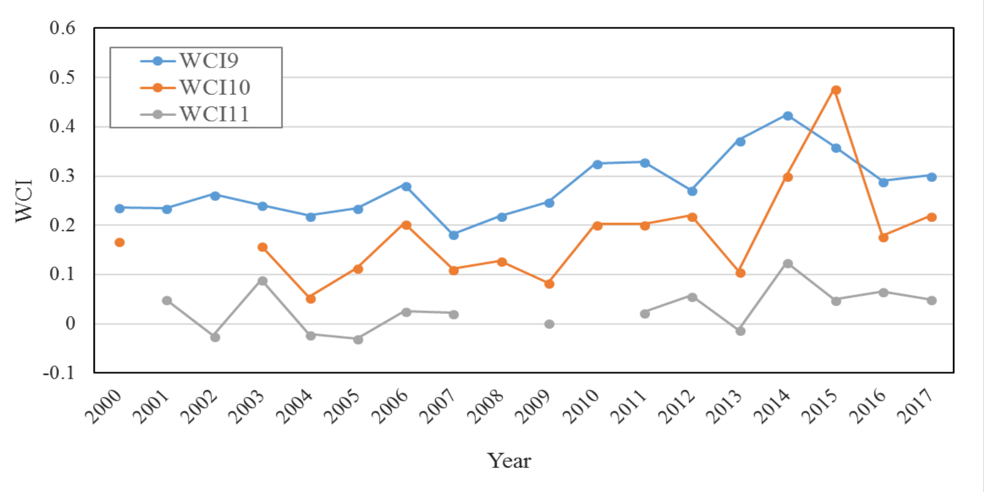

Figure 13 – Time series of WCI for the months of September (WCI_9), October (WCI_{10}) and November (WCI_{11})

All WCI time series show an increase in time. Considering the chronology of LRWH implementation in the watershed, time series of WCI have been analysed considering 2000-2008 as period ‘before full implementation’ and 2009 – 2017 as period ‘after full implementation’.

For each month considered for the analysis, WCI after the implementation is higher. Differences between the two periods have been statistically evaluated with the Student’s t-test on means difference. For WCI_9, an increase of 38 % is evidenced, with strong statistical significance ($P < 0.01$). For WCI_{10} and WCI_{11} the statistical significance is lower, with P-values of 0.083 and 0.218 respectively, correspondent to a probability of 91 % and 78 % that the observed differences are not casual. The increase of WCI_{10} is equal to 65 %, while the increase of WCI_{11} shows a value of 181 %. This latter one is, however, driven by the low values of NDII for November (Table 7 and Figure 14).

Table 7 – Values of WCI averages and standard deviations for the periods 2000-2008 (before full LRWH implementation) and 2009 – 2017 (after full LRWH implementation), with statistical Student’s t test on means difference results.

	September	October	November
WCI Average 2000-2008	0.235 (0.028)	0.134 (0.049)	0.016 (0.044)
WCI Average 2009-2017	0.325 (0.038)	0.221 (0.095)	0.045 (0.034)
WCI Difference before and after full implementation	0.090	0.087	0.029
WCI Difference before and after full implementation (%)	38%	65%	181%
P- value, test on differences	0.00047	0.08330	0.21833
Statistical signifiance	> 99%	91%	78%

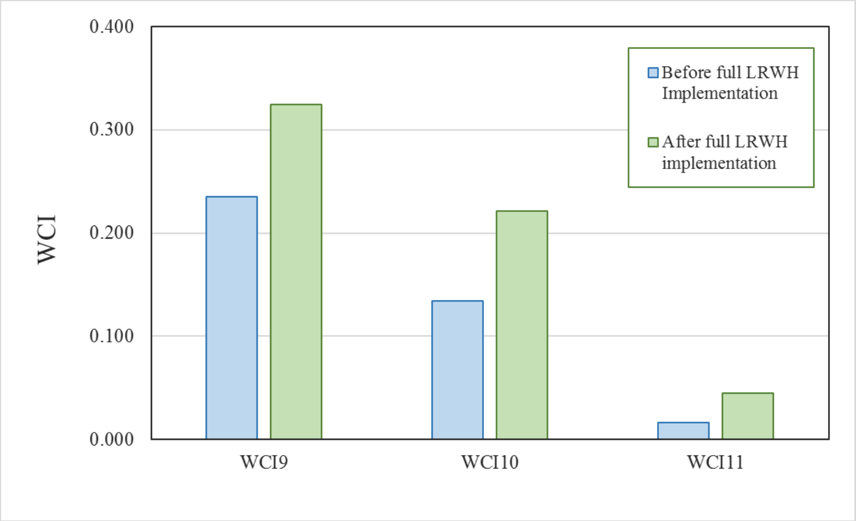

Figure 14 - Values of WCI averages for the periods 2000-2008 (before full LRWH implementation) and 2009 – 2017 (after full LRWH implementation)

It can be concluded that LRWH produced an increase of water conservation at catchment scale, for Enabered catchment. Results show that the effect of LRWH can be considered significant for September ($P<0.01$) and October ($P<0.1$), the latter with higher positive variations. It should be noticed how these two months are the ones when rain-fed agriculture suffers most of moisture deficiency in Tigray region (Gebreegziabher et al., 2009). Differences of WCI in November are also evident, but with low absolute value and low statistical significance ($P>0.2$).
Scripts for data download are reported in Annex A.

4.2 Normalised temperature index (t)

The analysis of LST and t shows always lower values for the period 2009-2017, considered representative for the situation after LRWH full implementation (Figure 15, Figure 18 and Table 8). Coherently with the study area seasonality, average LST increases from September to December. However, year 2009 showed extreme high temperatures, especially during September.
This behaviour can be related to the extreme dry year occurred in 2009 as reported by Winkler et al., 2017. The work explains also the other peak of LST occurring in October 2011. Moreover, a visual comparison of rainfall, T_{850}, and the Surface Solar Radiation Downwards in September was conducted to evidence possible extremely hot years. The analysis showed that September 2009 was among the driest months, being characterised by the second highest temperature and by the highest downwards radiation energy (Figure 16 and Figure 17). The surface solar radiation downwards data were obtained by the ERA-INTERIM reanalysis dataset.

Given the extreme climatic conditions for 2009, we considered two different intervals for the period after LRWH full implementation: (1) 2009 – 2017; (2) 2010 – 2017, to evidence possible bias induced by 2009 extreme climatic conditions.

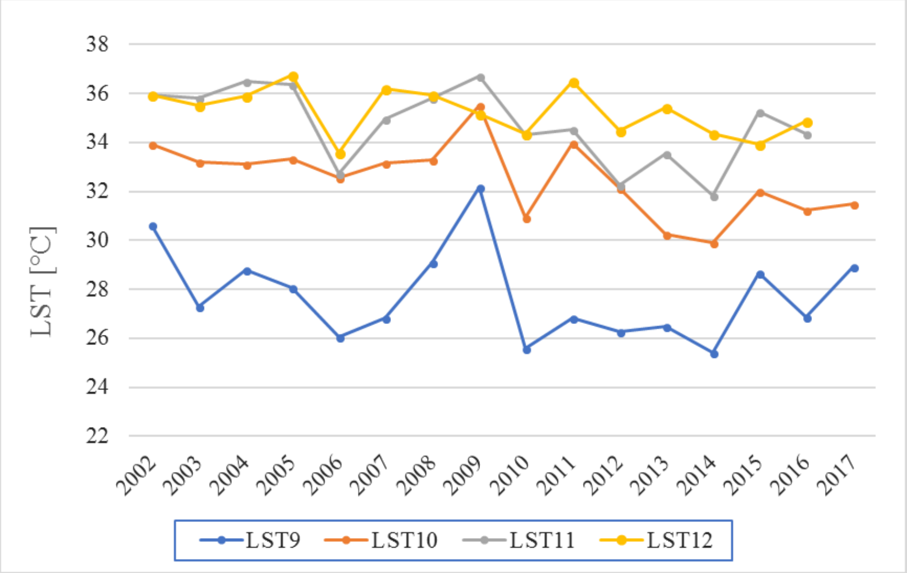

Figure 15 – Time series of LST for Enabered catchment

Table 8 – Absolute values of LST for periods 2002-2008, 2009-2017 and 2010-2017, and differences (all values in °C)

Month	September	October	November	December
Average LST (2002-2008)	28.13	33.24	35.45	35.68
Average LST (2009-2017)	27.48	31.94	34.10	34.89
Average LST (2010-2017)	26.89	31.49	33.73	34.85
Difference LST (2002-2008) – LST (2009-2017)	0.65	1.30	1.35	0.80
Difference LST (2002-2008) – LST (2010-2017)	1.24	1.74	1.72	0.84

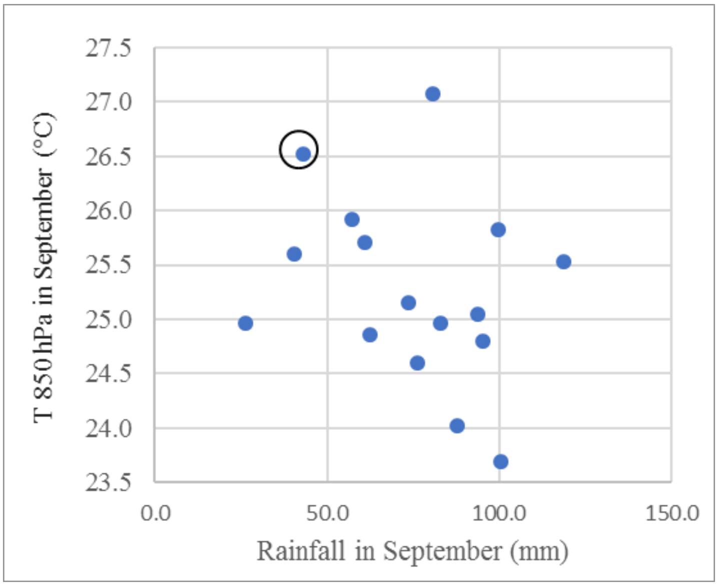

Figure 16 - T_{850} – Rainfall scatter plot in September. Year 2009 is evidenced by a dark circle

