Airborne thermal infrared data for the estimation of evapotranspiration and crop water use

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Objectives

1. To investigate the **variability of evapotranspiration** (ET) by integrating very **high spatial resolution (1 to 4 m)** thermal infrared (TIR) data from airborne measurements and visible to near infrared data from Planet satellite with a numerical water-energy balance model, a simplified energy balance model and a diagnostic surface energy balance model.

2. To calibrate/validate the models **against eddy covariance data**

3. To evaluate the **stress conditions** and the **effect of irrigation** considering different ET and LST spatial resolution

4. To test the feasibility of **estimating soil moisture** by combining the high spatial resolution thermal infrared (TIR) and the numerical water-energy balance model FEST-EWB

An intensive airborne campaign was organized in the summer of 2022 for three consecutive days in July in central Italy.

Burana Irrigation Consortium – survey campaign areas

Pear tree fields – time continuous measurements

Mazzoni farm

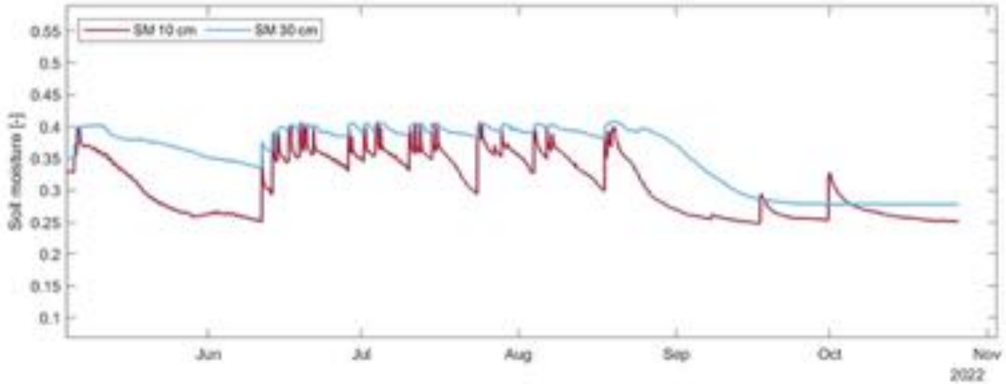
Eddy covariance station

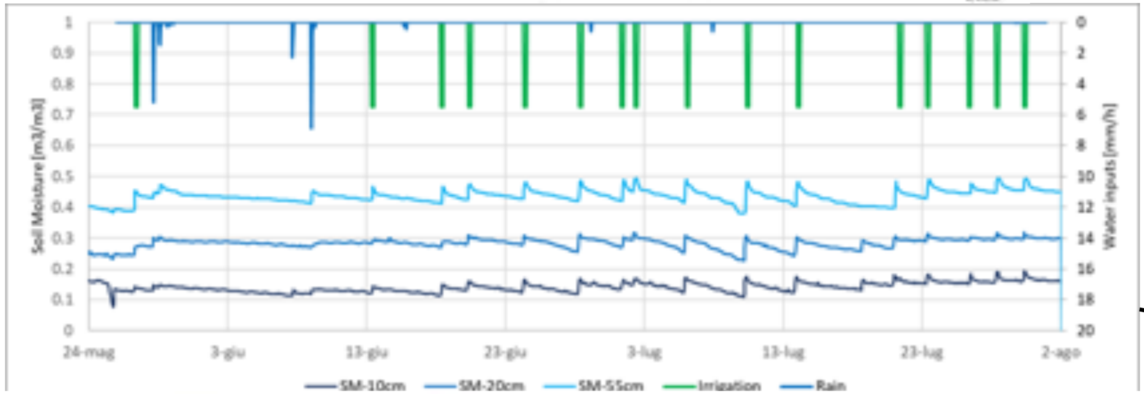
Reggianini farm

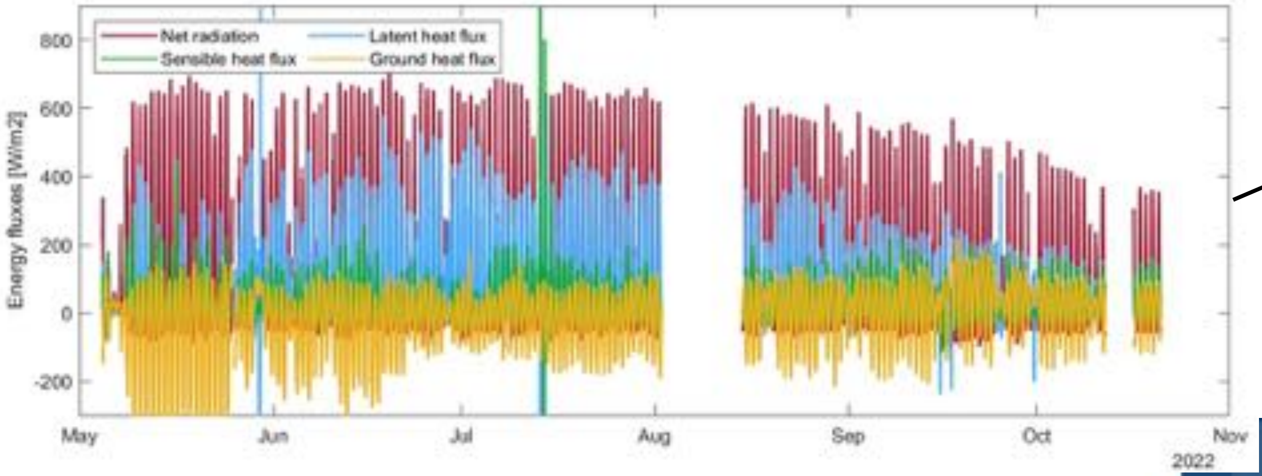
A Bowen ratio closure correction was applied (Twine eat., 2010) to the EC data before the comparison

