Mesoclimatic Regulation Induced by Landscape Restoration and Water Harvesting in Agroecosystems of the Horn of Africa

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Agroecosystems: communities of plants and animals interacting with their physical and chemical environments that have been modified by people to produce food, fiber, fuel and other products for human consumption and processing (Altieri, 2002).

Agroecosystems offer a myriad of possibilities for the implementation of new practices and management techniques, larger than other ecosystems. Agroecosystems management can be shifted on agricultural production AND Ecosystems services provision with relatively small changes (DeClerck et al., 2016).

Landscape Restoration/Water Harvesting (LRWH)

**Water Harvesting** is the process of concentrating precipitation through runoff and storing it for beneficial use (Critchley et al., 1991)

It is key to **cope with water scarcity** for both sustaining agricultural production (Rockström et al., 2002) and **restore degraded landscapes** (Oweis, 2017).

The main effect of LRWH is to **retain rain water and runoff** in an **Agroecosystem**, in open storage reservoirs, in the soil or for aquifer recharge.


Soil Moisture-Temperature Coupling (SMTC)

Soil moisture ($\theta$) can influence near surface air-temperature ($T$) (Schwingshackl et al., 2017, and cited literature)

$$LH + SH + G = R_{net}$$

LH – Latent Heat flux  
SH – Sensible Heat flux  
G – Ground heat flux  
$R_{net}$ – Net incoming Radiation

Feedback “dry”: $\theta \downarrow$ LH $\downarrow$ SH $\uparrow$ T $\uparrow$  
Feedback “wet”: $\theta \uparrow$ LH $\uparrow$ SH $\downarrow$ T $\downarrow$

Taken from Schwingshackl et al. (2017)
Soil Moisture-Temperature Coupling (SMTC)

Soil moisture deficit - heat waves feedback has been largely discussed and documented:

Hirschi et al. (2014) SMTC dynamics are mostly evident when considering root-zone soil moisture (evaluated with SPI), rather than surface soil moisture (~5-10 cm, evaluated with remote sensing)

Mostly evident in locations with Transitional Soil moisture and evapotranspiration regimes Regions including Sahelian areas and Mediterranean climates.


Taken from Schwingshackl et al. (2017)
Problem Statement

- Many studies have been carried out on the increase of soil moisture given by LRWH, but at local level and/or with modelling. A data-based assessment on possibility of storing water at landscape (agroecosystem) level with LRWH is still lacking.

- Studies on agricultural microclimate, and on meso-climate at urban and forest scale have been realised. Few studies on meso-climatic modification at agroecosystem scale are present.

- Studies demonstrate how SMTC affects continent and regional level heatwaves. Can it be used in a proactive way (meso-climate modification)?
Research Question

Mueller and Seneviratne (2012)
Hirschi et al. (2014)
Schwingshackl et al. (2017)
Case Study

**Enabered Watershed**, Adwa district, Tigray Region, Ethiopia.

Between 38°53’ to 38°57’E and 14°08’ to 14°11’N

**Elevations**: from 1,850 to 2,540 m a.s.l.

Average annual precipitation (1998-2008): 742 mm
Average daily temperature (1998-2008): 19.8 °C
Rainy season: **June-September** (85% of rainfall)

**Transitional soil moisture and evapotranspiration regime**

LRWH interventions implemented between **2004 and 2008**

Haregeweyn et al. (2012) reported the **full list of the techniques implemented in the area**
### Extent of LRWH

