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

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Photography encouraged

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Agroecosystems

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).

Altieri, M.A., 2002 Agroecology The science of natural resource management for poor farmers in marginal environments Agric. Ecosyst. Environ., 93 (2002), pp. 1-24
DeClerck, F.A.J., et al., 2016. Agricultural ecosystems and their services: the vanguard of sustainability? Curr. Opin. Environ. Sustain

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).

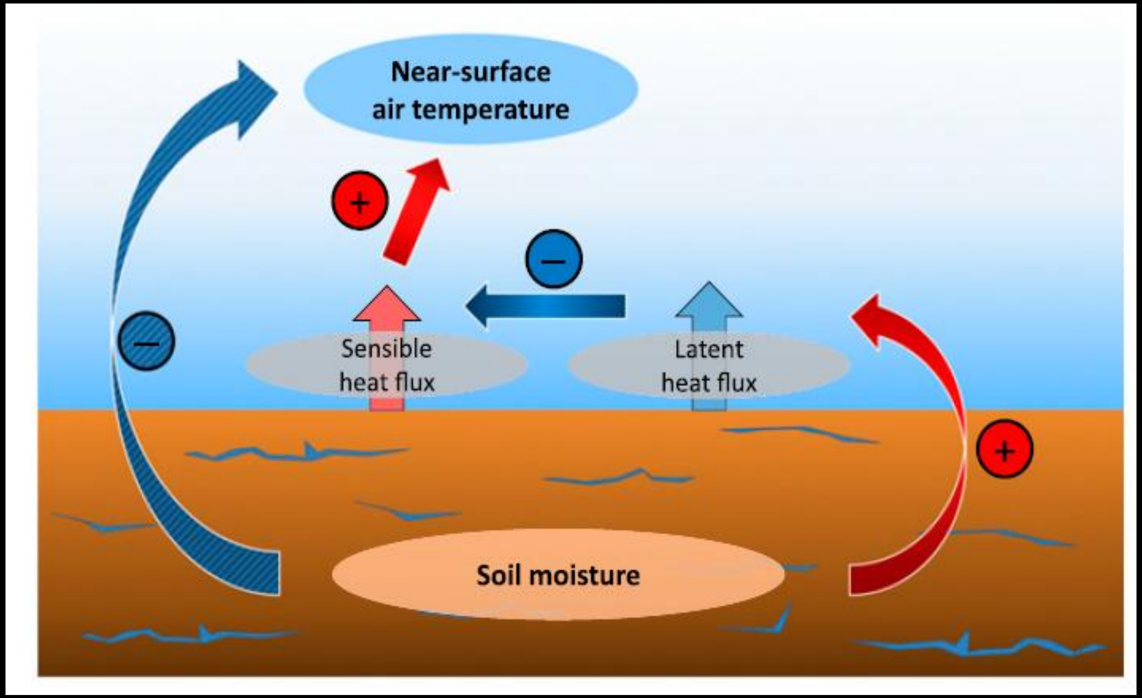
The main effect of LRWH is to **retain rain water and runoff** in an **Agroecosystem**, in open storage reservoirs, in the soil or for aquifer recharge.

Critchley, W., et al. 1991. Water harvesting (AGL/MISC/17/91). FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome, Italy.
Rockström, J., et al., 2002. Rainwater management for increased productivity among small-holder farmers in drought prone environments. Phys. Chem. Earth 27, 949–959.
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.

Soil Moisture-Temperature Coupling (SMTC)

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

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



Taken from Schwingshackl et al. (2017)

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

Feedback “dry”: θ↓ LH↓ SH↑ T↑
Feedback “wet”: θ↑ LH↑ SH↓ T↓

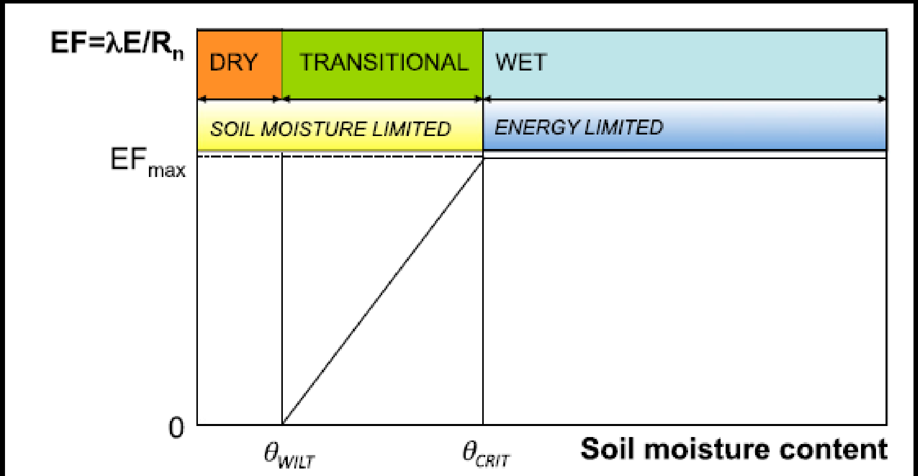
Schwingshackl, C., et al., 2017. Quantifying Spatiotemporal Variations of Soil Moisture Control on Surface Energy Balance and Near-Surface Air Temperature. J. Clim. 30, 7105–7124

Soil Moisture-Temperature Coupling (SMTC)

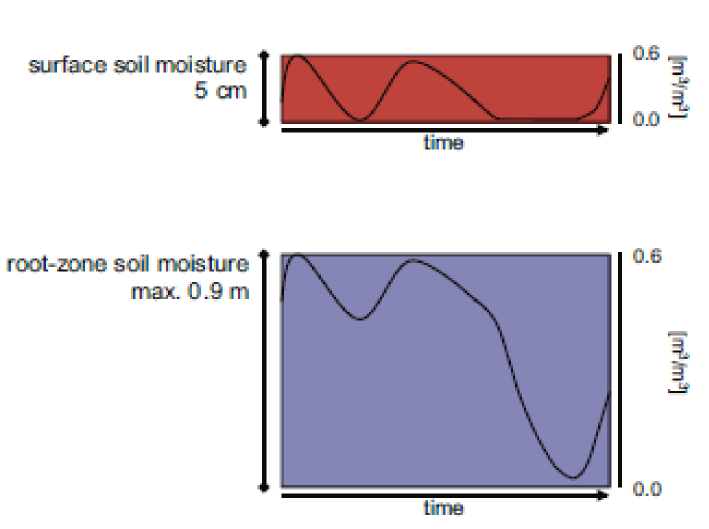
Soil moisture deficit - heat waves feedback has been largely discussed and documented:

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)



Taken from
Hirschi et al. (2014)

Hirschi, M., et al., 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.

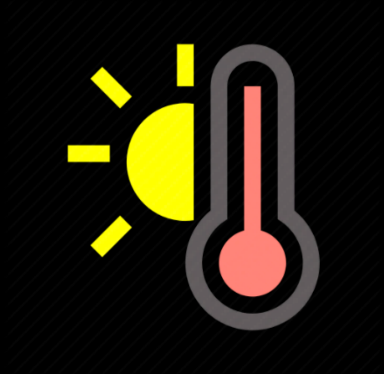
Problem Statement

- 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.

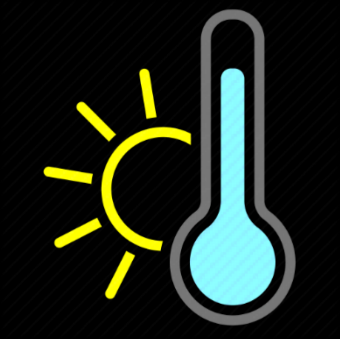
- Studies on agricultural microclimate, and on meso-climate at urban and forest scale have been realised. Few studies on **meso-climatic modification at agroecosystem** scale are present.