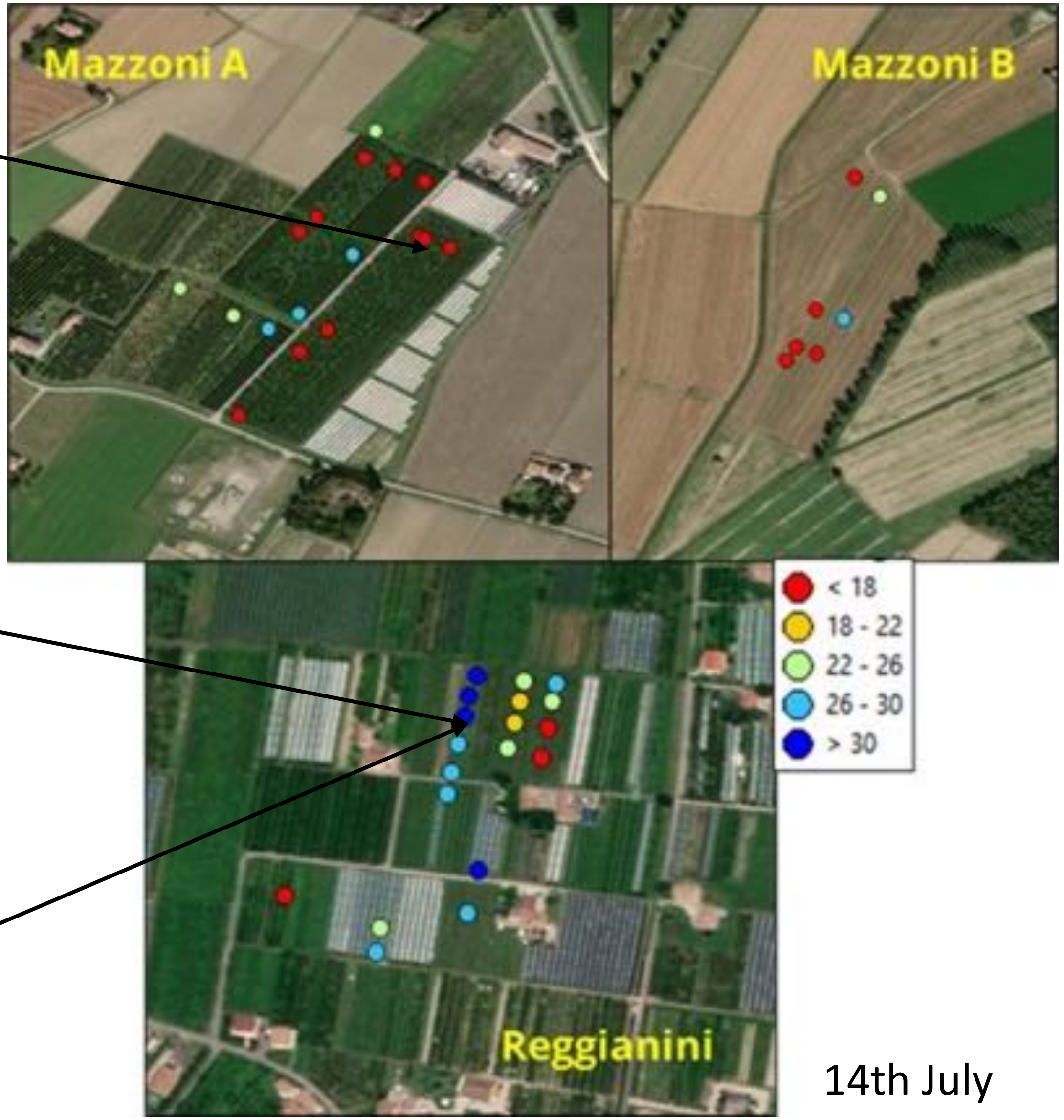
Pear fields	Reggianini	Mazzoni
Area	1.02 ha	2.4 ha
Irrigation system	Sprinkler	Drip
Irrigation volume	570 mm	335 mm
Montoring setup	Flux tower + SM probes	SM probes

Surface soil measurements and eddy covariance









14th July

Airborne survey

Planning of the Burana airborne survey

Segment	Duration (min.)
Airport – Modena transit	15
Modena survey at 4 m	14
Descent from 2900 m to 700 m	5
Diamante survey at 1 m	7
Modena-Concordia transit & ascent from 700 m to 2900 m	15
Concordia survey at 4 m	38
Descent from 2900 m to 700 m	5
Mazzoni 1m survey	13
Concordia – Airport transit	15
Total time per survey	**127**
Total survey time (30 hrs)	1800
Number of surveys	**14.2**

Hyper-Cam-LW specifications

Parameter	Unit	Hyper-Cam-LW
Spectral Range	μm	7.7 – 12
Spectral Resolution	cm^{-1}	0.25 to 150 (user adjustable)
Image Format	-	320 x 256 pixels
Field of View	Degrees	6.4 x 5.1 (nominal)
	Degrees	25.6 x 20.4 (0.25X telescope)
Typical NESR	$nW/cm^2 sr cm^{-1}$	< 20
Radiometric Accuracy	K	<1

64 bands of TIR aquisition

Hyper-Cam on motion compensated and stabilised airborne platform with GPS/INS unit

Overview of acquired airborne TIR data

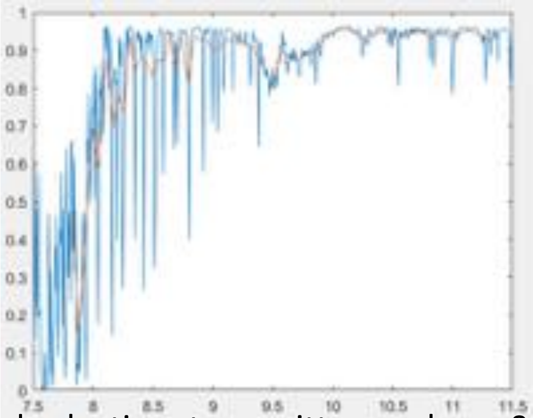
SMARTIES airborne campaign - data processing overview (06/12/2022)