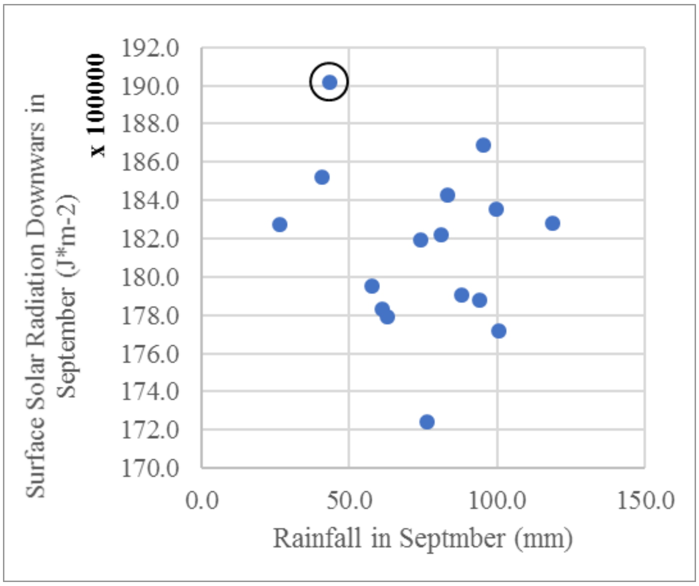

Figure 17 – Surface solar radiation downwards – Rainfall scatter plot in September. Year 2009 is evidenced by a dark circle

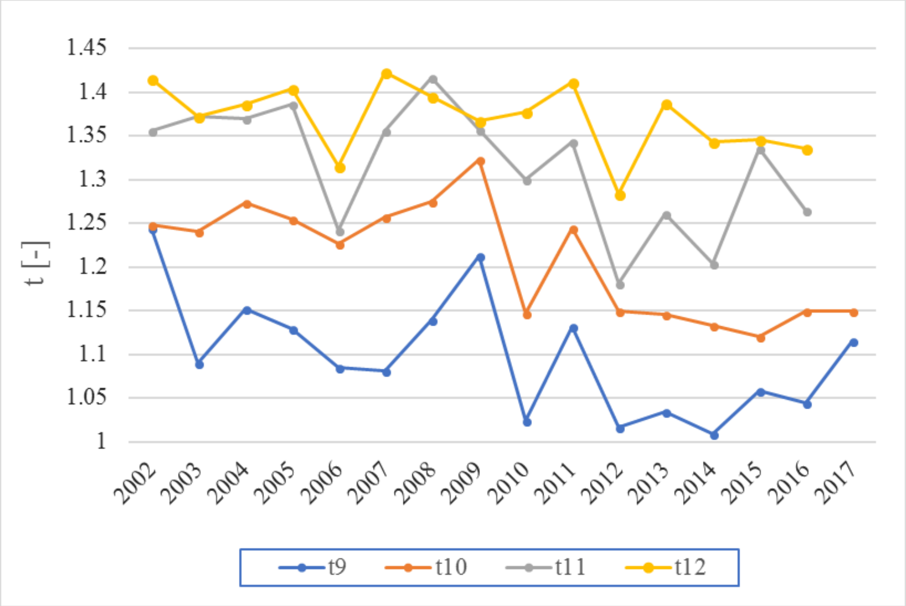

Figure 18 - Time series of t for Enabered catchment

The statistical analysis carried out on t value is reported in Table 9, Table 10, Figure 19 and Figure 20. In both cases, whether if 2009 is considered or not, t_{12} differences are not statistically relevant (with $P > 0.1$). We conclude that a lag effect is not statistically evident, even if further investigation can be suggested. For the other months, the results are as follows:

- **September:** Considering 2009 within the analysis, LST is lowered by 0.65 °C and t is lowered by 0.060 ($P < 0.1$) after LRWH implementation. Without considering 2009 LST is lowered by 1.24 °C and t is lowered by 0.077 ($P < 0.05$).
- **October:** Considering 2009 within the analysis, LST is lowered by 1.30 °C and t is lowered by 0.080 ($P < 0.01$) after LRWH implementation. Without considering 2009 LST is lowered by 1.74 °C and t is lowered by 0.099 ($P < 0.01$).
- **November:** Considering 2009 within the analysis, LST is lowered by 1.35 °C and t is lowered by 0.076 ($P < 0.05$) after LRWH implementation. Without considering 2009 LST is lowered by 1.72 °C and t is lowered by 0.087 ($P < 0.05$).

Average LST are lowered, and t are lowered with statistical significance. The extreme hot and dry conditions of 2009 affect the analysis for September. This effect is visible also for October and November, but with lower intensity. Differences in LST and t are less evident for September, while they are very similar for October and November.

Coding used for the analysis is reported in Annex A.2

Table 9 – Values and standard deviation of t for periods 2002-2008, 2009-2017, differences and values of Student's t test on means

Month	September	October	November	December
Average t (2002-2008)	1.132 (0.057)	1.254 (0.017)	1.357 (0.055)	1.387 (0.036)
Average t (2009-2017)	1.072 (0.068)	1.174 (0.066)	1.281 (0.065)	1.357 (0.039)
p-value	0.083	0.008	0.030	0.266
Difference t (2002-2008) – t (2009-2017)	0.06	0.08	0.076	0.03
	5%	6%	6%	2%

Table 10 - Values and standard deviation of t for periods 2002-2008, 2010-2017, differences and values of Student's t test on means

Month	September	October	November	December
Average t (2002-2008)	1.132 (0.057)	1.254 (0.017)	1.357 (0.055)	1.387 (0.036)
Average t (2010-2017)	1.054 (0.046)	1.155 (0.038)	1.270 (0.062)	1.355 (0.042)
p-value	0.012	0.000	0.016	0.152
Difference t (2002-2008) – t (2010-2017)	0.077	0.099	0.087	0.032
	7%	8%	6%	2%

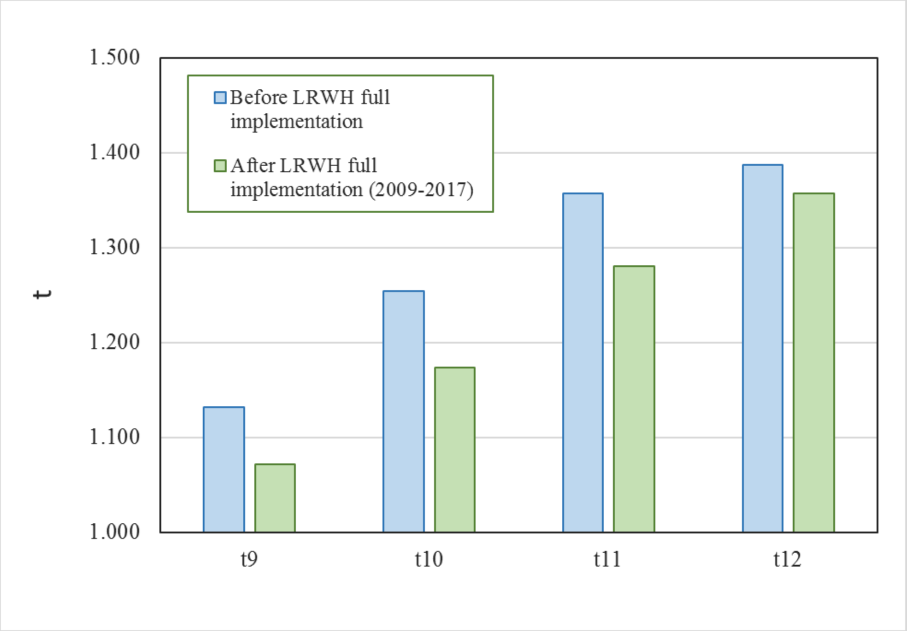

Figure 19 - Values of t averages for the periods 2000-2008 (before full LRWH implementation) and 2009 – 2017 (after full LRWH implementation, interval (1))

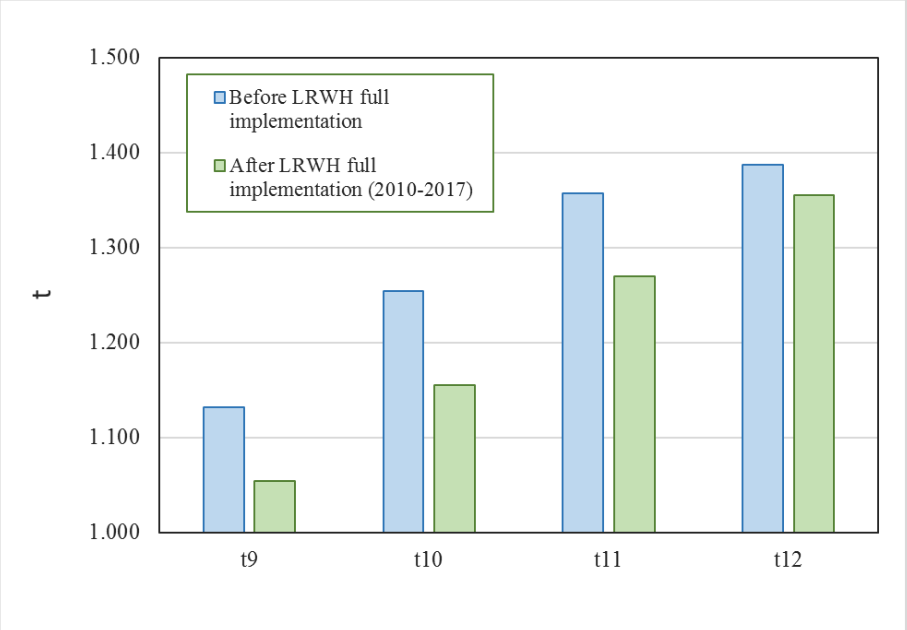

Figure 20 - Values of t averages for the periods 2000-2008 (before full LRWH implementation) and 2010 – 2017 (after full LRWH implementation, interval (2))

4.3 Soil Moisture – Temperature Coupling (SMTC) at catchment scale

To evaluate the occurrence of SMTC dynamics, WCI and t time series analysis were compared. Starting from the visual inspection of WCI- t scatter plots, t was modelled as a linear function of WCI. The analysis was conducted considering 2009 (Figure 21, Table 11 and Table 12) and without 2009 (Figure 22, Table 13 and Table 14).