- 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)



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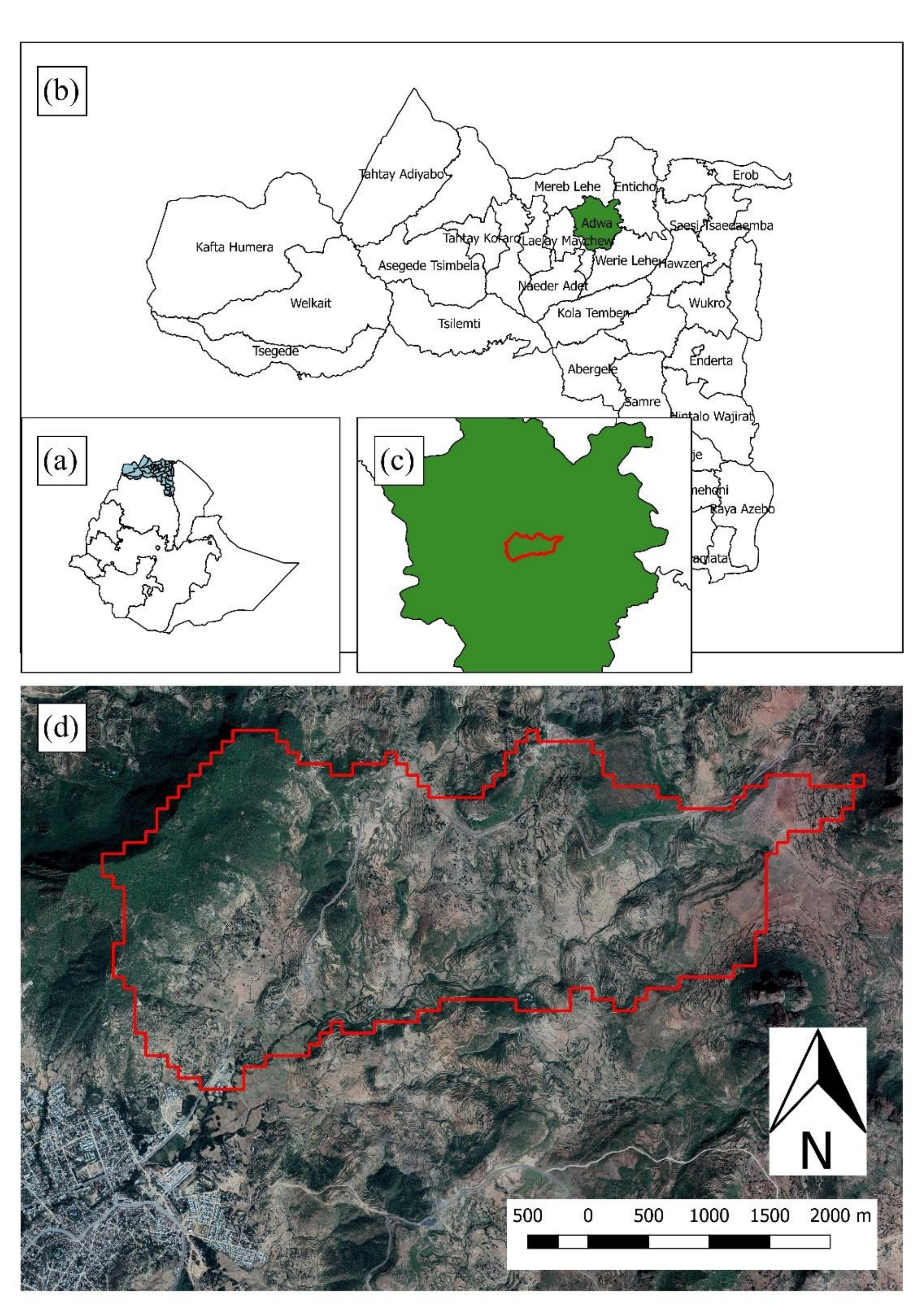


Case Study

Enabered Watershed, Adwa district, Tigray Region, Ethiopia.

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

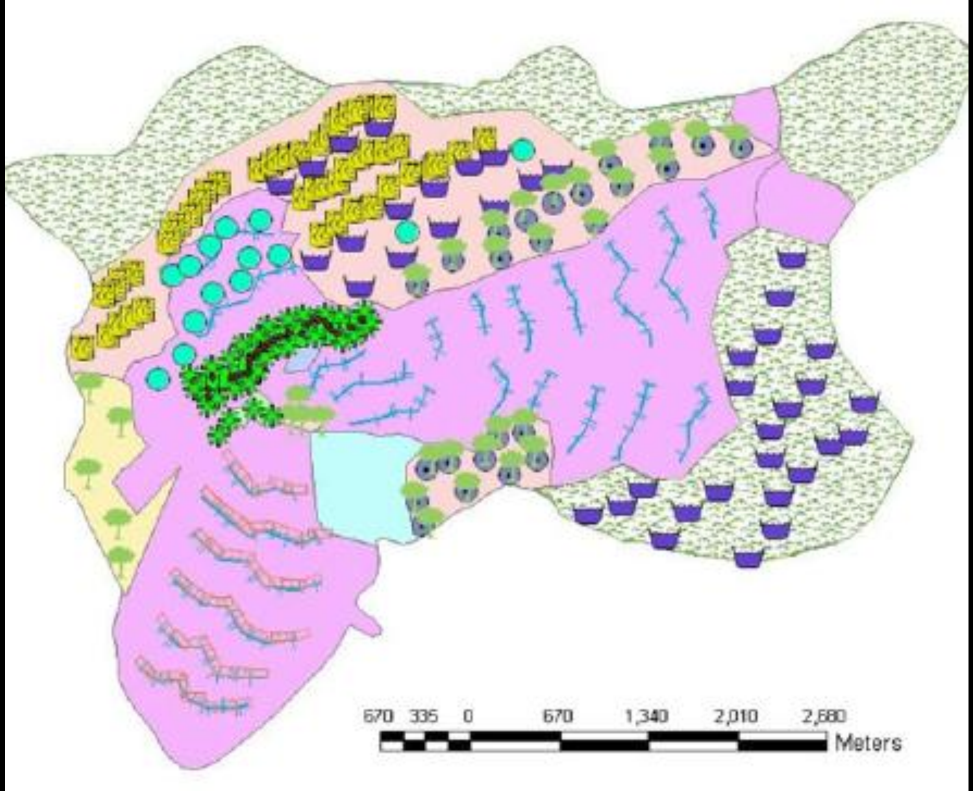
Elevations: from 1,850 to 2,540 m a.s.l.

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**



Taken from 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

Materials and Methods: Water Conservation Index (WCI)

$$WCI_i(y) = 100\,\frac{NDII_i(y)}{R_{rs}(y)}$$

- **WCI_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);
- **$NDII_i$ (y)** -Normalised Difference Infrared Index for the i-th month of the year y

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

- ρ_{B4} - reflectance in **Landsat 7 ETM+** sensor Band 4 (0.77-0.90 µm)
- ρ_{B5} - reflectance in **Landsat 7 ETM+** sensor Band 5 (1.55-1.75 µm)
- 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)

$$WCI_i(y) = 100 \, \frac{NDII_i(y)}{R_{rs}(y)}$$

- WCI time series calculated for respectively for the months of **September (WCI_9), October (WCI_{10}) and November (WCI_{11}),** 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) [$R^2 = 0.87$]

Funk, C., et al., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066.
Gorelick, N.,et al., 2017. Remote Sensing of Environment Google Earth Engine : Planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27.
Sriwongsitanon, N., et al., 2016. Comparing the Normalized Difference Infrared Index (NDII) with root zone storage in a lumped conceptual model. Hydrol. Earth Syst. Sci. 20, 3361–3377.