Date	Start Time [UTC]	Diamante 1m	Modena 4m	Concordia 4m	Mazzoni 1m
13.07.22	07:45	GPS problem			
	08:25		mosaicked		
	08:55			mosaicked	
	09:30				mosaicked
	11:27	mosaicked			
	12:04		mosaicked		
	12:27			mosaicked	
	13:23				mosaicked
	15:02	mosaicked			
	15:29		mosaicked		
	15:51			mosaicked	
	16:46				mosaicked
14.07.22	07:40	mosaicked			
	08:04		mosaicked		
	08:25			mosaicked	
	09:13				GPS problem
	10:45	mosaicked			
	11:08		mosaicked		
	11:29			mosaicked	
	12:20				mosaicked
	14:06	mosaicked			
	15:09		mosaicked		
	15:29			mosaicked	
	16:14				mosaicked
15.07.22	06:59	mosaicked			
	07:26		mosaicked		
	07:48			mosaicked	
	08:32				mosaicked
	10:31	mosaicked			
	10:53		mosaicked		
	11:18			mosaicked	
	12:06				mosaicked
	13:13	mosaicked			
	13:54		Only one line recorded, [illegible]		

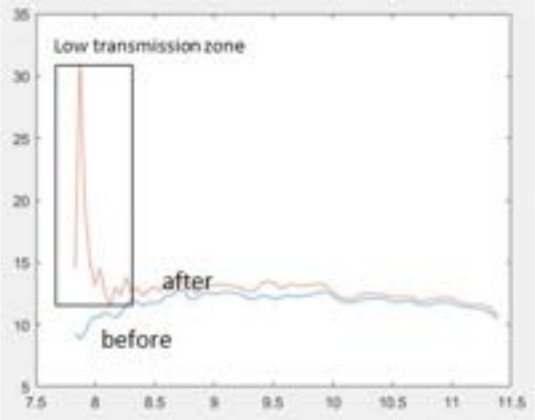
Green: Uploaded to project directory @USTFileServer
Red: Unable to further process, only spectrally calibrated raw image slices (no geocoding etc.)

Airborne LST and emissivity retrieval

Atmospheric correction: MODTRAN + ERA5 atmospheric profiles

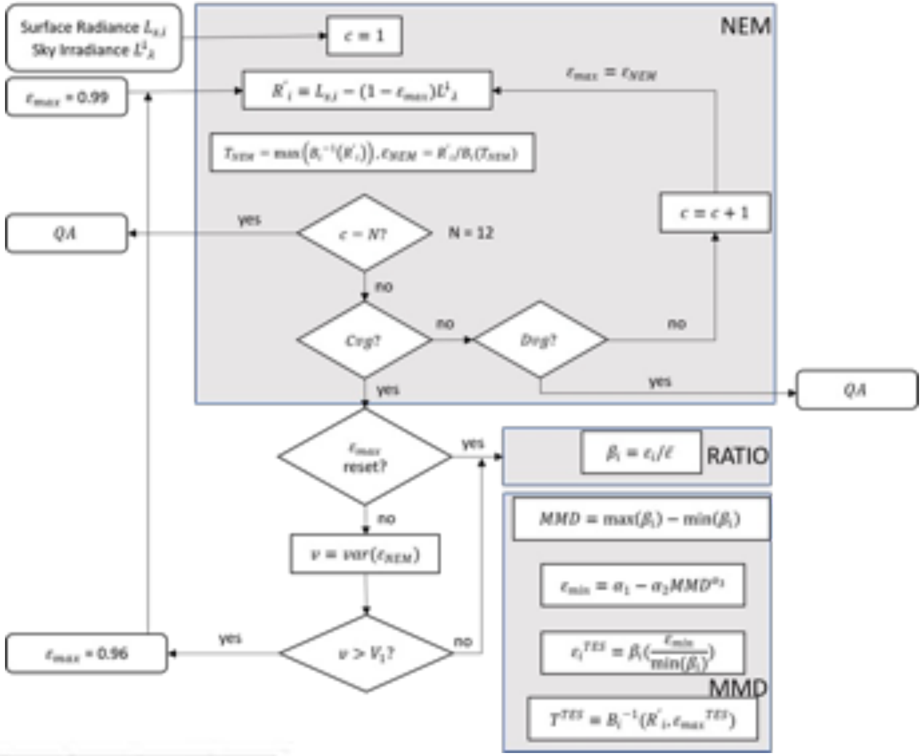


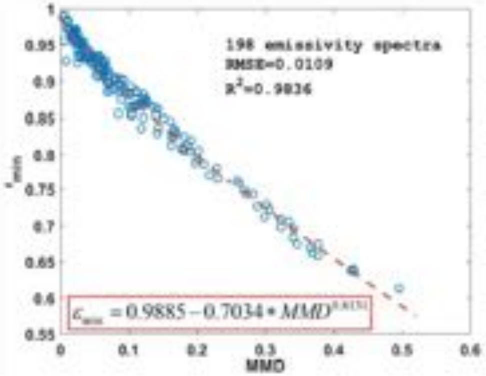
Band selection: transmittance above 0.9
Simulated transmittance from MODTRAN