Results shows the expected negative SMTC in all cases analysed. For all the cases involving the temperatures of September (9) and October (10), namely Figure 21.a, 21.b, 21.c, 22.a, 22.b and 22.c, there is a clear separation between the catchment status before full LRWH implementation and after, since the catchment wetter and cooler, except for 2009. For the case of 2009, it can be concluded that the excessive heat induced by El Nino Southern Oscillation (Winkler et al., 2017), could not be buffered by the available soil moisture.

Following the approach introduced by Schwingshackl et al. (2017), the strength of the coupling is evaluated as $\partial t/\partial WCI$, and R^2 parameter has been utilised for investigate how the model fits the data. To detect possible lag effects, two version of the linear model have been investigated: (i) $t_i = f(WCI_{i-1})$ (with lag of one month); (ii) $t_i = f(WCI_i)$ (without lag).

The WCI-t couples show the highest SMTC is the one characterised by the relation $t_{10} = f\ (WCI_9)$. This latter one explains the coupling of the root zone soil moisture conserved at catchment scale in September and the catchment average temperature in

October. This dynamic can be explained considering that the soil moisture available in September is depleted as evapotranspiration from September to October, having a major impact on October temperatures.

Considering 2009, the coupling strength is the maximum analysed, $\partial t / \partial WCI = -0.75$, correspondent to an average decrease in LST of 1.30 °C, with an R^2 of 0.5653.

Without considering 2009, the coupling strength is the maximum analysed, $\partial t / \partial WCI = -0.6932$, correspondent to an average decrease in LST of 1.74 °C, with an R^2 of 0.6065.

Since the overall approach allows to interpret coherently the anomaly of 2009, we conclude to define the first version of the model as the most adequate one.

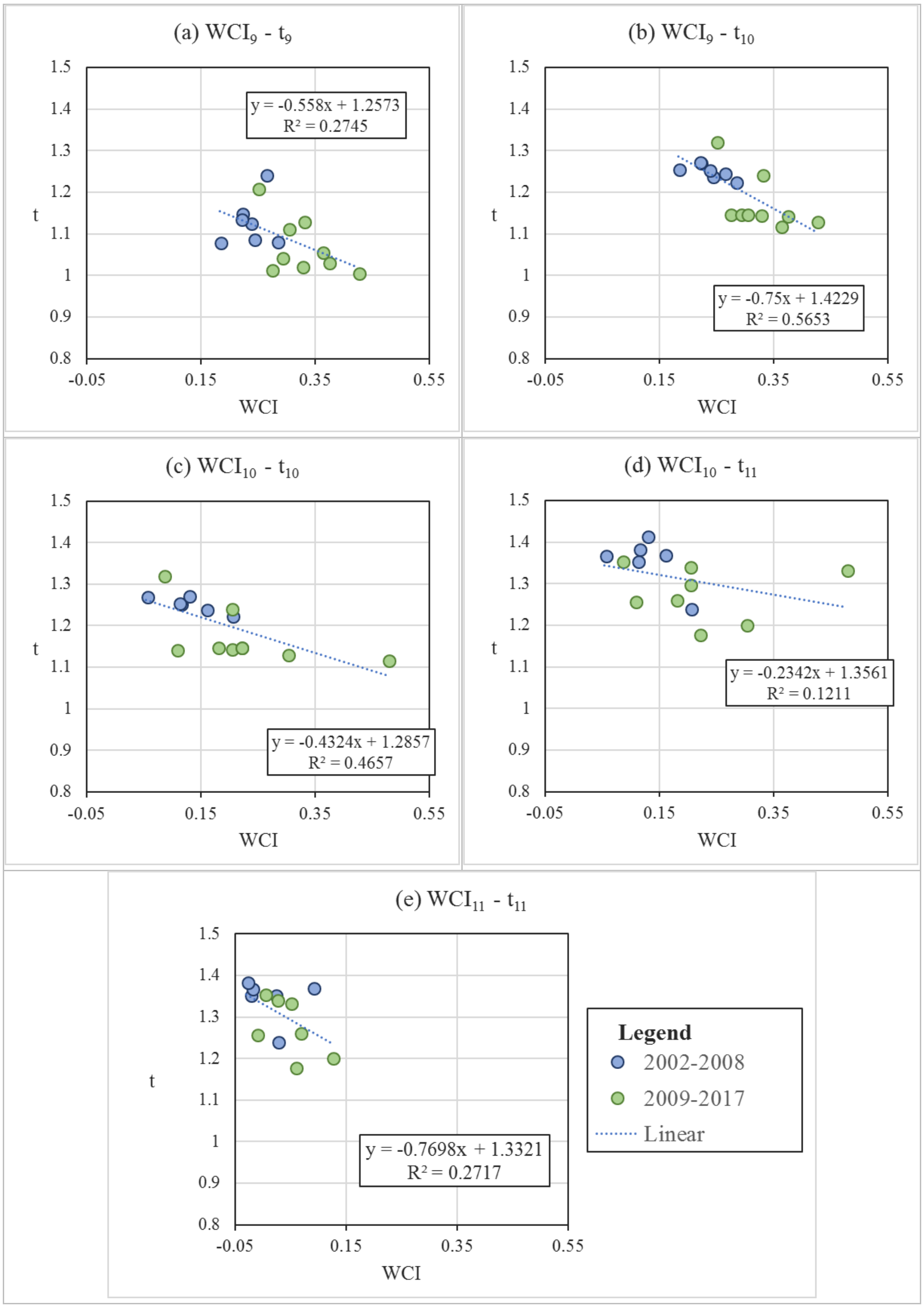

Figure 21 – Distribution of (WCI,t) values for each year considered in the analysis and linear regression model of SMTC: (a) WCI_9 - t_t ; (b) WCI_9 – t_{10} ; (c) WCI_{10} – t_{10} ; (d) WCI_{10} – t_{11} ; (e) WCI_{11} – t_{11}

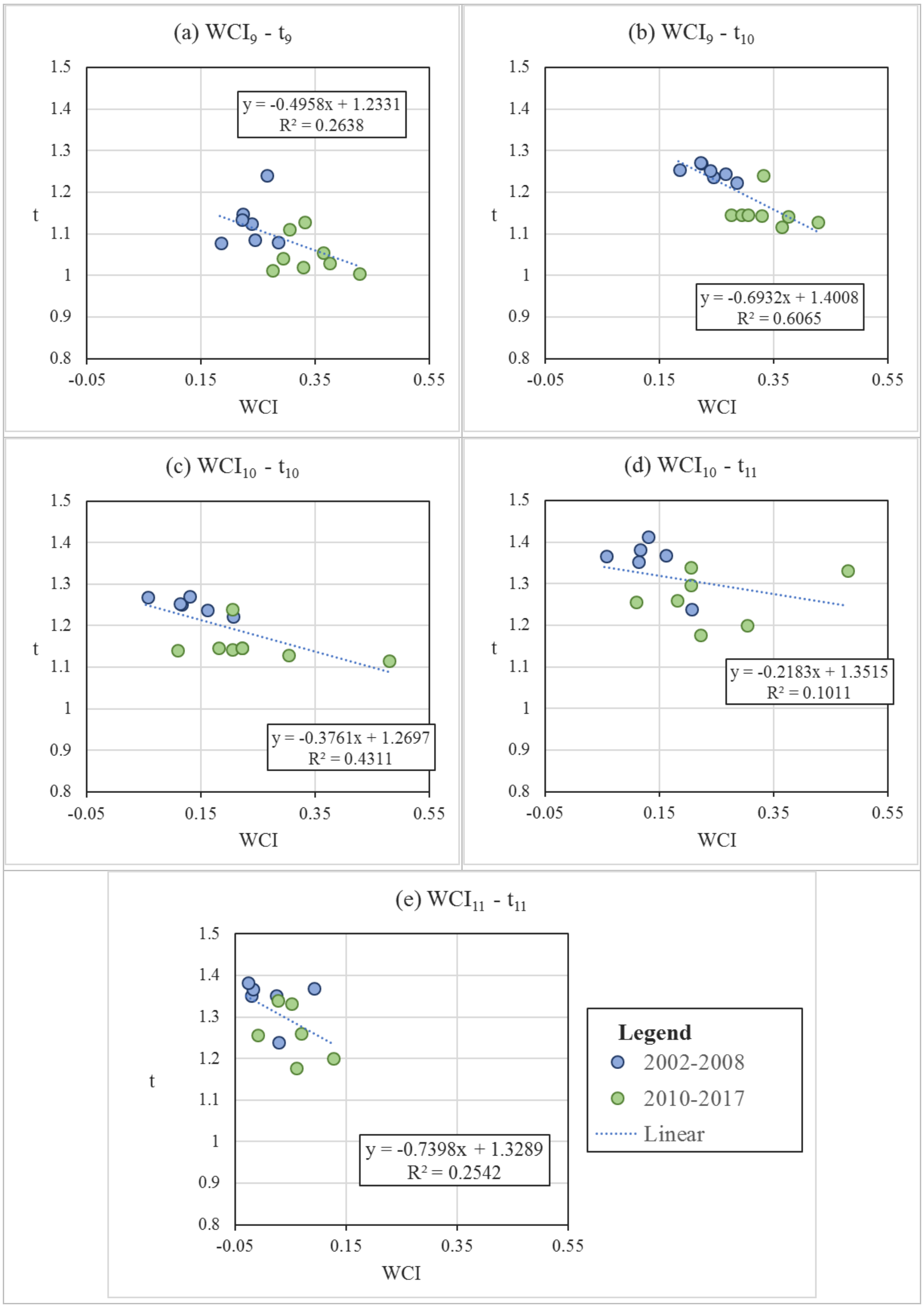

Figure 22 – Distribution of (WCI,t) values for each year considered in the analysis and linear regression model of SMTC without 2009 anomalous year: (a) WCI_9 - t_t ; (b) WCI_9 – t_{10} ; (c) WCI_{10} – t_{10} ; (d) WCI_{10} – t_{11} ; (e) WCI_{11} – t_{11}

Table 11 - Values of R^2 for SMTC linear coupling model

	t_9	t_{10}	t_{11}
WCI_9	0.2745	0.5653	
WCI_{10}		0.4657	0.1211
WCI_{11}			0.2717

Table 12 - Values of ∂t/∂WCI for SMTC linear coupling model

	t_9	t_{10}	t_{11}
WCI_9	-0.558	-0.7500	
WCI_{10}		-0.4324	-0.2342
WCI_{11}			-0.7698

Table 13 - Values of R^2 for SMTC linear coupling model, without 2009 anomalous year

	t_9	t_{10}	t_{11}
WCI_9	0.2638	0.6065	
WCI_{10}		0.3761	0.1011
WCI_{11}			0.2542

Table 14 - Values of ∂t/∂WCI for SMTC linear coupling model, without 2009 anomalous year

	t_9	t_{10}	t_{11}
WCI_9	-0.4958	-0.6932	
WCI_{10}		-0.3761	-0.2183
WCI_{11}			-0.7398

5 Discussion

The present PhD dissertation aimed to test the hypothesis of the occurrence of SMTC (Hirschi et al., 2014; Schwingshackl et al., 2017) at catchment scale, and to verify if the implementation of LRWH interventions can shift a watershed in a 'cooler' situation, as a consequence of the increased soil moisture.