Materials and Methods: Normalised temperature index (t)

$$t_i(y) = {LST_i(y)} / {T_{850,i}(y)}$$

- $\boldsymbol{LST_i(y)}$, average Land Surface Temperature (°C) for the i-th month of the year y

  MODIS MYD11A2.006 Aqua Land Surface Temperature and Emissivity 8-Day Global at 1 km from Google Earth Engine (NASA LP DAAC, 2018).
- $\boldsymbol{T_{850,i}(y)}$ - 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

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).
Balsamo, G.,et al,, 2015. ERA-Interim/Land: A global land surface reanalysis data set. Hydrol. Earth Syst. Sci. 19, 389–407.

Materials and Methods: SMTC

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

$$\frac{\partial T}{\partial \theta} = \frac{\partial T_F}{\partial E}\frac{\partial E^F}{\partial \theta}$$

With a proxy approach:

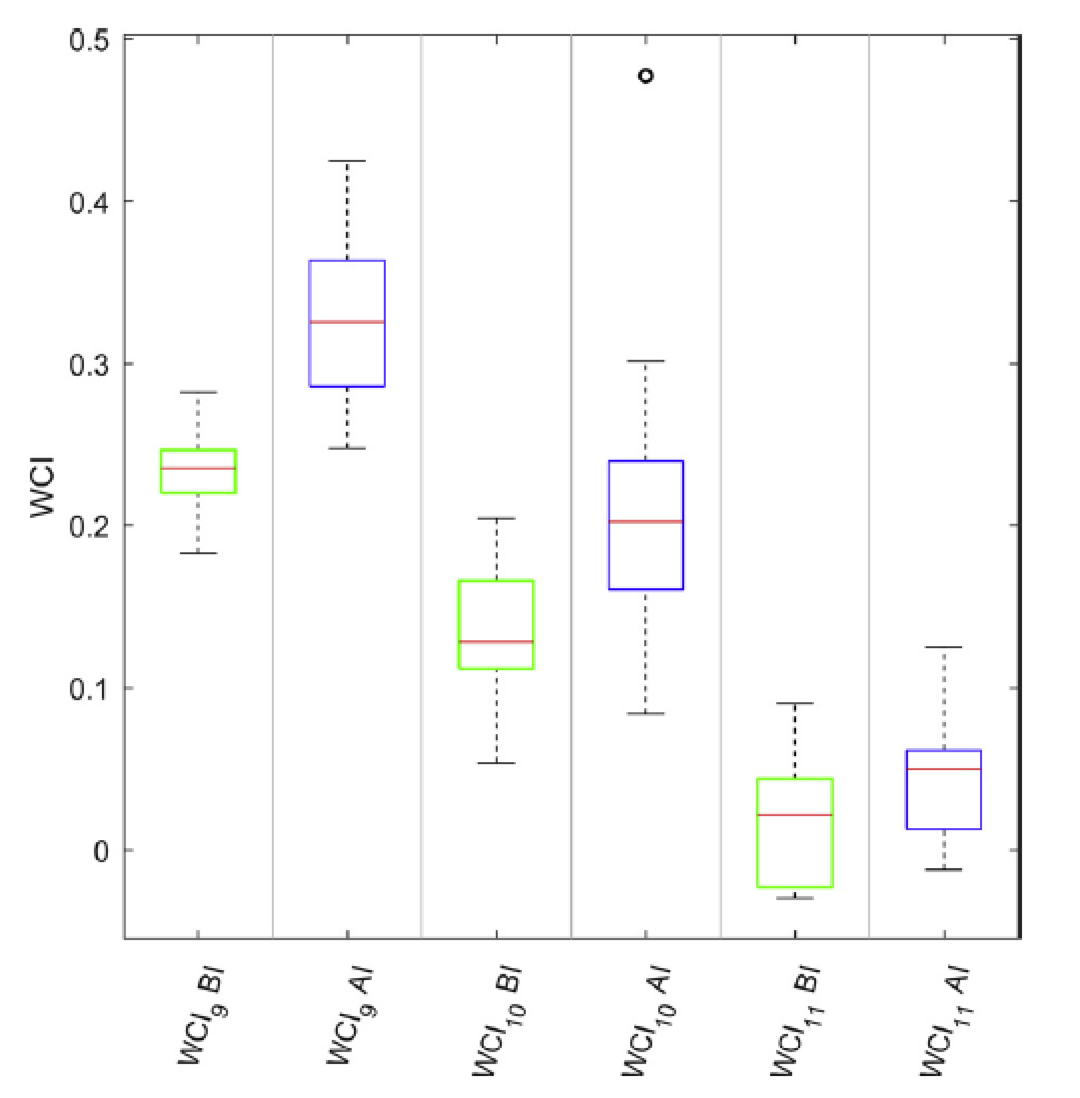
$$\partial \mathrm{t} / \partial \mathrm{WCI}$$

To detect possible lag effects, two version of a linear model have been investigated:

(i) $\mathrm{t_i = f(WCI_{i\text{-}1})}$ (with lag of one month);

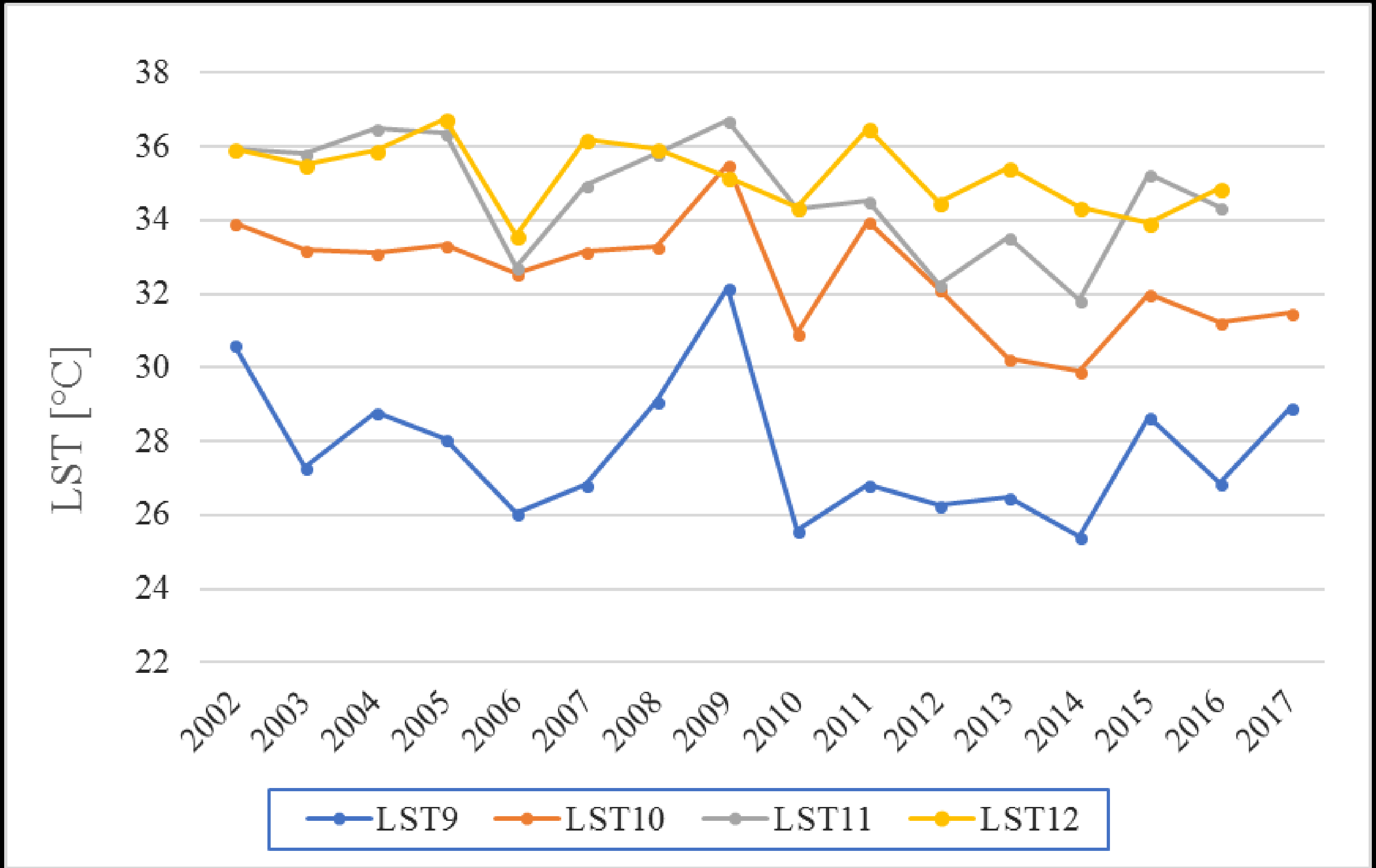
(ii) $\mathrm{t_i = f(WCI_i)}$ (without lag).