Radiance before and after atmospheric correction

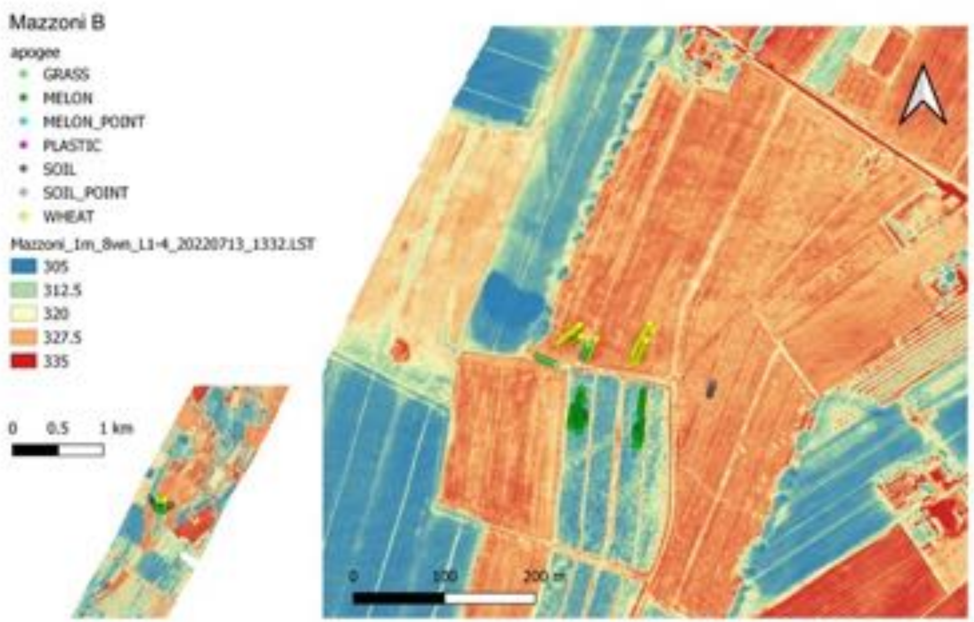
TES schematic flowchart

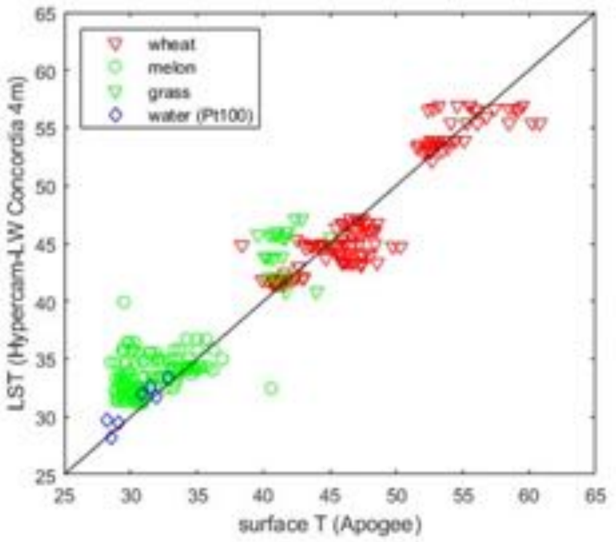




Credit to Gao et al. (2022)

Airborne LST validation





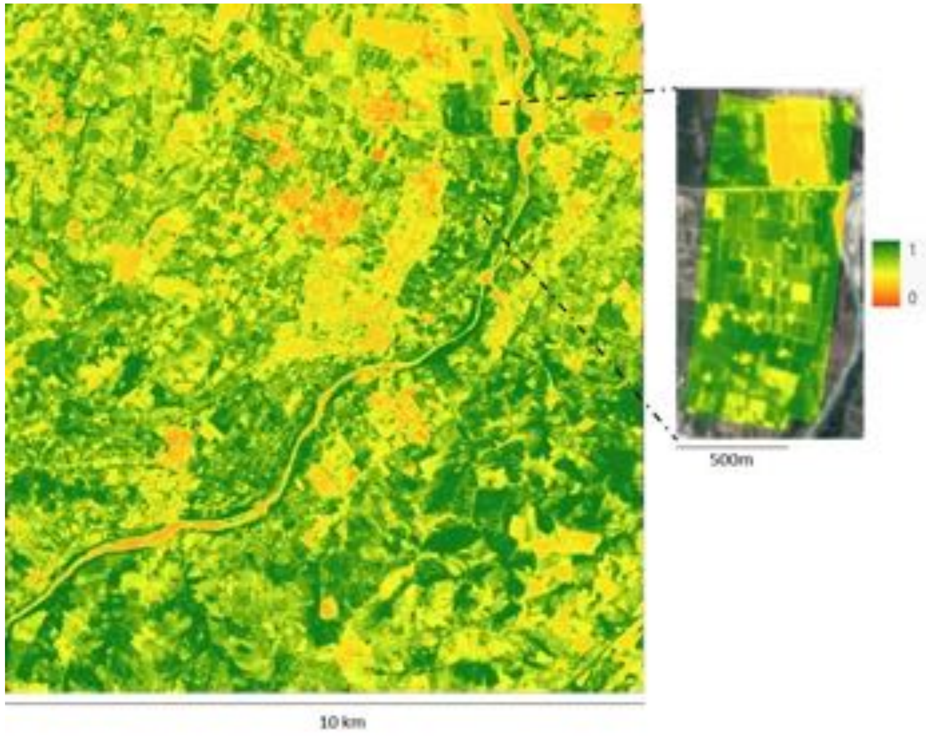
Time lag between aircraft overpass and ground measurements was typically between 3 and 36 minutes.

Site	Surface type	Measurement devices	Variables	Sample size
Mazzoni-B	Wheat, melon, soil, grass, plastic	Apogee	Ts	463
Mazzoni-B	Wheat, melon, bare soil	Cimel	Ts ε (6 channels)	58
Quarry Lake	Water, lotus	Pt-100, IR-thermometer	Ts	18

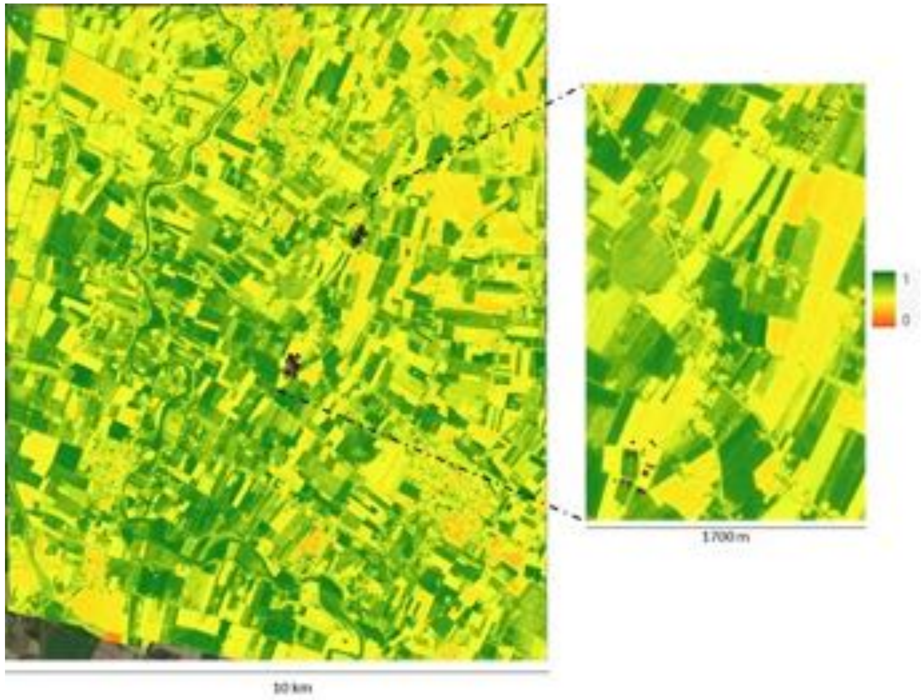
Planet data for vegetation information

High resolution vegetation images **at 3.7 m** have been employed, from **PlanetScope sensors** on board cubesat satellites. These sensors have 8 spectral bands (red edge, red, green, green I, yellow, blue, coastal blue and near infra-red), which allowed to retrieve vegetation indices, as NDVI, vegetation fraction and Leaf area index.