According to Schwingshackl et al. (2017), this effect is more evident where climatic conditions determines a *Transitional soil moisture and evapotranspiration regime* (Budyko, 1974, 1956), where evapotranspiration, is limited by available soil moisture.

These conditions typically occur in arid to semi-arid regions of the world (Schwingshackl et al., 2017), where also land degradation and desertification phenomena are occurring as a consequence of increased pressure on natural resources.

On the other hand, these regions can represent a critical hotspot to meet global food needs, if land and water resources will be properly managed (Rockstrom and Falkenmark, 2015). In particular, with regards to water, water harvesting, defined as the collection and concentration of rainwater and runoff for productive purposes and for ecosystem restoration, will be a key element (Jägermeyr et al., 2016; Rockström et al., 2002; Rockstrom and Falkenmark, 2015), both for increasing agricultural production and to restore degraded ecosystems (García-ávalos et al., 2018; Oweis, 2016; Rango and Havstad, 2009).

Water harvesting, integrated with other measures aiming to conserve soil moisture and revert desertification, such as reforestation, gully rehabilitation and terracing, can then produce a set of ES at a catchment scale.

Given the increase of soil moisture availability in arid areas that can be obtained through LRWH (see, for example, Previati et al., 2010; Tubeileh et al., 2016), we aimed to test if this increase can generate an additional regulating ES of climate mitigation, as a decrease of temperature values in hot months. If this hypothesis is confirmed, the study can add elements to the call for increasing water harvesting, and landscape restoration in arid areas (Rockstrom and Falkenmark, 2015).

The analysis was carried out for Enabered watershed in Tigray region, Ethiopia. The case study was selected for multiple advantages: the location in an area characterised by transitional soil moisture and evapotranspiration regime (Schwingshackl et al., 2017), and the presence of a detailed record of LRWH interventions. These ones were implemented recently (from 2004 to 2008) (Haregeweyn et al., 2012), allowing an analysis of the catchment before and after the implementation.

The analysis was concentrated after the rainy season, in the most critical period for crop growth in the area (Gebreegziabher et al., 2009). It followed three successive steps: an evaluation of possible soil moisture increases at catchment scale (par. 4.1);

an evaluation of possible temperature decreases at catchment scale (par. 4.2); and a comparison of the two time series to assess the degree of SMTC and, if SMTC can generate a cooling effect at catchment scale, as a consequence of LRWH implementation (par. 4.3). To define a suitable timescale for the analysis, we defined the period before 2008 as “before full LRWH implementation” and the period running from 2009 to 2017 as “after full LRWH implementation”. Implications of this choice will be discussed afterwards.

The analysis of the soil moisture status of the watershed has been carried out by the means of a synthetic indicator, namely the Water Conservation Index (WCI), defined in equation (9) as the fraction of NDII and the precipitation of the rainy season. The use of an index, normalised by the rainfall value of the rainy season, allows to assess how much moisture the catchment can retain for a given rainfall amount. The index was defined for three successive months: September, October and November.

Results highlighted a clear increase of the WCI of the watershed after LRWH full implementation for all the months considered, even if the data of November show low statistical significance.

The result offers a direct information supporting other studies that assess how water harvesting, SWC and more in general LRWH techniques can increase soil moisture at catchment scale, by measuring or modelling the runoff reductions and the increase of crop yields at catchment scale in Ethiopia (Grum et al., 2017; Sultan et al., 2018; Wolka et al., 2018). It also confirms the more general observations about the change in water partitioning that can be induced by these measures (Rockstrom and Falkenmark, 2015; UNEP, 2009).

However, in this framework, it should be observed how any reduction in runoff should be carefully assessed. Since this kind of analysis are often limited at catchment scale, there is always the possibility that limiting runoff and conserving soil moisture, may limit downstream water availability (Dile et al., 2016). In this sense, a careful monitoring of upstream-downstream dynamics when implementing large scale LRWH should be always considered, in particular where seasonal water scarcity is not only given by the concentration of rainfall during few months, with heavy rains that generate high runoff amounts that should be managed, but by an overall low precipitation. In this latter case, conserving soil moisture may lead to imbalances in water allocation.

To evaluate the evolution of temperatures at the scale of Enabered catchment, the normalised t parameter was used, as a function of LST, considered as a proxy of near-surface air temperature. The proposed approach follows the procedures developed for similar analysis in urban areas (Cheng et al., 2008; Di Leo et al., 2016; Zareie et al., 2016), that adopted LST as an indicator of temperature decreases and increases. The analysis showed good accordance with the hypothesis of a general colder status of the watershed after LRWH implementation, with the exception for the year 2009, in particular for the months of September and October.

Literature shows how 2009 has been one of the hottest and driest years for East Africa (Winkler et al., 2017). The anomaly is also confirmed by the degree of climate forcing induced by Surface Solar Radiation Downwards retrieved from ERA-INTERIM dataset, that shows how September 2009 was characterised by the highest incoming radiation energy, and by the highest temperature forcing from macroclimatic variations (evaluated with T_{850}) parameter.

Considering the occurrence of an extreme hot year after LRWH full implementation, it can be observed that the effect of the lowering of dry season temperatures induced by SMTC did not occurred in 2009. This may be explained by hypothesizing that, despite the coupling dynamics, the soil moisture available at catchment scale in September 2009 was not sufficient to provide enough LH. The low level of the WCI for October 2009 (Figure 13) seems to indicate an almost complete depletion of soil moisture at catchment scale, that can confirm this explanation, but further analysis is recommended before drafting conclusions on these dynamics.

However, it should be observed that, even if LRWH interventions contributed to lower the average temperatures at the watershed scale, their influence can be limited in the case of extreme events. This is somehow similar to the role of water harvesting as a mean to deal with water scarcity: it is proven to be more effective in bridging short dry spells of 5 to 15 days, that however represent the first source of crop failure, rather than allowing to buffer prolonged droughts (Rockström et al., 2002).

In absolute terms, LRWH interventions determined an average decrease of LST of 1.30° C in October, that jumps to 1.74 °C, excluding the year 2009.

Since studies analysing heat mitigation induced by soil moisture status at catchment scale are currently lacking, results were compared with the magnitude of temperature differences retrieved within similar analysis developed for urban areas. Zareie et al. (2016) measured an increase of 1.45 °C given by the decrease of green areas in the Iranian city of Yazd, while Di Leo et al. (2016) measured a difference ranging from 0.31 to 1.74 °C between the greener and more vegetated outskirts and the centre of the Burkinabe city of Bobo-Dioulasso. Cheng et al. (2008) found higher variations, determining that an increase up to 3.1 °C may be expected if paddy fields in Taiwan will be converted to other type of land uses. This latter analysis, however, entailed the removal of open waters areas, similarly to the study of Mohamed et al. (2005), developed at regional scale, that predicted an increase of temperatures of 4 – 6 °C in the case of complete drainage of Sudd Swamp, in river Nile watershed.

It can be concluded that, in absolute terms, temperature variations induced by LRWH at catchment scale, in a region where the transitional soil moisture and evapotranspiration regime occur, are similar to the ones that can be induced in urban areas by the conversion of large green zones (including the so-called green and even blue infrastructures) to paved surfaces and built environment.

The analysis of SMTC has been realised by comparing the time series of t and WCI, by considering the occurrence of two possible relationships: (i) $t_i = f(WCI_{i-1})$ (temperature influenced by soil moisture, with lag of one month); (ii) $t_i = f(WCI_i)$ (without lag).

In the building of this simple, conceptual, model we adopted the general framework of Schwingshackl et al. (2017), that evaluates SMTC strength as $\partial T/\partial\theta$. In the original work, Schwingshackl et al. calculated $\partial T/\partial\theta$ with equation (6), as a product of $\partial EF/\partial\theta$ and $\partial T/\partial EF$. For the present work, it was chosen to evaluate directly $\partial T/\partial\theta$: T and θ were evaluated by the mean of proxy variables (t and WCI respectively) measured by satellite remote sensing. without calculating EF. To obtain a simple and parsimonious framework, it was chosen to not consider EF. Most of the remote sensing approaches to evaluate EF, in fact, are already strongly dependent on LST values (de Tomás et al., 2014; Nutini et al., 2014; Peng and Loew, 2014).

After a general analysis of possible coupling dynamics (Figure 21 and Figure 22), it was concluded that, considering a simple linear dependence, t values of October are correlated to the WCI values of September (Figure 21.b), with an R^2 of 0.56.

Moreover, considering that the hydro-climatic status of the watershed as defined by a couple of (WCI, t) values, results clearly show that the points representing the watershed status before full LRWH implementation are clustered in the ‘hot and dry’ part of the scatter plot WCI-t (upper left), while the points representing the watershed status after full LRWH implementation are clustered in a ‘wetter and cooler’ part (lower right). Since 2009 is coherently shown close to the ‘hot and dry’ cluster, it was decided to maintain this year for the model evaluation statistics, given that the considered framework seemed to represent well the occurrence of extremely hot and dry years, even after LRWH implementation.