Results: Water Conservation Index (WCI)



	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%

Results: LST



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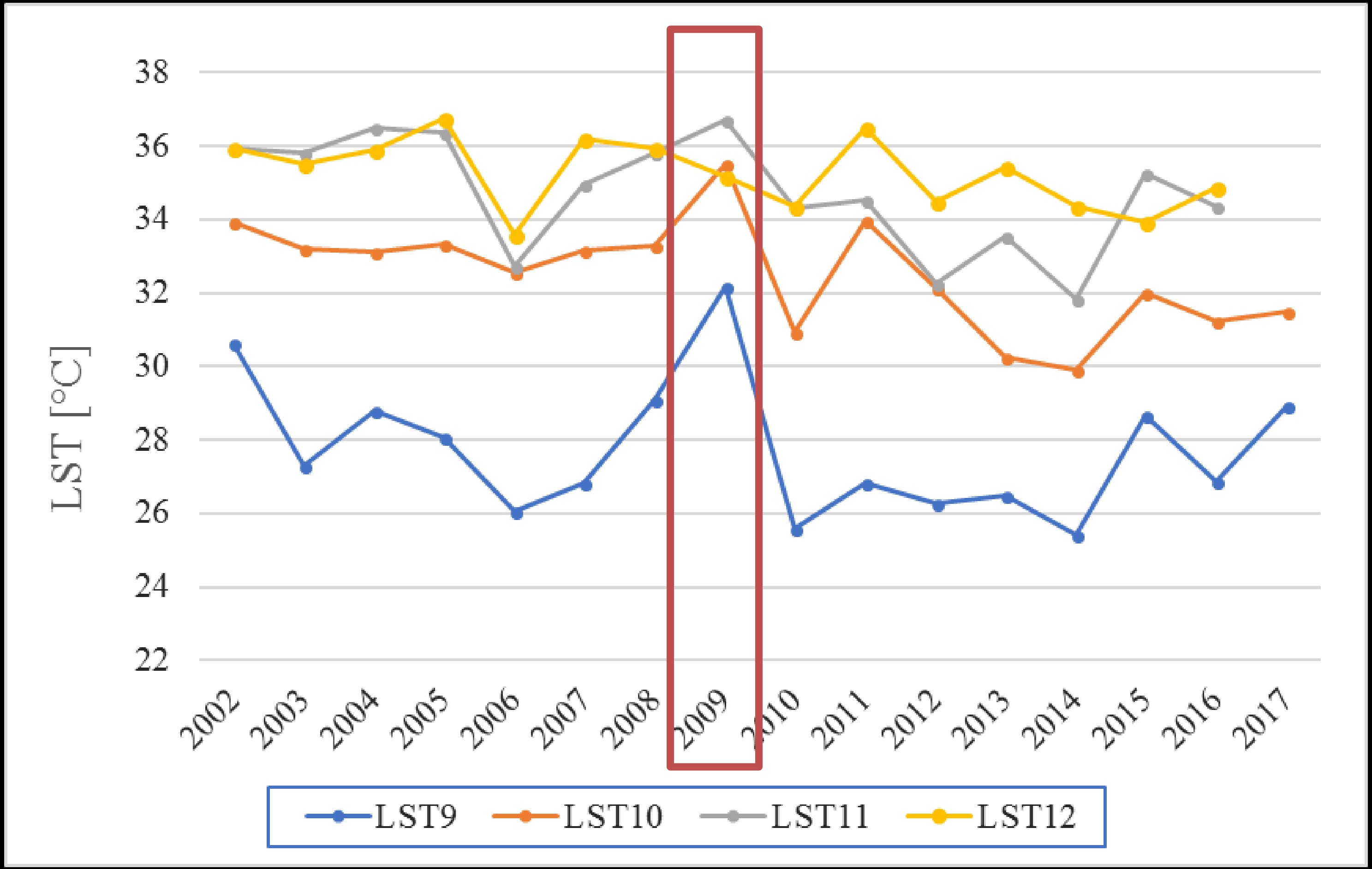
Results: LST



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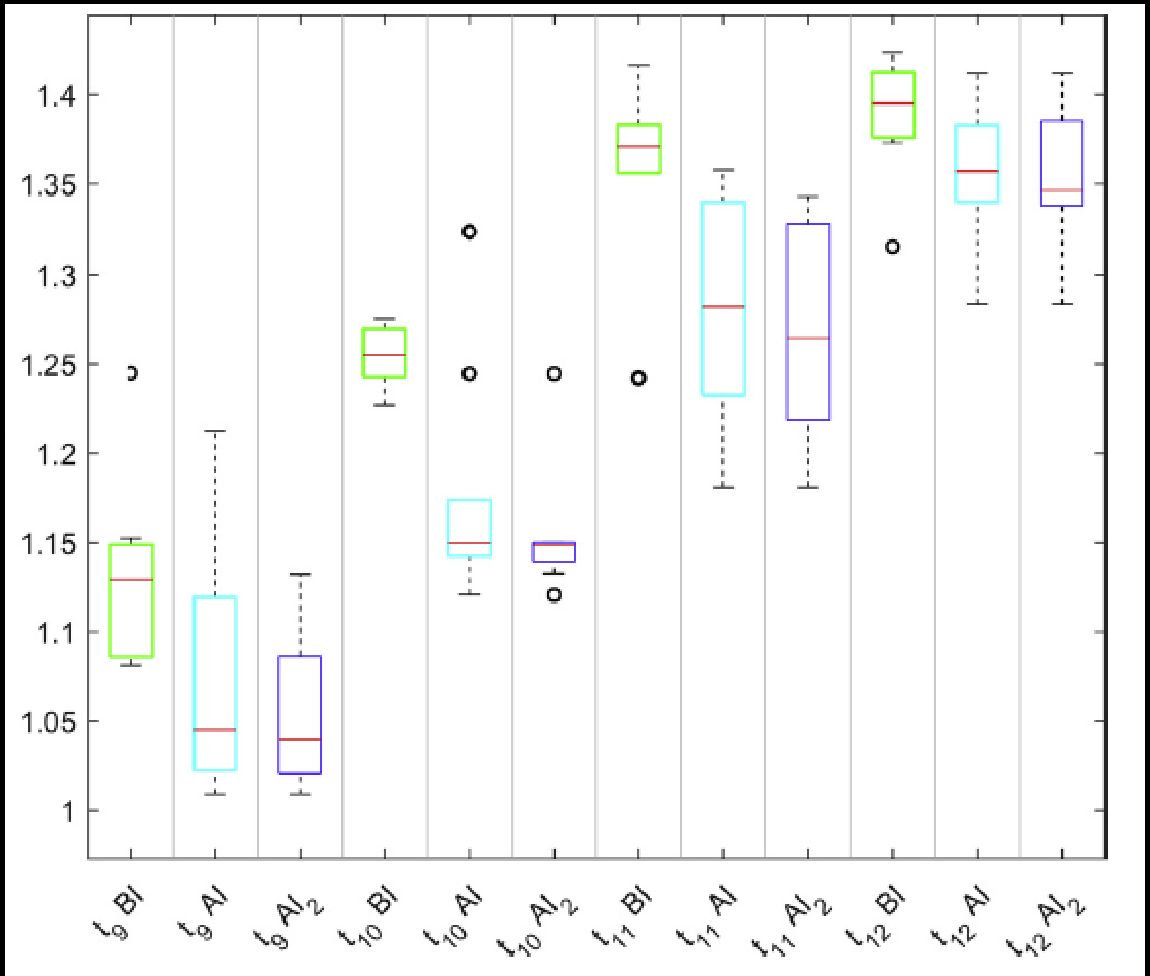
LST10
LST11
LST12