<table>
<thead>
<tr>
<th>Type of LRWH</th>
<th>Unit</th>
<th>Hillside</th>
<th>Gully</th>
<th>Cultivated and grazing land</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical measures</td>
<td>ha</td>
<td>1,108</td>
<td>8</td>
<td>1,036</td>
<td>2,152</td>
</tr>
<tr>
<td>Stone-faced bunds with trench</td>
<td>km</td>
<td>135</td>
<td></td>
<td></td>
<td>135</td>
</tr>
<tr>
<td>Stone and soil bunds</td>
<td>km</td>
<td>472</td>
<td></td>
<td>205</td>
<td>677</td>
</tr>
<tr>
<td>Deep trenches</td>
<td>km</td>
<td>1,592</td>
<td></td>
<td></td>
<td>1,592</td>
</tr>
<tr>
<td>Trenches</td>
<td>km</td>
<td></td>
<td>555</td>
<td></td>
<td>555</td>
</tr>
<tr>
<td>Loose-stone check dams</td>
<td>m³</td>
<td>38,999</td>
<td>23,150</td>
<td></td>
<td>62,149</td>
</tr>
<tr>
<td>Gabion check dams</td>
<td>m³</td>
<td></td>
<td>20,231</td>
<td></td>
<td>20,231</td>
</tr>
<tr>
<td>Retention walls</td>
<td>km</td>
<td>0.5</td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Sediment storage dams</td>
<td>m³</td>
<td></td>
<td>498</td>
<td></td>
<td>498</td>
</tr>
<tr>
<td>Microbasins</td>
<td>no.</td>
<td>50,629</td>
<td></td>
<td></td>
<td>50,629</td>
</tr>
<tr>
<td>Gully reshaping</td>
<td>m³</td>
<td></td>
<td></td>
<td>90,788</td>
<td>90,788</td>
</tr>
<tr>
<td>Pond construction</td>
<td>no.</td>
<td></td>
<td>10</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Bund stabilization</td>
<td>km</td>
<td></td>
<td></td>
<td>516</td>
<td>516</td>
</tr>
<tr>
<td>Biological measures</td>
<td>ha</td>
<td>1,201</td>
<td>28</td>
<td>635</td>
<td>1,931</td>
</tr>
<tr>
<td>Exclosures</td>
<td>ha</td>
<td>601</td>
<td></td>
<td></td>
<td>601</td>
</tr>
<tr>
<td>Grass/split planting</td>
<td>ha</td>
<td></td>
<td>8</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Grass sowing</td>
<td>ha</td>
<td>545</td>
<td>5</td>
<td>308</td>
<td>850</td>
</tr>
<tr>
<td>Enrichment plantations</td>
<td>ha</td>
<td>55</td>
<td>8</td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>Fruit trees</td>
<td>ha</td>
<td>2</td>
<td>7</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Forage trees</td>
<td>ha</td>
<td></td>
<td>8</td>
<td>320</td>
<td>400</td>
</tr>
</tbody>
</table>

Taken from Haregeweyn et al. (2012)
Materials and Methods: Water Conservation Index (WCI)

\[
WC_i(y) = \frac{100}{R_{rs}(y)} \frac{NDI_i(y)}{NDI_i(y)}
\]

- **WC\(_i\)(y)** - WCI for the \(i\)-th month of the year \(y\)
- **\(R_{rs}(y)\)** - rainfall in the rainy season (June-August) in the year \(y\) (mm), from CHIRPS dataset (Funk et al., 2015);
- **\(NDI_i(y)\)** - Normalised Difference Infrared Index for the \(i\)-th month of the year \(y\)

\[
NDI = \frac{\rho_B - \rho_B}{\rho_B + \rho_B}
\]

- **\(\rho_B\)** - reflectance in **Landsat 7 ETM+** sensor Band 4 (0.77-0.90 \(\mu\)m)
- **\(\rho_B\)** - reflectance in **Landsat 7 ETM+** sensor Band 5 (1.55-1.75 \(\mu\)m)
- **NDII** - ‘**Landsat 7 Collection 1 Tier 1 8-Day NDWI Composite**’ on Google Earth Engine (Gorelick et al., 2017). **De facto** NDII
Materials and Methods: Water Conservation Index (WCI)

\[ WC_i(y) = 100 \frac{NDI_i(y)}{Rs(y)} \]

- WCI time series calculated for respectively for the months of September (WCI₉), October (WCI₁₀) and November (WCI₁₁), ranging from 2000 to 2017.
- Data "Before full LRWH implementation": 2000-2008
- Data “After full LRWH implementation”: 2009-2017
- Good accordance for values of NDII and root-zone soil moisture during the dry season (Sriwongsitanon et al., 2016) \([R^2 = 0.87]\)

Materials and Methods: Normalised temperature index (t)

\[ t_i(y) = \frac{L_S\ i(y)}{T_{85\ i(y)}} \]