It can be affirmed that, for the pilot case of Enabered catchment, SMTC dynamics are evident, since the soil moisture status of the watershed during the month after the rainy season (September) has an influence on temperatures in October. This 1-month lag can be well explained if one considers that the soil moisture available in September is converted in LH between September and October, and that a higher soil moisture content in September can then induce lower temperature in October, at a catchment scale. Moreover, lag-effects can be expected when analysing SMTC dynamics, and most of the latest literature shows lag times of up to three months (Hirschi et al., 2014; Schwingshackl et al., 2017).

5.1 Main limitations of the analysis

The main limitations of the proposed analysis are represented by (1) the division of the time series analysed in two distinct intervals (‘before full LRWH implementation’ and ‘after full LRWH implementation’) and (2) the proxy-based approach.

LRWH in the catchment was implemented between 2004 and 2008 (Haregeweyn et al., 2012). 01/01/2009 was selected as the date after which the catchment has been considered with LRWH interventions fully implemented. This may seem not in line with a hypothesis of a gradual implementation of LRWH between 2004 and 2008, since some structures could be already in place years before 2008. However, since the analysed time series show a clear change in the hydro-climatic status of the watershed after 2008, it can be hypothesized that some interventions have had an actual effect in some years after the implementation, and that most of the infrastructures were built in the latest years of the period 2004-2008, while in the earlier years site selection, design and work planning took place.

On the other hand, there may be the possibility that LRWH implementation continued after 2008. Within the scope of the analysis, this can be considered a minor issue (since the major intervention on Enabered catchment was conducted between 2004 and 2008) but it can represent a question mark in case of further analysis and/or modelling, aiming to check the relationship between LRWH intensification and SMTC are carried out.

With regards to the proxy approach, it is evident how the study has been based on the evaluation of NDII as a proxy for θ and of LST as a proxy of T. The main difficulty that induced the author to base the present research on indicators for soil moisture and temperature was represented by the need to analyse long and consistent time series for a catchment in semi-arid climate, where LRWH were implemented just recently. Most of these catchments are often ungauged, with not precise records with regards to LRWH implementation dates. As discussed earlier, Enabered catchment, represented a fruitful case study, even if long time series of more adequate variables (such as near-surface air temperature, in more than one point) were lacking. LST, in line with other works developed in urban areas, seemed to be an adequate parameter for long term temperature monitoring.

In addition, it should be observed that, with regards to soil moisture, remote sensing datasets for θ are often based on > 1 km cell size, making impossible a detailed local-scale analysis. Soil moisture values were substituted with NDII, and this latter parameter seemed to be adequate, considering its good accordance with root-zone soil moisture during dry periods (Sriwongsitanon et al., 2016). Moreover, it was demonstrated how SMTC is mostly determined by soil moisture stored in the root zone (Hirschi et al., 2014).

6 Conclusions

The present PhD dissertation aimed to evaluate the occurrence of SMTC dynamics (Schwingshackl et al., 2017; Seneviratne et al., 2010), at a catchment scale, for a transitional soil moisture and evapotranspiration regime (Budyko, 1974, 1956).

In particular, we focused on Enabered catchment, Tigray region, Ethiopia, where a set of LRWH measures aimed to reduce runoff and conserve and store soil moisture at catchment level. These measures were implemented during a limited timespan (2004-2008) allowing a detailed analysis of the hydro-climatic status of the watershed before and after the implementation.

Previous analysis on SMTC focused on the observation on how soil moisture deficit can generate and enhance heatwaves (Alexander, 2011; Hauser et al., 2016; Mueller and Seneviratne, 2012). The present work, on the other hand, proposed a pro-active approach, to analyse to what extent storing soil moisture, with adequate land and water management practices, can reduce temperatures in the hot months after the rainy season. The presented study analyses SMTC for September, October and November, that, in Ethiopia, are the most critical ones for crop growth, and thus for food security (Gebreegziabher et al., 2009). The rainy season for the considered area ends in August.

The dissertation has been structured to answer to three research questions:

1. **To what extent can LRWH enhance soil moisture retention at landscape (catchment) level?**

Soil moisture retention at catchment scale has been evaluated by the means of WCI parameter, calculated as shown in equation (9). Results showed that an increase of WCI is visible after the full LRWH implementation, namely after 2008. The effect has been evaluated as difference of WCI for September, October and November. It can be concluded that LRWH enhance the soil moisture retention capacity at catchment scale for September ($P < 0.01$) and October ($P < 0.1$). Effects in November are not evident for this scale of analysis. This result represents a direct confirmation, obtained through remote sensing analysis, of other, numerous, studies that analyzed soil moisture increase indirectly, by measuring or modelling the runoff reductions and the increase of crop yields at catchment scale in Ethiopia (Grum et al., 2017; Sultan et al., 2018; Wolka et al., 2018). It also confirms the more general observations about the change in water partitioning that can be induced by these measures at a catchment scale (Rockstrom and Falkenmark, 2015; UNEP, 2009)

2. **To what extent can LRWH modify temperature patterns at landscape (catchment) level?**

Changes in temperature were analyzed with a temperature parameter t, calculated as a fraction of LST and T_{850} to eliminate the dependence of the value from macro climatic forcing.
Results showed that, after LRWH full implementation, temperature decreased in September ($P<0.1$), October ($P<0.01$) and November ($P<0.05$). The analysis has also taken into account the exceptional year of 2009, where higher surface solar radiation input, probably induced by El Nino Oscillation (Winkler et al., 2017), causing extremely high temperatures. By removing 2009 from the analysis, the study shows an average decrease in LST of 1.74 °C. The variation, in absolute terms, is similar to the ones that can be induced in urban areas by the conversion of large areas of paved surfaces and built environment into green infrastructures and vegetated areas (Di Leo et al., 2016; Zareie et al., 2016).

3. (a) What is the micro-climate effect of modified soil moisture on temperature given by LRWH?

These effects have been evaluated in the framework of SMTC analysis at the catchment scale. By the mean of a simple, parsimonious linear model, based on the framework of Schwingshackl et al. (2017) the analysis demonstrates that SMTC is evident at catchment scale and that the implementation of LRWH measures provided a climate mitigation effect in the watershed. WCI values of September evidence a negative linear correlation to t values of October ($R^2 = 0.59$). The 1-month lag can be well justified by considering the framework for the modelling of SMTC presented by Schwingshackl et al. (2017) (Figure 2 and equations (1) and (2)). Soil moisture available in September is converted in LH between September and October, and that a higher soil moisture content in September can then induce lower temperature in October, at a catchment scale.
Moreover we analysed the hydro-climatic status of the watershed as defined by a couple of (WCI, t) values. Results clearly shows that the points representing the watershed status before full LRWH implementation are clustered in the ‘hot and dry’ part of the WCI-t scatter plot (upper left), while the points representing the watershed status after full LRWH, are located in the ‘cool and wet’ part of it, clearly indicating a separation between the Enabered catchment status before and after LRWN measures implementation.

(b) What is most suitable remote sensing methodology to monitor SMTC at landscape (catchment) level?

Considering the framework of the present dissertation, it has been found that an approach based on simple parameters, such as LST and NDII can evidence dynamics of SMTC at a catchment scale. In particular, NDII appears to be particularly indicated for its good accordance with root-zone soil moisture (Sriwongsitanon et al., 2016), as a determinant of SMTC (Hirschi et al., 2014). Additional datasets, such as CHIRPS (Funk et al., 2015) and ERA-INTERIM (Balsamo et al., 2015), that are based on remote sensing observations, may support similar analysis, considering that they can provide information related to macro-climate parameters that can be use as a benchmark of micro-climate variations induced by LWRH.

The use of simple proxy parameter can be recommended to analyse the evidence of similar dynamics in other regions of the world. The opinion of the author is that, for analyzing more in detail the evolution of such dynamics, more advanced remote sensing datasets will be needed (such as the recent Sentinel-2 imagery, but available only from 2015), together with downscaling of global (Schwingshackl et al., 2017) or regional (Mohamed et al., 2005) size modelling tools. In addition, investments in long-term experiments for the analysis of SMTC at catchment scale may be considered if further studies will confirm this initial one.

~

Within the general framework described in the introduction, this PhD dissertation aimed to demonstrate that careful and wise land and water management can also support unexpected Ecosystem Services such as climate mitigation. Results make evident the occurrence of climate mitigation given by the increase of soil moisture availability in a restored catchment in the semi-arid Tigray region of Ethiopia, as a direct effect of Soil Moisture Temperature Coupling. The author hopes that the results of the present work may reinforce the call for an increased adoption of water harvesting (Rockstrom and Falkenmark, 2015), land restoration and green water management (Keys and Falkenmark, 2018), to increase the resilience of agricultural ecosystem located in arid and semi-arid areas, that represents a key element to achieve global food security.

7 Bibliography

Al-Seekh, S.H., Mohammad, A.G., 2009. The Effect of Water Harvesting Techniques on Runoff, Sedimentation, and Soil Properties. Environ. Manage. 44, 37–45. doi:10.1007/s00267-009-9310-z

Alexander, L., 2011. Climate science: Extreme heat rooted in dry soils. Nat. Geosci 4, 12–13.

Amsalu, A., de Graaff, J., 2007. Determinants of adoption and continued use of stone terraces for soil and water conservation in an Ethiopian highland watershed. Ecol. Econ. 61, 294–302. doi:10.1016/J.ECOLECON.2006.01.014

Anderson, P.D., Larson, D.J., Chan, S.S., 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. For. Sci. 53, 254–269.

Asfaha, T.G., Frankl, A., Haile, M., Nyssen, J., 2016. Catchment Rehabilitation and Hydro-geomorphic Characteristics of Mountain Streams in the Western Rift Valley Escarpment of Northern Ethiopia. L. Degrad. Dev. 27, 26–34. doi:10.1002/ldr.2267

Balsamo, G., Albergel, C., Beljaars, A., Boussetta, S., Brun, E., Cloke, H., Dee, D., Dutra, E., Munõz-Sabater, J., Pappenberger, F., De Rosnay, P., Stockdale, T., Vitart, F., 2015. ERA-Interim/Land: A global land surface reanalysis data set. Hydrol. Earth Syst. Sci. 19, 389–407. doi:10.5194/hess-19-389-2015

Berkes, F., Folke, C. (Eds.), 2000. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, New York.