Results: LST

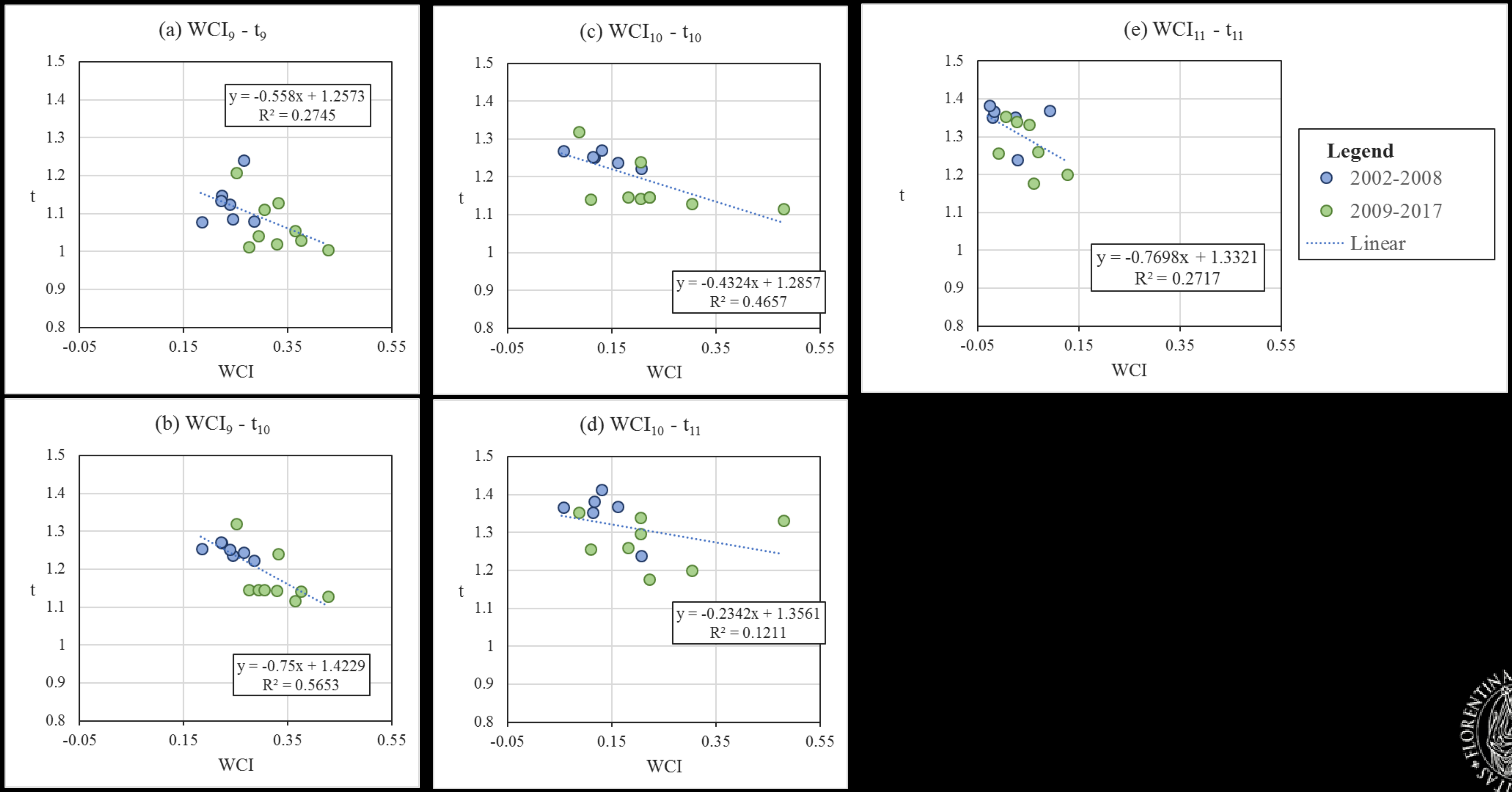
Month	September	October	November	December
Average LST (2002-2008)	28.13	33.24	35.45	35.68
Average LST (2009-2017)	27.48	31.94	34.10	34.89
Average LST (2010-2017)	26.89	31.49	33.73	34.85
Difference LST (2002-2008) – LST (2009-2017)	0.65	1.30	1.35	0.80
Difference LST (2002-2008) – LST (2010-2017)	1.24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

Results: Normalised temperature index (t)