vegetation fraction (Modena and Diamante)

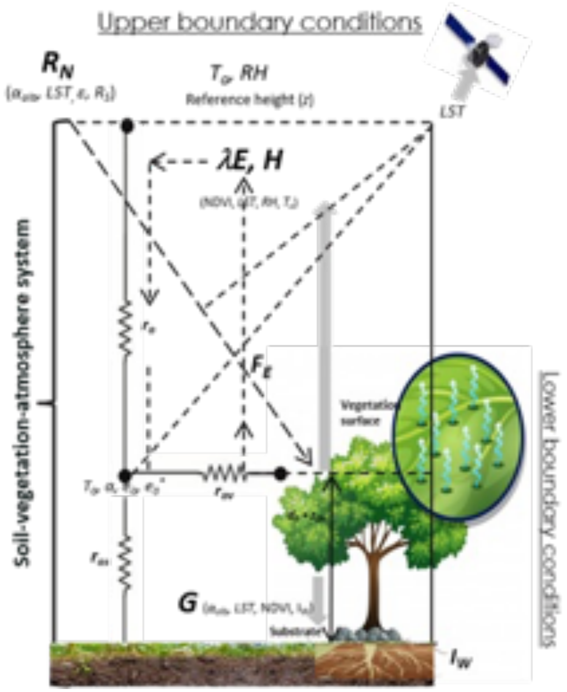


vegetation fraction (Concordia and Mazzoni)



Evapotranspiration models

STIC analytical model

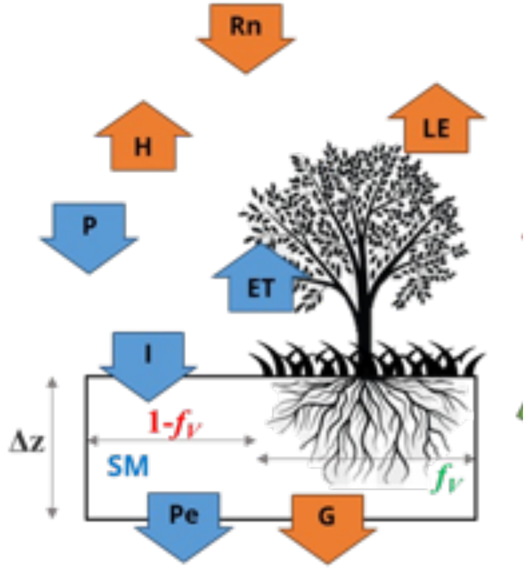


resolves evaporative fraction, aerodynamic temperature, and aerodynamic and surface conductances simultaneouly under an analytical framework through injecting radiative surface temperature into the Penman-Monteith (PM) equation

FESTresidual model

LE=Rn-H-G

Corbari et al., 2015 (Jh)
Corbari & Mancini, 2014 (JHM)
Corbari et al., 2014 (HSJ)



A SEB model that parameterize conductances to retrieve the energy fluxes, LE is the residual term of the energy budget