Biggs, R., Schlüter, M., Schoon, M.L. (Eds.), 2015. Principles for Building Resilience Sustaining Ecosystem Services in Social-Ecological Systems. Cambridge University Press, New York.

Brown, R.D., 2011. Ameliorating the effects of climate change: Modifying microclimates through design. Landsc. Urban Plan. 100, 372–374. doi:10.1016/j.landurbplan.2011.01.010

Budyko, M.I., 1974. Climate and Life. Academic Press.

Budyko, M.I., 1956. Тепловой баланс земной поверхности (Heat Balance of the Earth’s Surface). Gidrometeoizdat, Leningrad, USSR.

Bureau of Agriculture and Rural Development, 2008. Annual report of natural resource development and utilization. Adwa, Ethiopia.

Carlson, T.N., Traci Arthur, S., 2000. The impact of land use - Land cover changes due to urbanization on surface microclimate and hydrology: A satellite perspective. Glob. Planet. Change 25, 49–65. doi:10.1016/S0921-8181(00)00021-7

Chen, J., Saunders, S.C., Crow, T.R., Naiman, R.J., Brosofske, K.D., Mroz, G.D., Brookshire, B.L., Franklin, J.F., Frankiln, J., 1999. Microclimate in forest ecosystem and landscape ecology: Variations in local climate can be used to monitor and compare the effects of different management regimes. Bioscience 49, 288–297. doi:10.1086/250095

Cheng, K.S., Su, Y.F., Kuo, F.T., Hung, W.C., Chiang, J.L., 2008. Assessing the effect of landcover changes on air temperature using remote sensing images-A pilot study in northern Taiwan. Landsc. Urban Plan. 85, 85–96. doi:10.1016/j.landurbplan.2007.09.014

Ciampalini, R., Billi, P., Ferrari, G., Borselli, L., Follain, S., 2012. Soil erosion induced by land use changes as determined by plough marks and field evidence in the Aksum area (Ethiopia). Agric. Ecosyst. Environ. 146, 197–208. doi:10.1016/J.AGEE.2011.11.006

Correggiari, M., Castelli, G., Bresci, E., Salbitano, F., 2017. Fog Collection and Participatory Approach for Water Management and Local Development: Practical Reflections from Case Studies in the Atacama Drylands, in: Ouessar, M., Gabriels, D., Tsunekawa, A., Evett, S. (Eds.), Water and Land Security in Drylands: Response to Climate Change. Springer International Publishing, Cham, pp. 141–158. doi:10.1007/978-3-319-54021-4_14

Critchley, W., Siegert, K., Chapman, C., 1991. Water harvesting (AGL/MISC/17/91). FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome, Italy.

De Frenne, P., Rodríguez-Sánchez, F., Coomes, D.A., Baeten, L., Verstraeten, G., Vellen, M., Bernhardt-Römermann, M., Brown, C.D., Brunet, J., Cornelis, J., Decocq, G.M., Dierschke, H., Eriksson, O., Gilliam, F.S., Hédl, R., Heinken, T., Hermy, M., Hommel, P., Jenkins, M.A., Kelly, D.L., Kirby, K.J., Mitchell, F.J.G., Naaf, T., Newman, M., Peterken, G., Petřík, P., Schultz, J., Sonnier, G., Van Calster, H., Waller, D.M., Walther, G.-R., White, P.S., Woods, K.D., Wulf, M., Graae, B.J., Verheyen, K., 2013. Microclimate moderates plant responses to macroclimate warming. Proc. Natl. Acad. Sci. U. S. A. 110, 18561–18565. doi:10.1073/pnas.1311190110

de Tomás, A., Nieto, H., Guzinski, R., Salas, J., Sandholt, I., Berliner, P., 2014. Validation and scale dependencies of the triangle method for the evaporative fraction estimation over heterogeneous areas. Remote Sens. Environ. 152, 493–511. doi:10.1016/j.rse.2014.06.028

DeClerck, F.A.J., Jones, S.K., Attwood, S., Bossio, D., Girvetz, E., Chaplin-Kramer, B., Enfors, E., Fremier, A.K., Gordon, L.J., Kizito, F., Lopez Noriega, I., Matthews, N., McCartney, M., Meacham, M., Noble, A., Quintero, M., Remans, R., Soppe, R., Willemen, L., Wood, S.L.R., Zhang, W., 2016. Agricultural ecosystems and their services: the vanguard of sustainability? Curr. Opin. Environ. Sustain. 23, 92–99. doi:10.1016/j.cosust.2016.11.016

Di Leo, N., Escobedo, F.J., Dubbeling, M., 2016. The role of urban green infrastructure in mitigating land surface temperature in Bobo-Dioulasso, Burkina Faso. Environ. Dev. Sustain. 18, 373–392. doi:10.1007/s10668-015-9653-y

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K.M.A., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G.M., Martin-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E.S., Reyers, B., Roth, E., Saito, O., Scholes, R.J., Sharma, N., Tallis, H., Thaman, R., Watson, R., Yahara, T., Hamid, Z.A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E., Asah, T.S., Asfaw, Z., Bartus, G., Brooks, A.L., Caillaux, J., Dalle, G., Darnaedi, D., Driver, A., Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A.M.M., Fu, B., Gundimeda, H., Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W.A., Mandivenyi, W., Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J.P., Mikissa, J.B., Moller, H., Mooney, H.A., Mumby, P., Nagendra, H., Nesshover, C., Oteng-Yeboah, A.A., Pataki, G., Roué, M., Rubis, J., Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y., Zlatanova, D., 2015. The IPBES Conceptual Framework - connecting nature and people. Curr. Opin. Environ. Sustain. 14, 1–16. doi:10.1016/j.cosust.2014.11.002

Dile, Y.T., Karlberg, L., Daggupati, P., Srinivasan, R., Wiberg, D., Rockström, J., 2016. Assessing the implications of water harvesting intensification on upstream – downstream ecosystem services : A case study in the Lake Tana basin. Sci. Total Environ. 542, 22–35. doi:10.1016/j.scitotenv.2015.10.065

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.A., Justes, E., Journet, E.P., Aubertot, J.N., Savary, S., Bergez, J.E., Sarthou, J.P., 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron. Sustain. Dev. 35, 1259–1281. doi:10.1007/s13593-015-0306-1

Evans, J.M., De Schiller, S., 1996. Application of microclimate studies in town planning: A new capital city, an existing urban district and urban river front development. Atmos. Environ. doi:10.1016/1352-2310(94)00138-3

FAO, 2016. Physical factors affecting soil organisms [WWW Document]. URL http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/soil-biodiversity/soil-organisms/physical-factors-affecting-soil-organisms/en/ (accessed 12.1.16).

Foken, T., 2008. Micrometeorology. Springer-Verlag, Berlin-Hedelberg.

Folke, C., Biggs, R., Norström, A. V., Reyers, B., Rockström, J., 2016. Social-ecological resilience and biosphere-based sustainability science. Ecol. Soc. 21. doi:10.5751/ES-08748-210341

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066.

Garbach, K., Milder, J.C., DeClerck, F.A.J., Montenegro de Wit, M., Driscoll, L., Gemmill-Herren, B., 2017. Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. Int. J. Agric. Sustain. 15, 11–28. doi:10.1080/14735903.2016.1174810

García-ávalos, S., Rodriguez-caballero, E., Miralles, I., Luna, L., Angel, M., Solé-benet, A., Cantón, Y., 2018. Water harvesting techniques based on terrain modi fi cation enhance vegetation survival in dryland restoration. Catena 167, 319–326. doi:10.1016/j.catena.2018.05.004

Gebreegziabher, T., Nyssen, J., Govaerts, B., Getnet, F., Behailu, M., Haile, M., Deckers, J., 2009. Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. Soil Tillage Res. 103, 257–264. doi:10.1016/J.STILL.2008.05.021

Gebremeskel, G., Gebremicael, T.G., Abbadi, G., 2017. Economic and environmental rehabilitation through soil and water conservation, the case of Tigray in northern Ethiopia. J. Arid Environ.

Gebremicael, T., Mohamed, Y., Van Der Zaag, P., Berhe, A., Haile, G., Yazew, E., Kifle, M., 2018. Comparative evaluation of multiple satellite rainfall products over the complex terrains of Tekeze-Atbara sub-basin , Nile River basin, in: EGU General Assembly 2018, Geophysical Research Abstracts. p. 5979.

Gelaro, R., McCarty, W., Suárez, M.J., Todling, R., Molod, A., Takacs, L., Randles, C.A., Darmenov, A., Bosilovich, M.G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A.M., Gu, W., Kim, G.K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J.E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S.D., Sienkiewicz, M., Zhao, B., 2017. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). J. Clim. 30, 5419–5454. doi:10.1175/JCLI-D-16-0758.1

Gliessman, S.R., 2015. Agroecology; the ecology of sustainable food systems, Taylor & F. ed.

Gordon, L.J., Finlayson, C.M., Falkenmark, M., 2010. Managing water in agriculture for food production and other ecosystem services. Agric. Water Manag. 97, 512–519. doi:10.1016/j.agwat.2009.03.017

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Remote Sensing of Environment Google Earth Engine : Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27. doi:10.1016/j.rse.2017.06.031

Grum, B., Hessel, R., Baartman, J.E.M., Abdulkadir, M., Yazew, E., Kessler, A., Ritsema, C.J., Geissen, V., 2017. Assessing the effect of water harvesting techniques on event-based hydrological responses and sediment yield at a catchment scale in northern Ethiopia using the Limburg Soil Erosion Model (LISEM). Catena 159, 20–34. doi:10.1016/j.catena.2017.07.018

Hardisky, M.A., Klemas, V., Smart, R.M., 1983. The influence of soil salinity, growth form, and leaf moisture on the spectral radiance of Spartina alterniflora canopies. Photogramm. Eng. & Remote Sens. 49, 77–83.