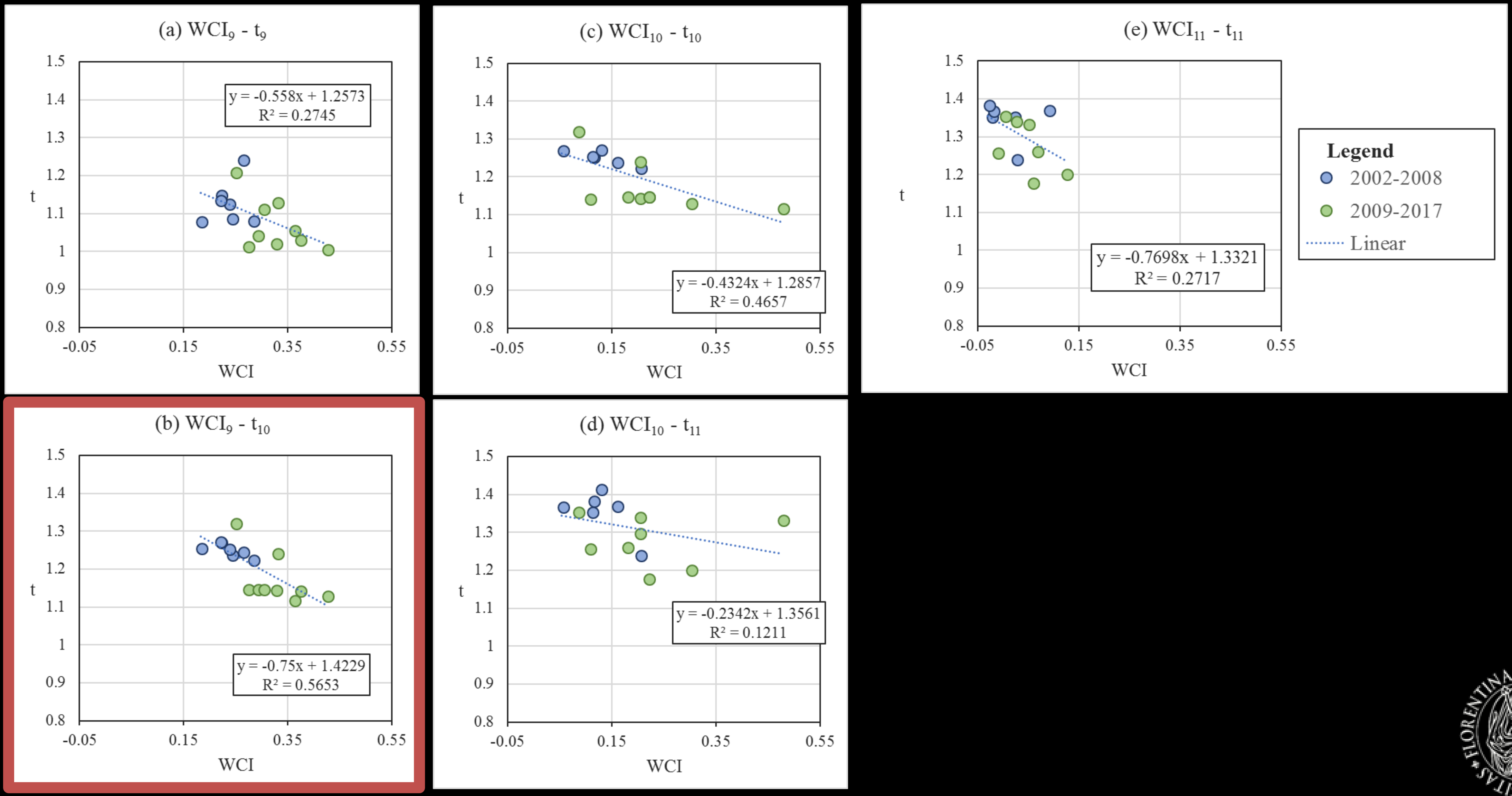


Month	September	October	November	December
Average t (2002-2008)	1.132 (0.057)	1.254 (0.017)	1.357 (0.055)	1.387 (0.036)
Average t (2009-2017)	1.072 (0.068)	1.174 (0.066)	1.281 (0.065)	1.357 (0.039)
p-value	0.083	0.008	0.030	0.266
Statistical significance	**90 %**	**> 99 %**	**> 95 %**	**73 %**
Difference t (2002-2008) – t (2009-2017)	0.06	0.08	0.076	0.03
Relative difference	5%	6%	6%	2%