S-SEBI model

instantaneous evaporative fraction

$$\Lambda = \frac{\lambda E}{\lambda E + H} = \frac{\lambda E}{R_n - G_0}$$

$$\Lambda = \frac{T_H - T_0}{T_H - T_{\lambda E}}$$

temperatures corresponding to dry and wet conditions

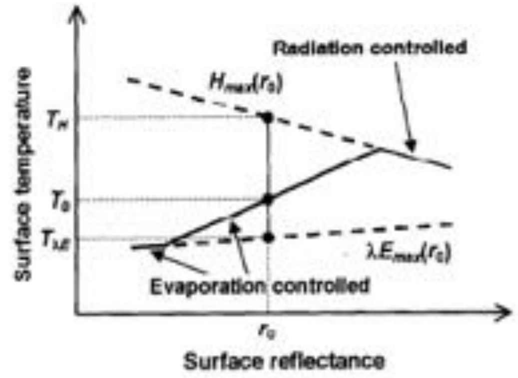
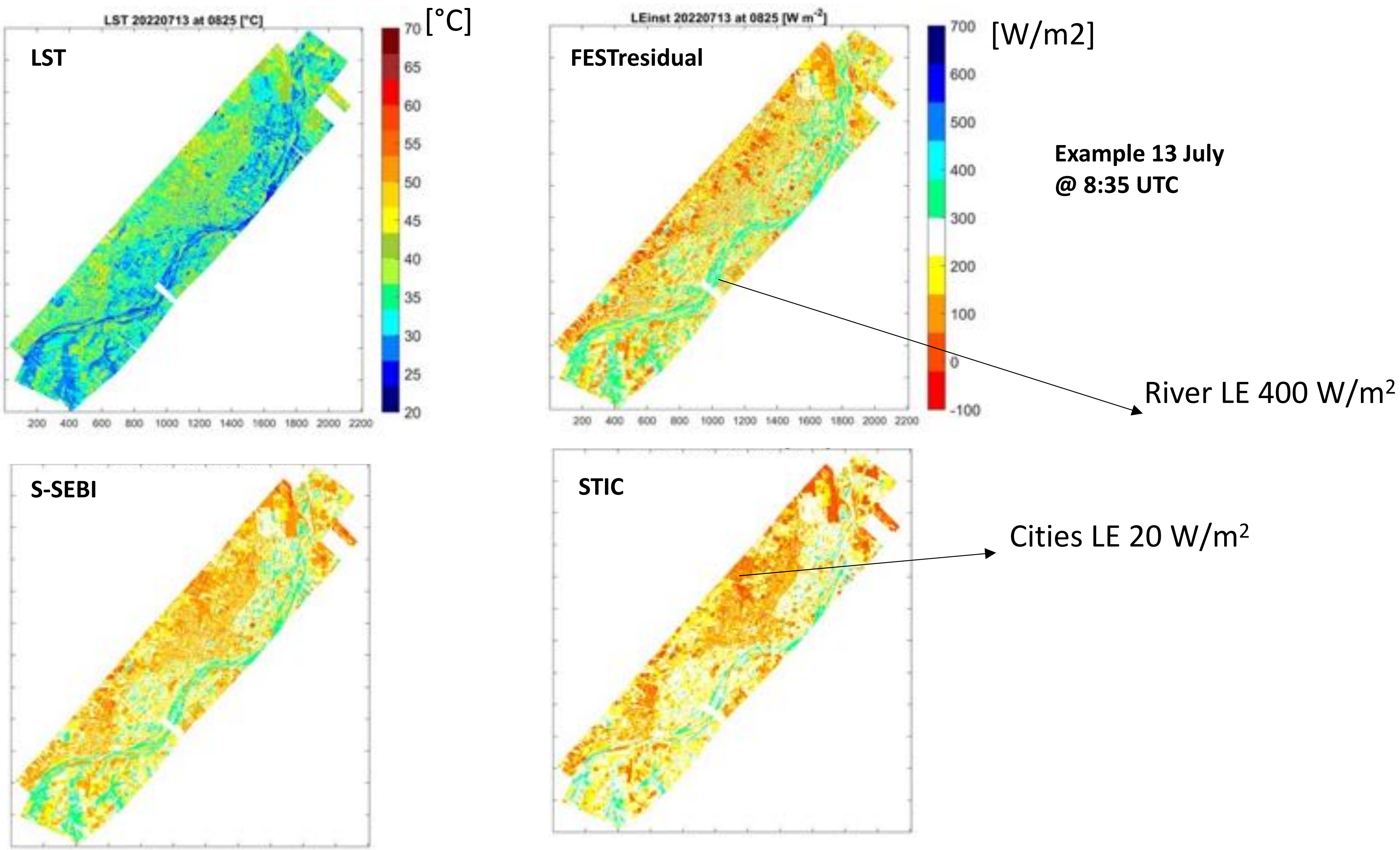


Fig. 2. Schematic representation of the relationship between surface reflectance and temperature together with the basic principles of S-SEBI.

Roerink et al. (2000)

ET estimates for Modena 4m LST

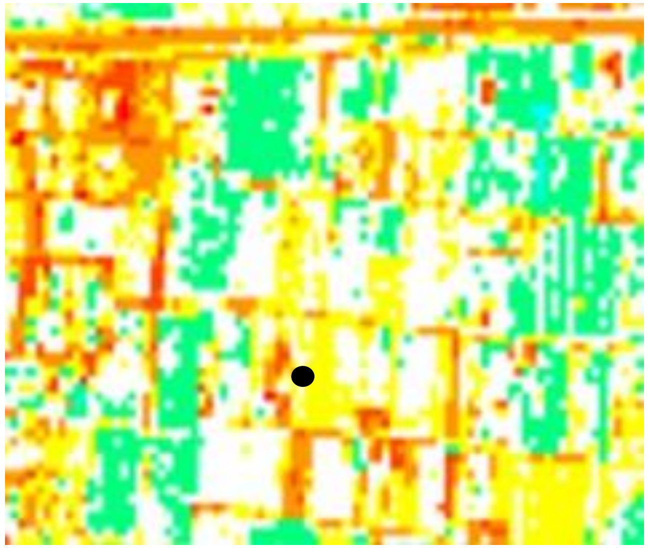


Example 13 July @ 8:35 UTC

Zoom to the eddy station area: ET estimates for Modena 4m LST

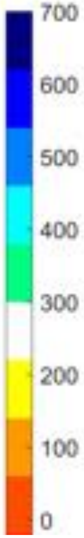
LST **LE eddy= 241.5 W/m2**

FESTresidual LE (footprint)= 230.3 W/m2

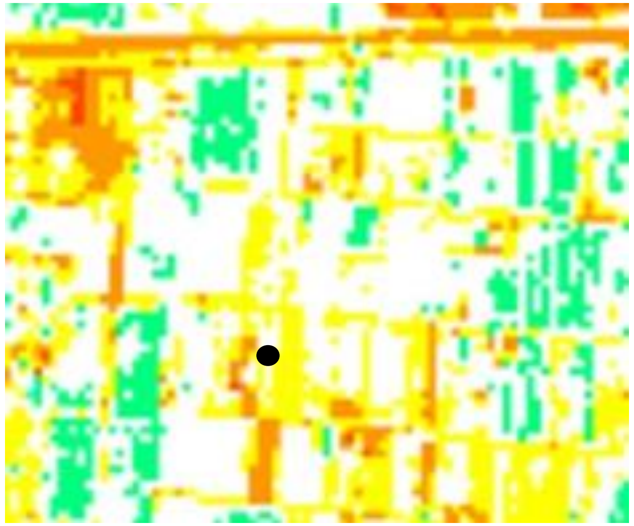


Example 13 July
@ 8:35 UTC

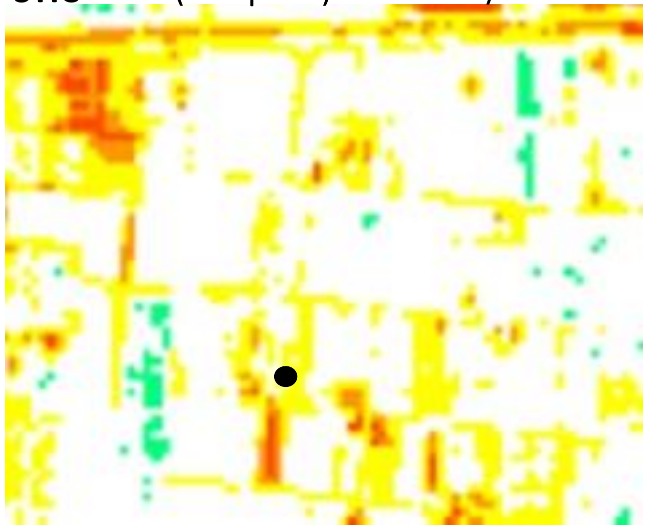
[W/m2]