Haregeweyn, N., Berhe, A., Tsunekawa, A., Tsubo, M., Meshesha, D.T., 2012. Integrated Watershed Management as an Effective Approach to Curb Land Degradation: A Case Study of the Enabered Watershed in Northern Ethiopia. Environ. Manage. 50, 1219–1233. doi:10.1007/s00267-012-9952-0

Hauser, M., R, O., Seneviratne, S.I., 2016. Role of soil moisture versus recent climate change for the 2010 heat wave in western Russia. Geophys. Res. Lett. 43, 2819–2826. doi:10.1002/2016GL068036

Herold, N., Kala, J., Alexander, L. V, 2016. The influence of soil moisture deficits on Australian heatwaves. Environ. Res. Lett. 11. doi:10.1088/1748-9326/11/6/064003

Hirschi, M., Mueller, B., Dorigo, W., Seneviratne, S.I., 2014. Using remotely sensed soil moisture for land-atmosphere coupling diagnostics: The role of surface vs. root-zone soil moisture variability. Remote Sens. Environ. 154, 246–252. doi:10.1016/j.rse.2014.08.030

Hirschi, M., Seneviratne, S.I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O.B., Formayer, H., Orlowsky, B., Stepanek, P., 2010. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. Nat. Geosci. 4, 17.

Hishe, S., Lyimo, J., Bewket, W., 2017. Soil and water conservation effects on soil properties in the Middle Silluh Valley, northern Ethiopia. Int. Soil Water Conserv. Res. 5, 231–240. doi:10.1016/j.iswcr.2017.06.005

Ismangil, D., Wiegant, D., Hagos, E., van Steenbergen, F., Kool, M., Sambalino, F., Castelli, G., Bresci, E., Hagos, F., 2016. Managing the Microclimate, Practical Note Spate Irrigation.

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., Rockström, J., 2016. Integrated crop water management might sustainably halve the global food gap. Environ. Res. Lett. 11, 025002. doi:10.1088/1748-9326/11/2/025002

Keys, P.W., Falkenmark, M., 2018. Green water and African sustainability. Food Secur in Press. doi:10.1007/s12571-018-0790-7

Keys, P.W., Wang-erlandsson, L., Gordon, L.J., 2016. Revealing Invisible Water : Moisture Recycling as an Ecosystem Service. PLoS One 1–16. doi:10.4121/uuid

Keys, P.W., Wang-erlandsson, L., Gordon, L.J., Galaz, V., Ebbesson, J., 2017. Approaching moisture recycling governance. Glob. Environ. Chang. 45, 15–23. doi:10.1016/j.gloenvcha.2017.04.007

Klemm, O., Schemenauer, R.S., Lummerich, A., Cereceda, P., Marzol, V., Corell, D., Van Heerden, J., Reinhard, D., Gherezghiher, T., Olivier, J., Osses, P., Sarsour, J., Frost, E., Estrela, M.J., Valiente, J.A., Fessehaye, G.M., 2012. Fog as a fresh-water resource: Overview and perspectives. Ambio 41, 221–234. doi:10.1007/s13280-012-0247-8

Kuyah, S., Öborn, I., Jonsson, M., Dahlin, A.S., Barrios, E., Muthuri, C., Malmer, A., Nyaga, J., Magaju, C., Namirembe, S., Nyberg, Y., Sinclair, F.L., 2016. Trees in agricultural landscapes enhance provision of ecosystem services in Sub-Saharan Africa. Int. J. Biodivers. Sci. Ecosyst. Serv. Manag. 12, 255–273. doi:10.1080/21513732.2016.1214178

Lhomme, J.P., Vacher, J.J., 2003. La mitigación de heladas en los camellones del altiplano andino. Bull. l’Institut Français d’Études Andin. 32, 377–399.

Li, X., Duan, Z., Liu, L., Tan, M., Chen, X., 2014. Variation of soil moisture under different rainwater harvesting and conservation practices in the western part of Loess Plateau. Nongye Jixie Xuebao/Transactions Chinese Soc. Agric. Mach. 45, 118–123. doi:10.6041/j.issn.1000-1298.2014.03.020

Lin, B.B., Egerer, M.H., Liere, H., Jha, S., Bichier, P., Philpott, S.M., 2018. Local- and landscape-scale land cover affects microclimate and water use in urban gardens. Sci. Total Environ. 610–611, 570–575. doi:10.1016/j.scitotenv.2017.08.091

Lombardo, U., Canal-Beeby, E., Fehr, S., Veit, H., 2011. Raised fields in the Bolivian Amazonia: A prehistoric green revolution or a flood risk mitigation strategy? J. Archaeol. Sci. 38, 502–512. doi:10.1016/j.jas.2010.09.022

Masek, J.G., Vermote, E.F., Saleous, N., Wolfe, R., Hall, F.G., Huemmrich, K.F., Gao, F., Kutler, J., Lim, T.K., 2013. LEDAPS Calibration, Reflectance, Atmospheric Correction Preprocessing Code, Version 2. doi:10.3334/ornldaac/1146

McCaskill, M.R., McClymont, L., Goodwin, I., Green, S., Partington, D.L., 2016. How hail netting reduces apple fruit surface temperature: A microclimate and modelling study. Agric. For. Meteorol. 226–227, 148–160. doi:10.1016/j.agrformet.2016.05.017

Mekdaschi Studer, R., Liniger, H., 2013. Water Harvesting: Guidelines to a Good Practice. entre for Development and Environment (CDE), Bern; Rainwater Harvesting Implementation Network (RAIN), Amsterdam; MetaMeta, Wageningen; The International Fund for Agricultural Development (IFAD), Rome.

Miralles, D.G., Teuling, A.J., van Heerwaarden, C.C., Vilà-Guerau de Arellano, J.,

2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nat. Geosci. 7, 345.

Mohamed, Y.A., Hurk, B.J.J.M. Van Den, Savenije, H.H.G., 2005. Impact of the Sudd wetland on the Nile hydroclimatology. Water Resour. Res. 41. doi:10.1029/2004WR003792

Moore, R.D., Spittlehouse, D.L., Story, A., 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. J. Am. Water Resour. Assoc.

Motsi, K.E., Chuma, E., Mukamuri, B.B., 2004. Rainwater harvesting for sustainable agriculture in communal lands of Zimbabwe. Phys. Chem. Earth, Parts A/B/C 29, 1069–1073. doi:10.1016/J.PCE.2004.08.008

Mueller, B., Seneviratne, S.I., 2012. Hot days induced by precipitation deficits at the global scale. Proc. Natl. Acad. Sci. 109, 12398 LP-12403.

NASA LP DAAC, 2018. MYD11A2.006 Aqua Land Surface Temperature and Emissivity 8-Day Global 1km. NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov). doi:http://dx.doi.org/10.5067/MODIS/MYD11A2.006

Nutini, F., Boschetti, M., Candiani, G., Bocchi, S., Brivio, P.A., 2014. Evaporative fraction as an indicator of moisture condition and water stress status in semi-arid rangeland ecosystems. Remote Sens. 6, 6300–6323. doi:10.3390/rs6076300

Nyssen, J., Frankl, A., Haile, M., Hurni, H., Descheemaeker, K., Crummey, D., Ritler, A., Portner, B., Nievergelt, B., Moeyersons, J., Munro, N., Deckers, J., Billi, P., Poesen, J., 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145years. Sci. Total Environ. 485–486, 164–179. doi:10.1016/j.scitotenv.2014.03.052

Nyssen, J., Haile, M., Moeyersons, J., Poesen, J., Deckers, J., 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional dagat technique and its integration with introduced techniques. L. Degrad. Dev. 11, 199–208. doi:10.1002/1099-145X(200005/06)11:3<199::AID-LDR376>3.0.CO;2-Y

Nyssen, J., Poesen, J., Gebremichael, D., Vancampenhout, K., D’aes, M., Yihdego, G., Govers, G., Leirs, H., Moeyersons, J., Naudts, J., Haregeweyn, N., Haile, M., Deckers, J., 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. Soil Tillage Res. 94, 151–163. doi:10.1016/J.STILL.2006.07.011

O’Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Clim. Change 122, 387–400. doi:10.1007/s10584-013-0905-2

Oliver, J.E., 1980. MONTHLY PRECIPITATION DISTRIBUTION: A COMPARATIVE INDEX. Prof. Geogr. 32, 300–309. doi:10.1111/j.0033-0124.1980.00300.x

Ouessar, M., Hessel, R., Sghaier, M., Ritsema, C., 2012. WAHARA - Report Series. Report on Water Harvesting Inventory, History and Success Stories.

Oweis, T., Prinz, D., Hachum, A., 2012. Rainwater Harvesting for Agriculture in the Dry Areas. CRC Press/Balkema, Leiden, The Netherlands.

Oweis, T.Y., 2017. Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: A conceptual review of opportunities and constraints in a changing climate. Environ. Rev. 25, 135–149. doi:10.1139/er-2016-0069

Oweis, T.Y., 2016. Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: a conceptual review of opportunities and constraints in a changing climate. Environ. Rev. 25, 135–149. doi:10.1139/er-2016-0069

Peng, J., Loew, A., 2014. Evaluation of daytime evaporative fraction from MODIS TOA radiances using FLUXNET observations. Remote Sens. 6, 5959–5975. doi:10.3390/rs6075959

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. B Biol. Sci. 365, 2959–2971. doi:10.1098/rstb.2010.0143

Previati, M., Bevilacqua, I., Canone, D., Ferraris, S., Haverkamp, R., 2010. Evaluation of soil water storage efficiency for rainfall harvesting on hillslope micro-basins built using time domain reflectometry measurements. Agric. Water Manag. 97, 449–456. doi:10.1016/J.AGWAT.2009.11.004

Rango, A., Havstad, K., 2009. RESEARCH ARTICLE: Water-Harvesting Applications for Rangelands Revisited. Environ. Pract. 11, 84–94. doi:DOI: 10.1017/S1466046609090140

Rockström, J., Barron, J., Fox, P., 2002. Rainwater management for increased productivity among small-holder farmers in drought prone environments. Phys. Chem. Earth 27, 949–959. doi:10.1016/S1474-7065(02)00098-0

Rockstrom, J., Falkenmark, M., 2015. Increase water harvesting in Africa. Nature 8–10.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: Exploring the safe operating space for humanity. Ecol. Soc. 14. doi:10.5751/ES-03180-140232

Schwingshackl, C., Hirschi, M., Seneviratne, S.I., 2017. Quantifying Spatiotemporal Variations of Soil Moisture Control on Surface Energy Balance and Near-Surface Air Temperature. J. Clim. 30, 7105–7124. doi:10.1175/JCLI-D-16-

0727.1

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture-climate interactions in a changing climate: A review. Earth-Science Rev. 99, 125–161. doi:10.1016/j.earscirev.2010.02.004

Shashua-Bar, L., Potchter, O., Bitan, A., Boltansky, D., Yaakov, Y., 2010. Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel. Int. J. Climatol. 30, 44–57. doi:10.1002/joc.1869

Shuttleworth, W.J., 1993. Evaporation, in: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill Inc, New York, p. 4.1-4.5.3.