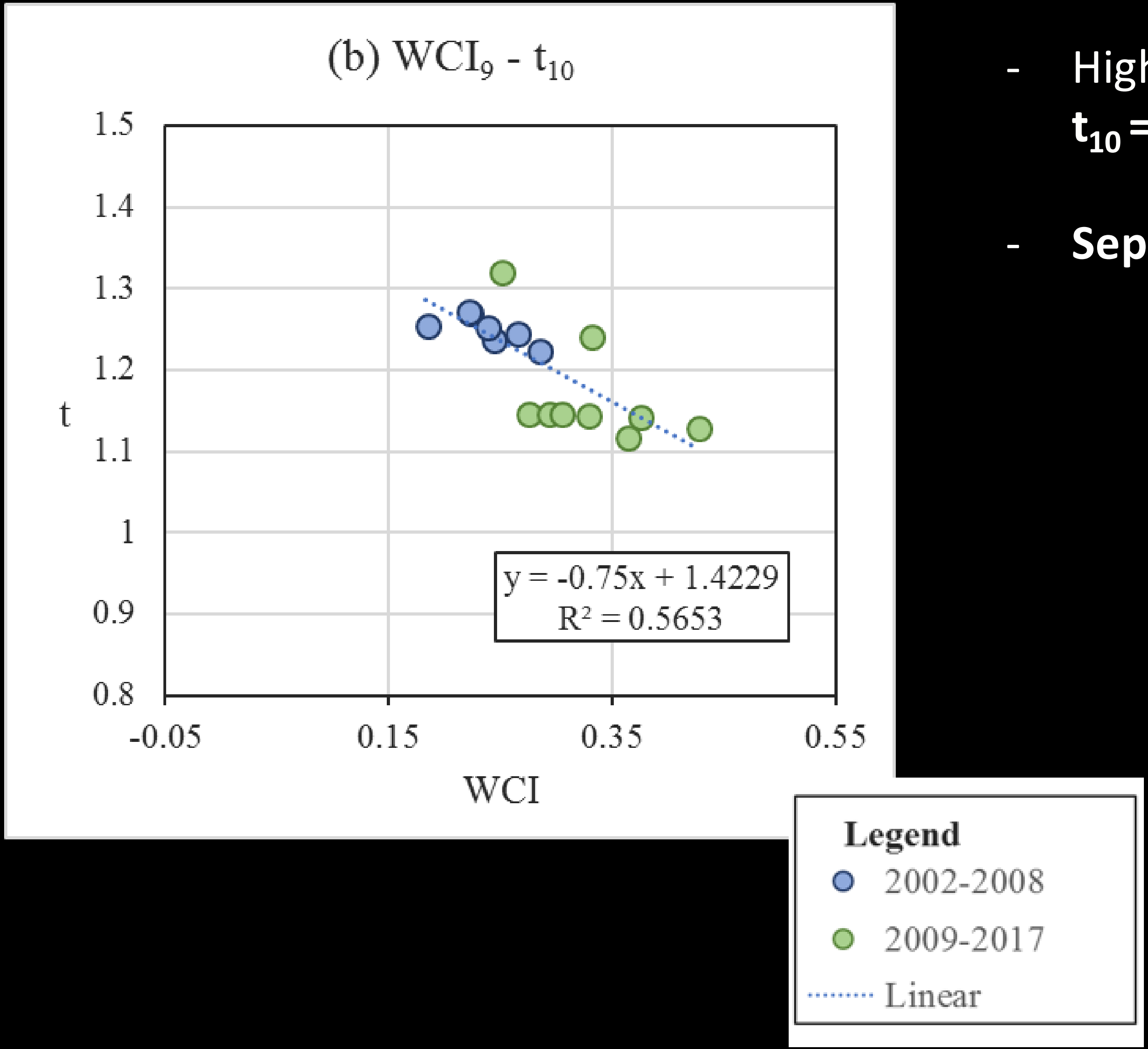
Results: SMTC at catchment scale



Results: SMTC at catchment scale

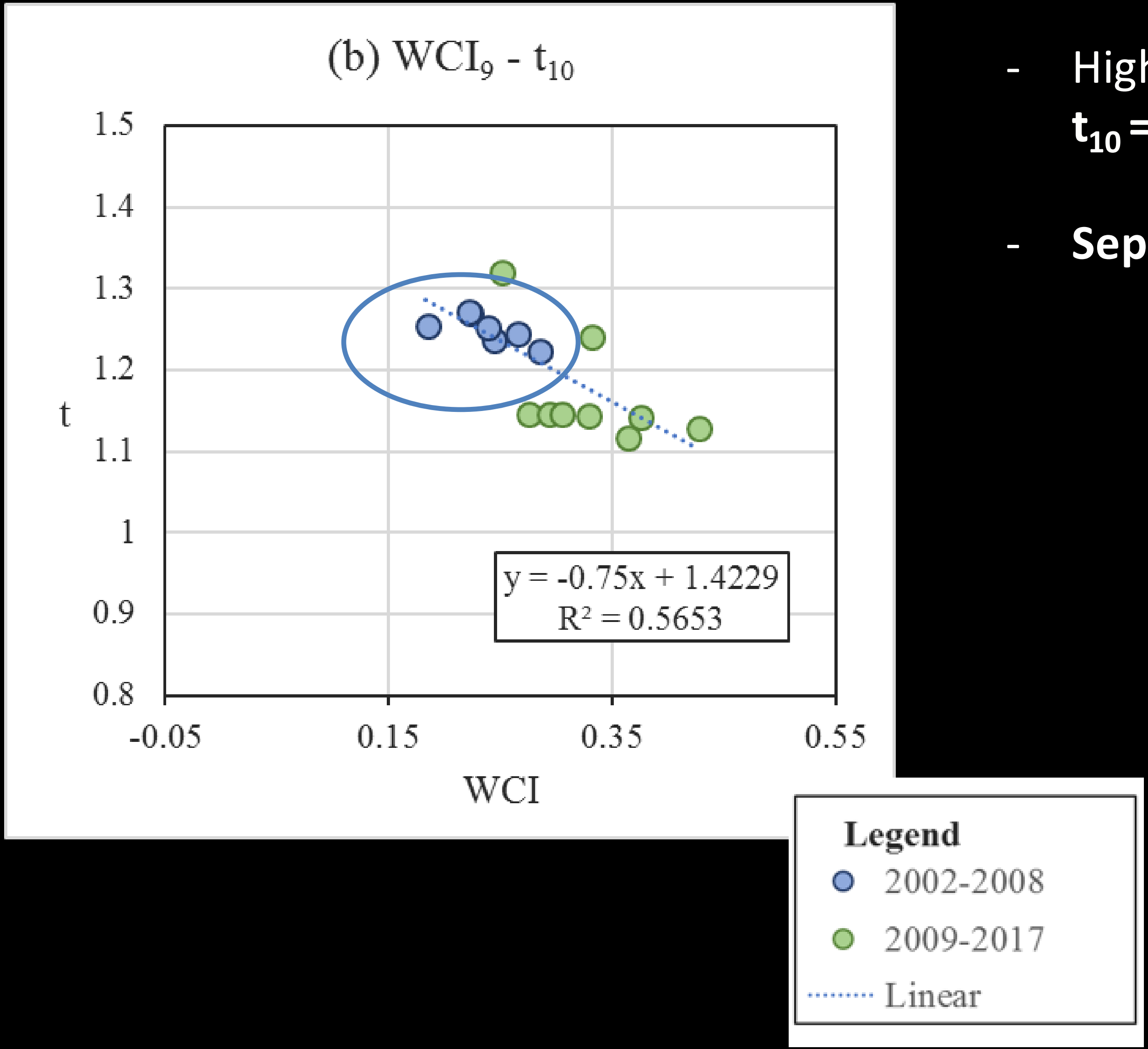


Results: SMTC at catchment scale



- Highest SMTC is the one characterised by the relation **t_{10} = f (WCI_9).**
- **Separation of populations**, except 2009

Results: SMTC at catchment scale



- Highest SMTC is the one characterised by the relation **$t_{10} = f\ (WCI_9)$.**
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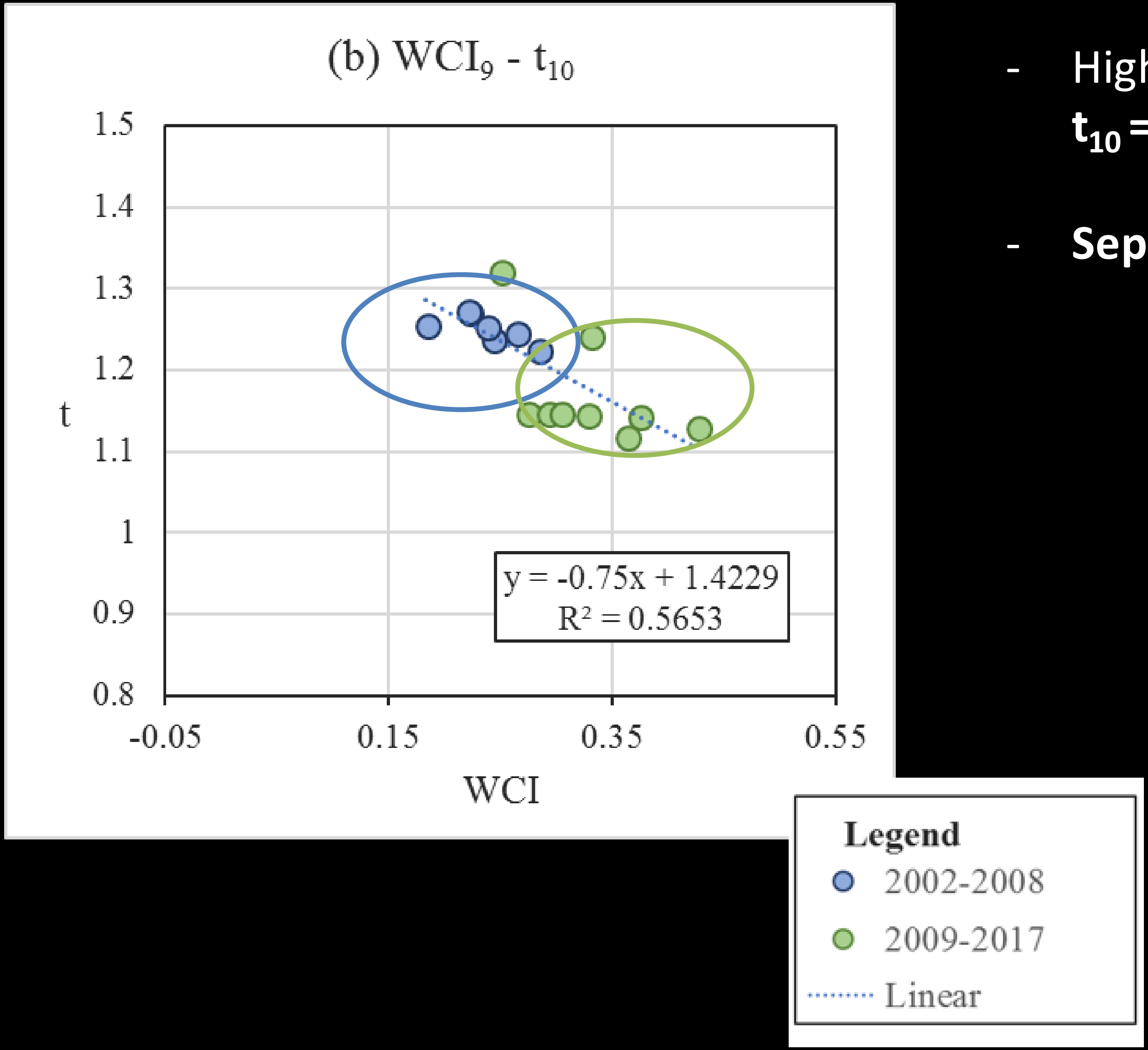
Results: SMTC at catchment scale



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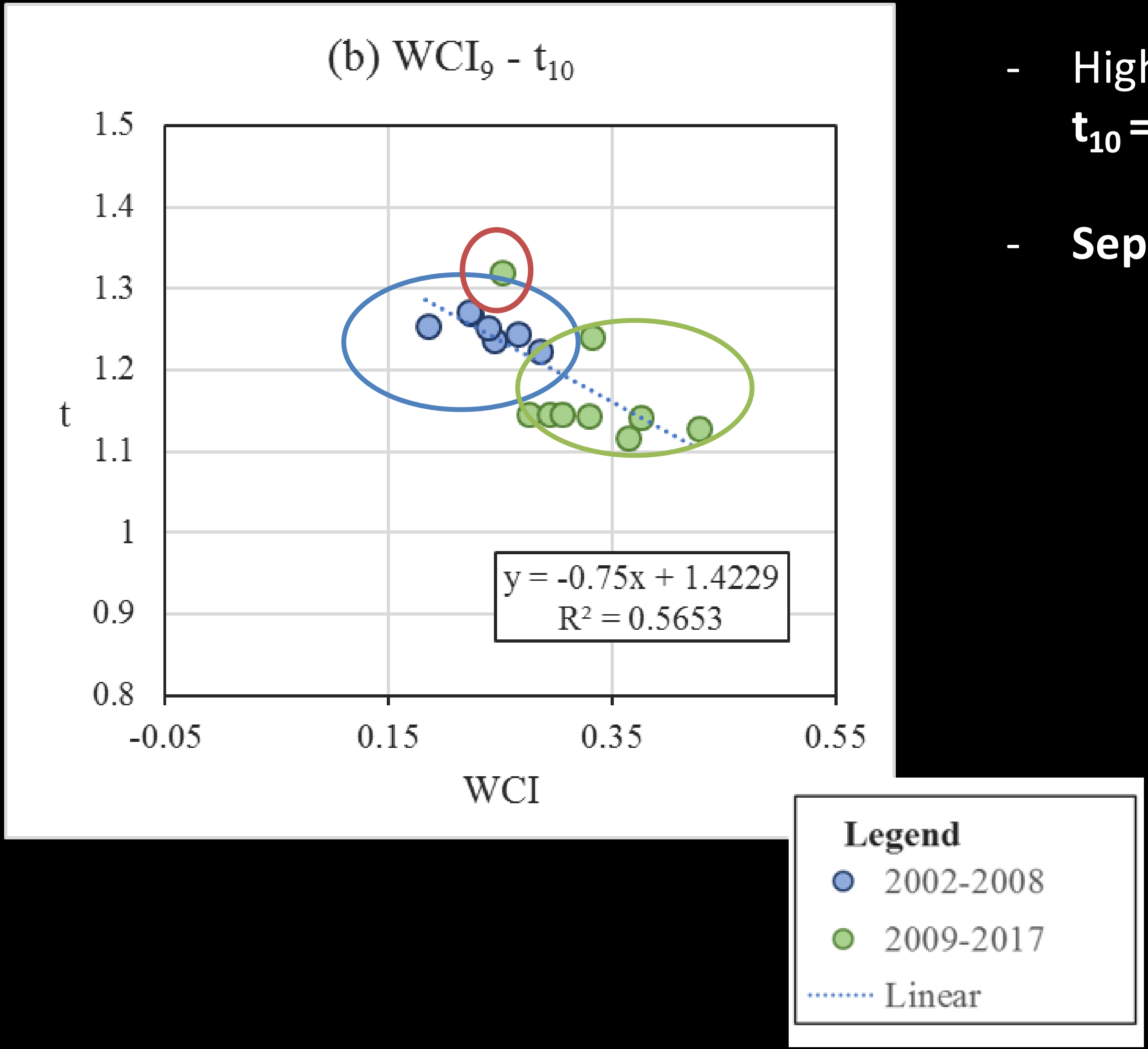
Results: SMTC at catchment scale