S-SEBI LE (footprint)= 230.1 W/m2



STIC LE (footprint)= 238.2 W/m2



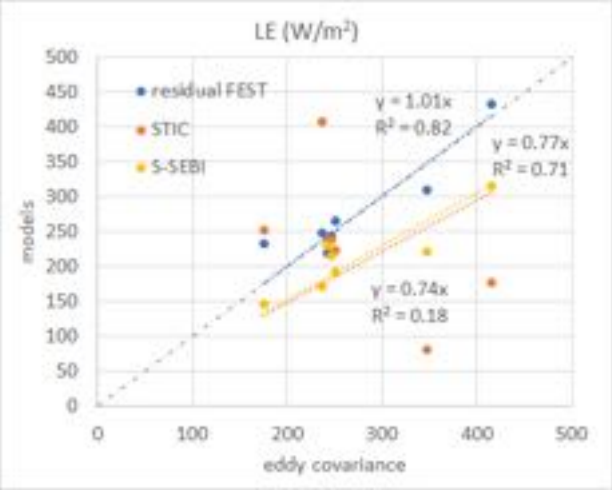
$$\bar{F} = \frac{\sum_{i=1}^{n} f(x_i, y_i, z_m) F(x_i, y_i)}{\sum_{i=1}^{n} f(x_i, y_i, z_m)}$$

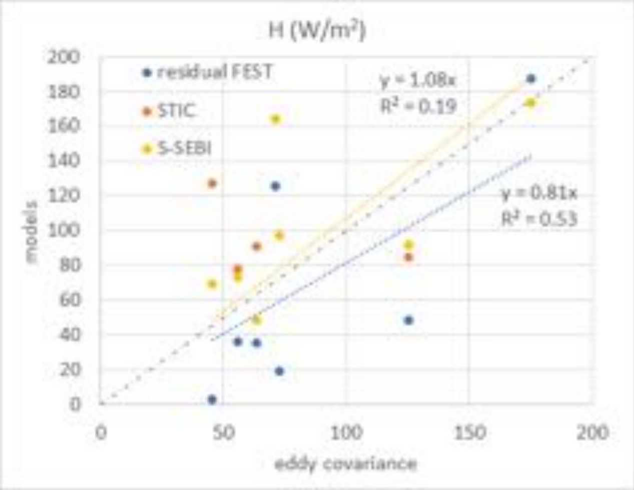
Detto et al. 2006

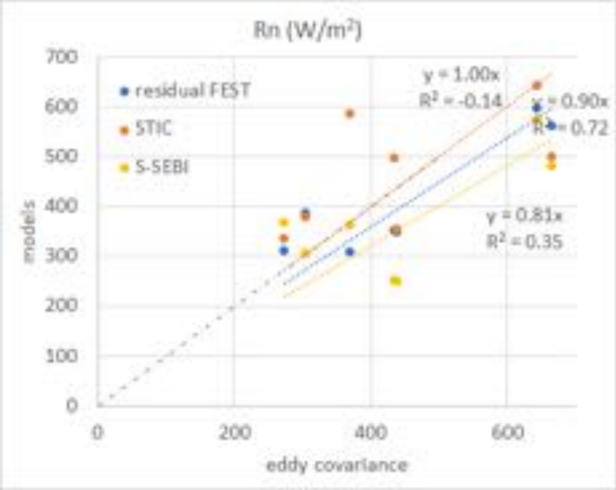
Energy fluxes comparison at eddy covariance station

Not-consistent performances **across different hours of the day** (highest differences at higher LST)

W/m2		FESTresidual	STIC	S-SEBI
LE - Modena	RMSE	50.2	109.5	60.9
	BIAS	32.1	-100.4	-39.7



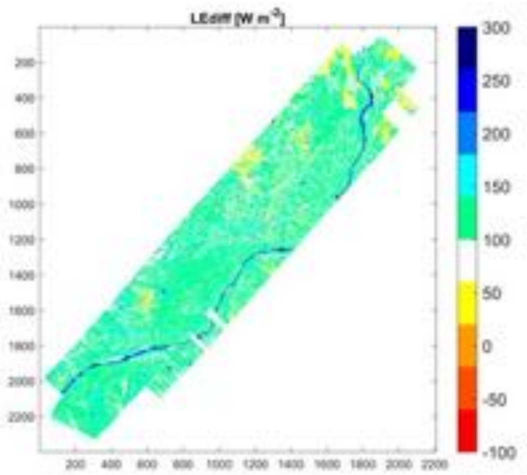




Abs Difference of ET estimates for Modena 4m

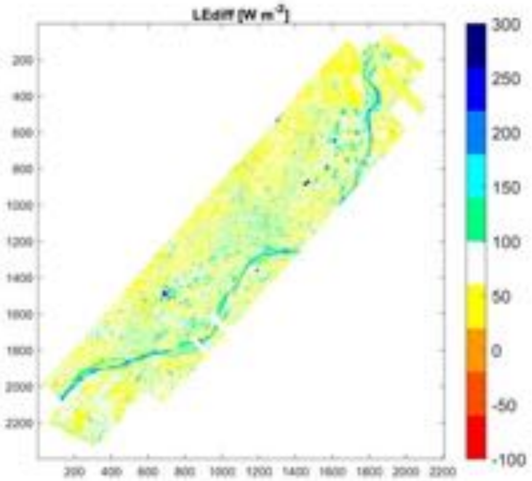
Average over the 7 flights

FESTresidual-STIC [W/m2]



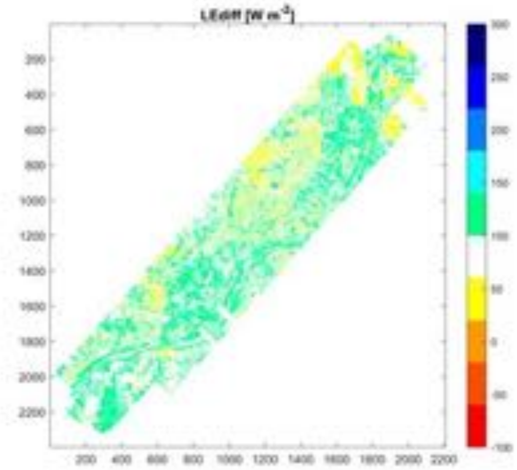
Mean abs (pixel diff) =113.4 W/m2
Mean (pixel diff) =15,4 W/m2