Singh, G., 2009. Soil water dynamics, growth of Dendrocalamus strictus and herbage productivity influenced by rainwater harvesting in Aravalli hills of Rajasthan. For. Ecol. Manage. 258, 2519–2528. doi:10.1016/J.FORECO.2009.09.008

Sriwongsitanon, N., Gao, H., Savenije, H.H.G., Maekan, E., Saengsawang, S., Thianpopirug, S., 2016. Comparing the Normalized Difference Infrared Index (NDII) with root zone storage in a lumped conceptual model. Hydrol. Earth Syst. Sci. 20, 3361–3377. doi:10.5194/hess-20-3361-2016

Stavi, I., Bel, G., Zaady, E., 2016. Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. Agron. Sustain. Dev. 36. doi:10.1007/s13593-016-0368-8

Stigter, C.J., 1984. Mulching as a traditional method of microclimate management. Arch. Meteorol. Geophys. Bioclimatol. Ser. B. doi:10.1007/BF02269417

Stigter, C.J., Oteng'I, S.B.B., Oluwasemire, K.O., Nasr Al-amin, N.K., Kinama, J.M., Onyewotu, L.O.Z., 2005. Recent answers to farmland degradation illustrated by case studies from african farming systems. Ann. Arid Zone 44, 255–276.

Suleman, S., Wood, M.K., Shah, B.H., Murray, L., 1995. Development of a rainwater harvesting system for increasing soil moisture in arid rangelands of PakistanRango, A., Havstad, K., 2009. RESEARCH ARTICLE: Water-Harvesting Applications for Rangelands Revisited. Environ. Pract. 11, 84–94. doi:DOI: 10.1017/S14. J. Arid Environ. 31, 471–481. doi:10.1016/S0140-1963(05)80130-2

Sultan, D., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Meshesha, D.T., Masunaga, T., Aklog, D., Fenta, A.A., Ebabu, K., 2018. Impact of Soil and Water Conservation Interventions on Watershed Runoff Response in a Tropical Humid Highland of Ethiopia. Environ. Manage. doi:10.1007/s00267-018-1005-x

Tianjiao, F., Wei, W., Liding, C., Keesstra, S.D., Yang, Y., 2018. Effects of land preparation and plantings of vegetation on soil moisture in a hilly loess catchment in China. L. Degrad. Dev. 29, 1427–1441. doi:10.1002/ldr.2867

Tomaszkiewicz, M., Abou Najm, M., Zurayk, R., El-Fadel, M., 2017. Dew as an adaptation measure to meet water demand in agriculture and reforestation. Agric. For. Meteorol. 232, 411–421. doi:10.1016/j.agrformet.2016.09.009

Tsirogiannis, I.L., Antoniadis, D., Katsoulas, N., Lykas, C., Christidou, V., Kitta, E., Kittas, C., 2015. Application of microclimatic landscape design in schoolyards in Greece. Acta Hortic.

Tsitoura, M., Michailidou, M., Tsoutsos, T., 2016. Achieving sustainability through the management of microclimate parameters in Mediterranean urban environments during summer. Sustain. Cities Soc. 26, 48–64. doi:https://doi.org/10.1016/j.scs.2016.05.006

Tubeileh, A., Bruggeman, A., Turkelboom, F., 2016. Water-harvesting designs for fruit tree production in dry environments. Agric. Water Manag. 165, 190–197. doi:10.1016/J.AGWAT.2015.11.006

UNEP, 2009. Rainwater harvesting: a lifeline for human well-being.

Valdivia, C., Seth, A., Gilles, J.L., García, M., Jiménez, E., Cusicanqui, J., Navia, F., Yucra, E., 2010. Adapting to climate change in Andean ecosystems: Landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. Ann. Assoc. Am. Geogr. 100, 818–834. doi:10.1080/00045608.2010.500198

Walraevens, K., Gebreyohannes Tewolde, T., Amare, K., Hussein, A., Berhane, G., Baert, R., Ronsse, S., Kebede, S., Van Hulle, L., Deckers, J., Martens, K., Van Camp, M., 2015. Water Balance Components for Sustainability Assessment of Groundwater-Dependent Agriculture: Example of the Mendae Plain (Tigray, Ethiopia). L. Degrad. Dev. 26, 725–736. doi:10.1002/ldr.2377

Wei, W., Chen, D., Wang, L., Daryanto, S., Chen, L., Yu, Y., Lu, Y., 2016. Global synthesis of the classifications, distributions, benefits and issues of terracing. Earth-Science Rev. 159, 388–403. doi:10.1016/j.earscirev.2016.06.010

Winkler, K., Gessner, U., Hochschild, V., 2017. Identifying droughts affecting agriculture in Africa based on remote sensing time series between 2000-2016: Rainfall anomalies and vegetation condition in the context of ENSO. Remote Sens. 9. doi:10.3390/rs9080831

Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer Van Garderen, E.R.M., Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Glob. Environ. Chang. 28, 325–336. doi:10.1016/j.gloenvcha.2013.12.002

Woldearegay, K., Tamene, L., Mekonnen, K., Kizito, F., Bossio, D., 2018. Fostering Food Security and Climate Resilience Through Integrated Landscape Restoration Practices and Rainwater Harvesting/Management in Arid and Semi-arid Areas of Ethiopia, in: Filho, W.L., de Trincheria Gomez, J. (Eds.), Rainwater-Smart Agriculture in Arid and Semi-Arid Areas: Fostering the Use of Rainwater for Food Security, Poverty Alleviation, Landscape Restoration and Climate Resilience. Springer International Publishing, pp. 37–57. doi:10.1007/978-3-319-66239-8

Wolka, K., Mulder, J., Biazin, B., 2018. Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review. Agric. Water Manag. 207, 67–79. doi:10.1016/j.agwat.2018.05.016

Zareie, S., Khosravi, H., Nasiri, A., Dastorani, M., 2016. Using Landsat Thematic Mapper (TM) sensor to detect change in land surface temperature in relation to land use change in Yazd, Iran. Solid Earth 7, 1551–1564. doi:10.5194/se-7-1551-2016

Annex A – Codes used in the thesis

Annex A.1 Code for WCI data download

Language type	Javascript
Platform	Google Earth Engine code editor

```
var enab =
ee.FeatureCollection("users/giuliocst/PhD_thesis/Enabered_cat
chment_ok"),
    l7_ndwi_8 =
ee.ImageCollection("LANDSAT/LE07/C01/T1_8DAY_NDWI"),
    chirps10 = ee.ImageCollection("UCSB-CHG/CHIRPS/PENTAD");

Map.addLayer(enab, {color: 'FF0000'}, 'colored');
Map.centerObject(enab, 14);

var f_ndwi = ee.ImageCollection(
l7_ndwi_8.filterDate('2000-01-01', '2017-12-31')
);

var f_chirps = ee.ImageCollection(
chirps10.filterDate('2000-01-01', '2017-12-31')
);

  print(ui.Chart.image.series({
  imageCollection:f_ndwi,
  region: enab,
  reducer: ee.Reducer.mean(),
  scale: 30
}).setOptions({title: 'Landsat-7 NDWI Time Series'}));

  print(ui.Chart.image.series({
  imageCollection:f_chirps,
  region: enab,
  reducer: ee.Reducer.mean(),
}).setOptions({title: 'CHIRPS decadal data'}));
```

Annex B.1 Code for LST and t data download

Language type	Javascript
Platform	Google Earth Engine code editor

```
var enab =
ee.FeatureCollection("users/giuliocst/PhD_thesis/Enabered_cat
chment_ok"),
    modis_t_1330_8d =
ee.ImageCollection("MODIS/006/MYD11A2");

  print(ui.Chart.image.series({
  imageCollection:modis_t_1330_8d.select('LST_Day_1km'),
  region: enab,
  reducer: ee.Reducer.mean(),
}).setOptions({title:  'MODIS  Aqua  LST  at  13:30  (8  Days
composite)'}));
```

Language type	Python
Platform	Idle -to download T850 (and T500) data from ECMWF Web-API

```
#!/usr/bin/env python
from ecmwfapi import ECMWFDataServer
server = ECMWFDataServer()
server.retrieve({
    "class": "ei",
    "dataset": "interim",
    "date": "2000-01-01/to/2017-12-31",
    "expver": "1",
    "grid": "0.75/0.75",
    "levelist": "500/850",
    "levtype": "pl",
    "param": "130.128",
    "step": "0",
    "stream": "oper",
    "time": "00:00:00/06:00:00/12:00:00/18:00:00",
    "type": "an",
    "target": "output",
    "area":"14.2/38.90/14.16/38.95",
    "format":"netcdf",
})
```

Language type	Python

Platform	Idle -to download surface solar radiation downwards data from ECMWF Web-API

```
#!/usr/bin/env python
from ecmwfapi import ECMWFDataServer
server = ECMWFDataServer()
server.retrieve({
    "class": "ei",
    "dataset": "interim",
    "date": "2000-01-01/to/2017-12-31",
    "expver": "1",
    "grid": "0.75/0.75",
    "levtype": "sfc",
    "param": "169.128",
    "step": "12",
    "stream": "oper",
    "time": "00:00:00/12:00:00",
    "type": "fc",
    "target": "output.nc",
    "area":"14.2/38.90/14.16/38.95",
    "format":"netcdf",
})
```