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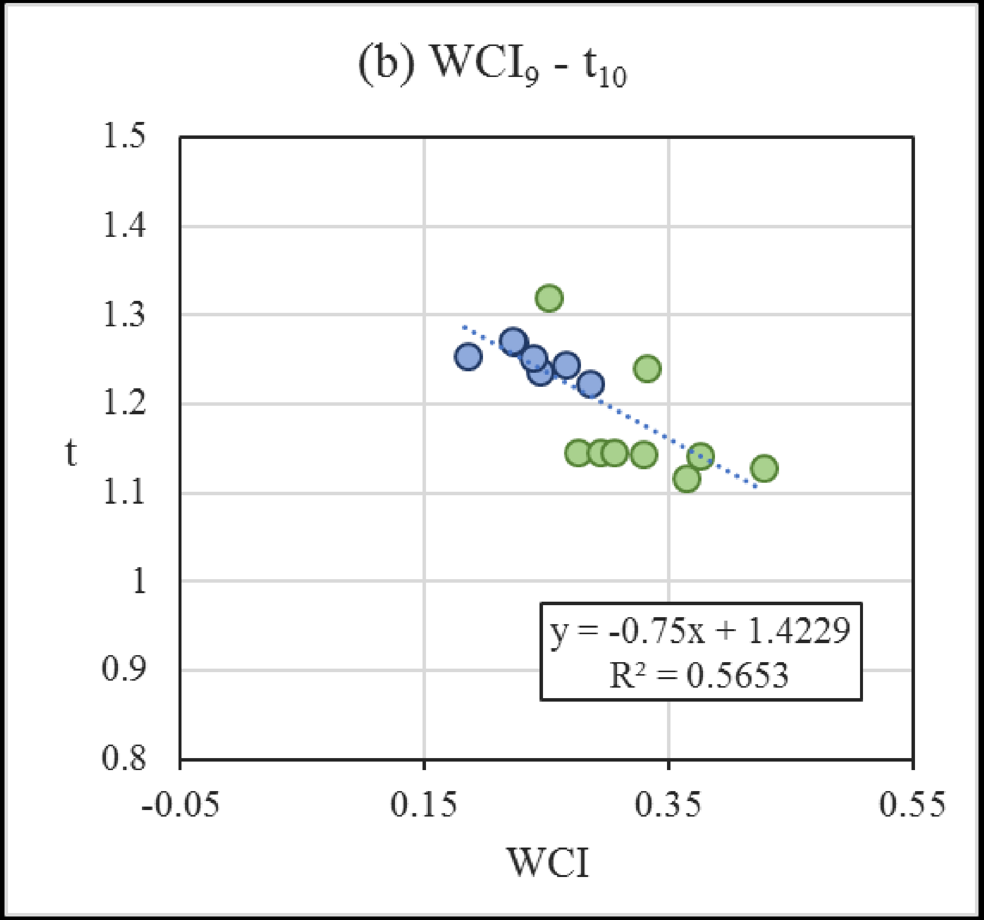
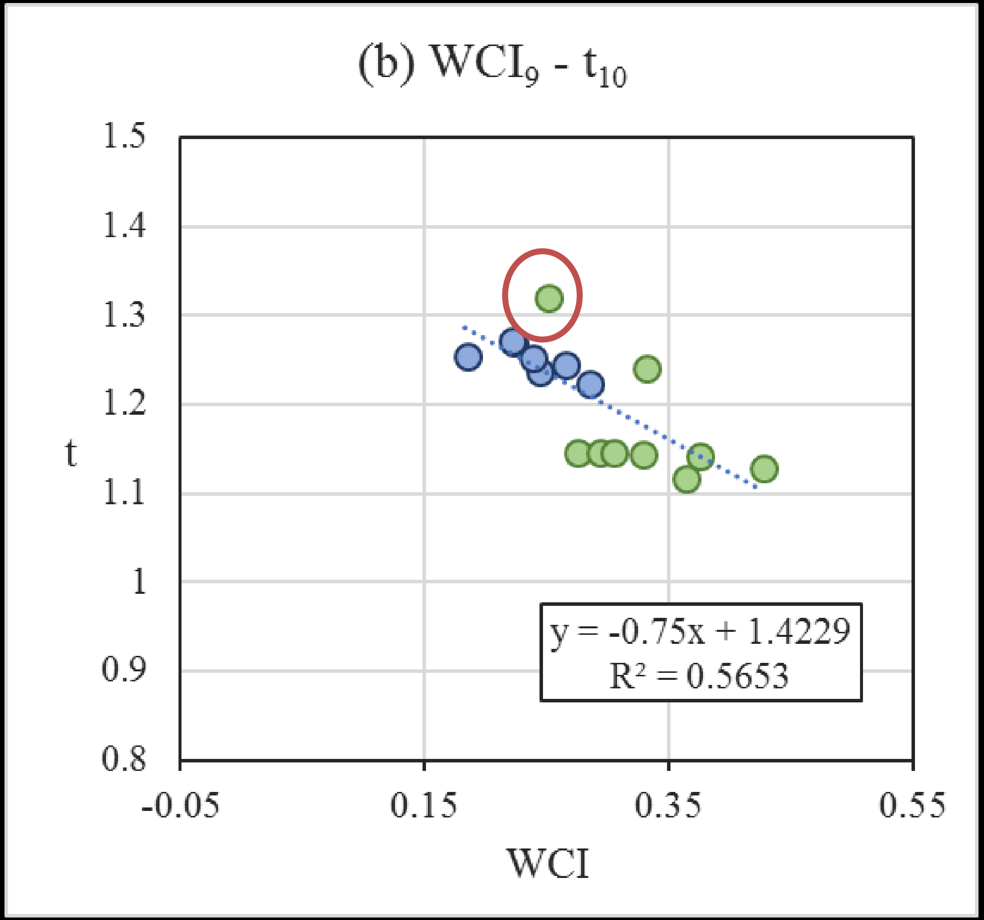
Results: SMTC at catchment scale



- 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, **∂t/∂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.

Winkler, K., et al. 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.

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) .

<u>The implementation of LRWH measures provided a climate regulation effect in the watershed.</u>

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

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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)