\( T \)
- \( L_S\ i(y) \), average Land Surface Temperature (°C) for the i-th month of the year y obtained from MODIS MYD11A2.006 Aqua Land Surface Temperature and Emissivity 8-Day Global at 1 km from Google Earth Engine (NASA LP DAAC, 2018).
- \( T_{85\ i(y)} \) - average the temperature at 850 hPa at 12:00 a.m. (°C) obtained from ERA-INTERIM climatic reanalysis dataset (Balsamo et al., 2015)
- Data ”Before full LRWH implementation”: 2002-2008
- Data “After full LRWH implementation”: 2009-2017

Materials and Methods: SMTC

Based on the framework of Schwingshackl et al. (2017):

\[
\frac{\partial T}{\partial \theta} = \frac{\partial T_F}{\partial E} \frac{\partial E}{\partial \theta}
\]

With a proxy approach:

\[
\frac{\partial t}{\partial WCI}
\]

To detect possible lag effects, two version of a 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).
Results: Water Conservation Index (WCI)

<table>
<thead>
<tr>
<th></th>
<th>September</th>
<th>October</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCI Average 2000-2008</td>
<td>0.235 (0.028)</td>
<td>0.134 (0.049)</td>
<td>0.016 (0.044)</td>
</tr>
<tr>
<td>WCI Average 2009-2017</td>
<td>0.325 (0.038)</td>
<td>0.221 (0.095)</td>
<td>0.045 (0.034)</td>
</tr>
<tr>
<td>WCI Difference before and after full implementation</td>
<td>0.090</td>
<td>0.087</td>
<td>0.029</td>
</tr>
<tr>
<td>WCI Difference before and after full implementation (%)</td>
<td>38%</td>
<td>65%</td>
<td>181%</td>
</tr>
<tr>
<td>P-value, test on differences</td>
<td>0.00047</td>
<td>0.08330</td>
<td>0.21833</td>
</tr>
<tr>
<td>Statistical significance</td>
<td>&gt; 99%</td>
<td>91%</td>
<td>78%</td>
</tr>
</tbody>
</table>
Results: LST
Results: LST
# Results: LST

<table>
<thead>
<tr>
<th>Month</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average LST (2002-2008)</td>
<td>28.13</td>
<td>33.24</td>
<td>35.45</td>
<td>35.68</td>
</tr>
<tr>
<td>Average LST (2009-2017)</td>
<td>27.48</td>
<td>31.94</td>
<td>34.10</td>
<td>34.89</td>
</tr>
<tr>
<td>Average LST (2010-2017)</td>
<td>26.89</td>
<td>31.49</td>
<td>33.73</td>
<td>34.85</td>
</tr>
<tr>
<td>Difference LST (2002-2008) – LST (2009-2017)</td>
<td>0.65</td>
<td>1.30</td>
<td>1.35</td>
<td>0.80</td>
</tr>
<tr>
<td>Difference LST (2002-2008) – LST (2010-2017)</td>
<td>1.24</td>
<td>1.74</td>
<td>1.72</td>
<td>0.84</td>
</tr>
</tbody>
</table>
Results: Normalised temperature index (t)

<table>
<thead>
<tr>
<th>Month</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average t (2002-2008)</td>
<td>1.132 (0.057)</td>
<td>1.254 (0.017)</td>
<td>1.357 (0.055)</td>
<td>1.387 (0.036)</td>
</tr>
<tr>
<td>Average t (2009-2017)</td>
<td>1.072 (0.068)</td>
<td>1.174 (0.066)</td>
<td>1.281 (0.065)</td>
<td>1.357 (0.039)</td>
</tr>
<tr>
<td>p-value</td>
<td>0.083</td>
<td>0.008</td>
<td>0.030</td>
<td>0.266</td>
</tr>
<tr>
<td>Statistical significance</td>
<td>90 %</td>
<td>&gt; 99 %</td>
<td>&gt; 95 %</td>
<td>73 %</td>
</tr>
<tr>
<td>Difference t (2002-2008) - t (2009-2017)</td>
<td>0.06</td>
<td>0.08</td>
<td>0.076</td>
<td>0.03</td>
</tr>
<tr>
<td>Relative difference</td>
<td>5%</td>
<td>6%</td>
<td>6%</td>
<td>2%</td>
</tr>
</tbody>
</table>
Results: SMTC at catchment scale

(a) WCI₉ - t₉

\[ y = -0.558x + 1.2573 \]
\[ R^2 = 0.2745 \]

(b) WCI₉ - t₁₀

\[ y = -0.75x + 1.4229 \]
\[ R^2 = 0.5653 \]

(c) WCI₁₀ - t₁₀

\[ y = -0.432x + 1.2857 \]
\[ R^2 = 0.4657 \]

(d) WCI₁₀ - t₁₁

\[ y = -0.2342x + 1.3561 \]
\[ R^2 = 0.1211 \]

(e) WCI₁₁ - t₁₁

\[ y = -0.7698x + 1.3321 \]
\[ R^2 = 0.2717 \]
Results: SMTC at catchment scale

(a) WCI₀ - t₀
\[ y = -0.558x + 1.2573 \]
\[ R^2 = 0.2745 \]

(b) WCI₀ - t₁₀
\[ y = -0.75x + 1.4229 \]
\[ R^2 = 0.5653 \]

(c) WCI₁₀ - t₁₀
\[ y = -0.4324x + 1.2857 \]
\[ R^2 = 0.4657 \]

(d) WCI₁₀ - t₁₁
\[ y = -0.2342x + 1.3561 \]
\[ R^2 = 0.1211 \]

(e) WCI₁₁ - t₁₁
\[ y = -0.7698x + 1.3321 \]
\[ R^2 = 0.2717 \]
Results: SMTC at catchment scale

- Highest SMTC is the one characterised by the relation $t_{10} = f(WCI_9)$.

- Separation of populations, except 2009
Results: SMTC at catchment scale

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Results: SMTC at catchment scale

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Results: SMTC at catchment scale

- Highest SMTC is the one characterised by the relation $t_{10} = f (WCI_9)$.

- **Separation of populations**, except 2009

- Coupling of the root zone soil moisture conserved at catchment scale in September and the catchment average temperature in October.

- Soil moisture available in September is depleted as evapotranspiration from September to October.

- **1-month lag** can be expected (up to three months for heatwaves in central Europe)
Results: SMTC at catchment scale

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

- Without 2009, decrease in LST is of 1.74 °C

- 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.

Discussion

- **High LST and t in 2009**: despite the coupling dynamics, the soil moisture available at catchment scale in September 2009 was not sufficient to provide enough LH.

- LRWH interventions contributed to lower the average temperatures at the watershed scale, their influence can be limited in the case of extreme events.

- **Similar** to the role of water harvesting as a mean to deal with water scarcity: more effective in bridging short **dry spells of 5 to 15 days**, that represent the first source of crop failure, rather than allowing to **buffer prolonged droughts** (Rockström et al., 2002).
Conclusions and further developments

- LRWH enhance the water 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.
- 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, with 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).
- SMTC is evident at catchment scale.
- 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).

The implementation of LRWH measures provided a climate regulation effect in the watershed.
Conclusions and further developments

Further Developments

Analysis of the evidence of similar dynamics in other regions of the world.

Use of more advanced remote sensing datasets such as the recent Sentinel-2 imagery, but available only from 2015.

Downscaling of global (Schwingshackl et al., 2017) or regional (Mohamed et al., 2005) size modelling tools.

Investments in long-term experiments for the analysis of SMTC at catchment scale may be considered if further studies will confirm this initial one.
Thank You

Mesoclimatic Regulation Induced by Landscape Restoration and Water Harvesting in Agroecosystems of the Horn of Africa

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Limitations of the analysis

LRWH in the catchment was implemented **between** 2004 and 2008. Some other interventions may be implemented afterwards

- Some interventions could have an actual effect in **some years after the implementation**
- In 2008 ALL infrastructures were in place and functioning
- **After 2008: minor interventions**

**Proxy approach with LST and NDII**

- Most of the catchments where LRWH is implemented recently are **often ungauged**
- NDII has good accordance with **root-zone soil moisture**
- LST is often used in landscape studies (e.g. urban environments)