FESTresidual-S-SEBI [W/m2]



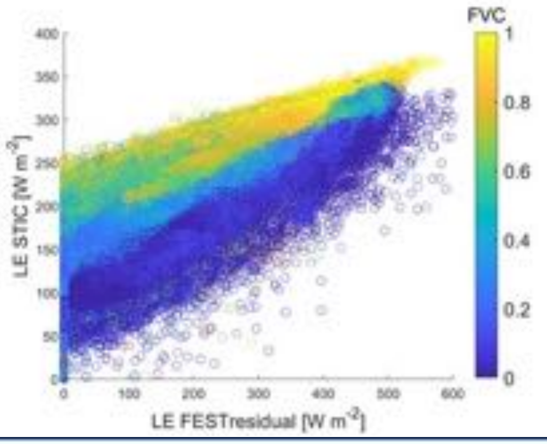
Mean abs (pixel diff) =86.7 W/m2
Mean (pixel diff) =57.2 W/m2

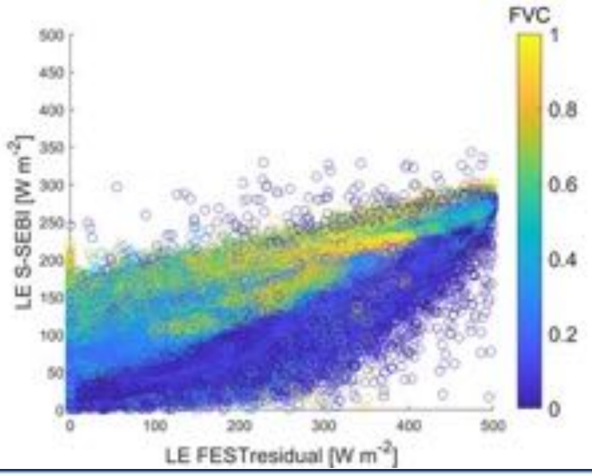
STIC-S-SEBI [W/m2]

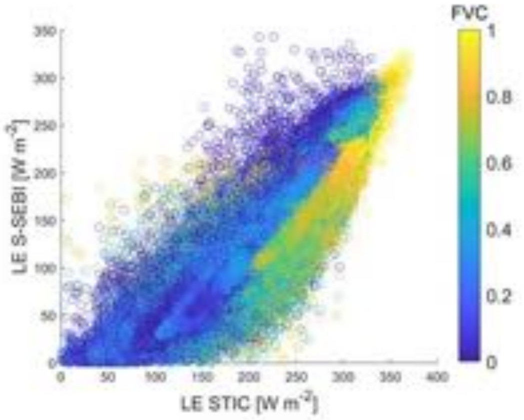


Mean abs (pixel diff) =93.8 W/m2
Mean (pixel diff) =13.9 W/m2

ET estimates and vegetation fraction





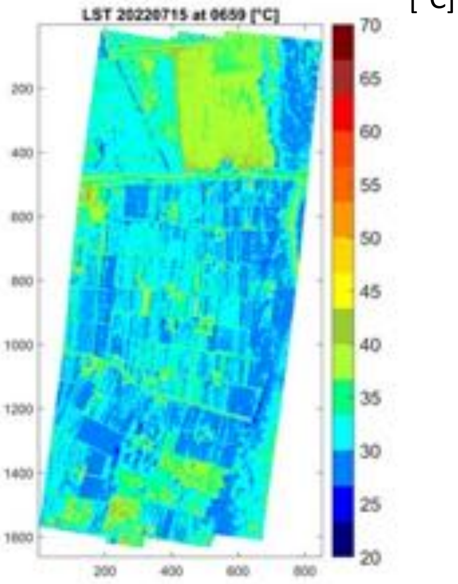


Not-consistent performances **across different land surface types**, vegetation fraction

-non-parameterized structure of STIC, with aerodynamic and surface resistances expressed through physical equations
-FESTresidual the calculation of aerodynamic resistance relies on wind speed
-S-SEBI small areas with difficult identification of dry-wet pixel

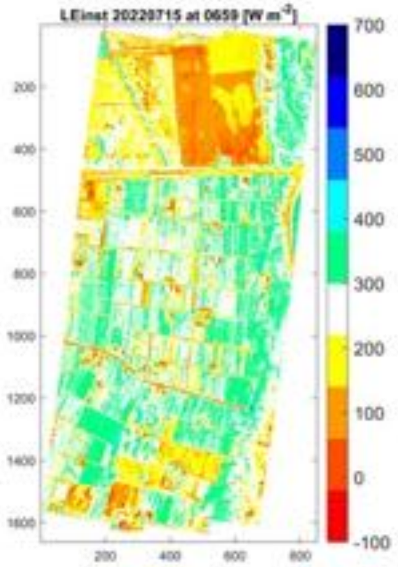
ET estimates for Diamante 1m LST

LST

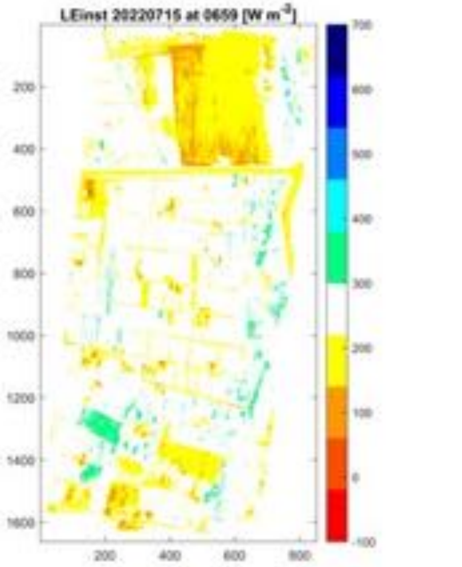


Example 15 july
@ 06:59 UTC

FESTresidual

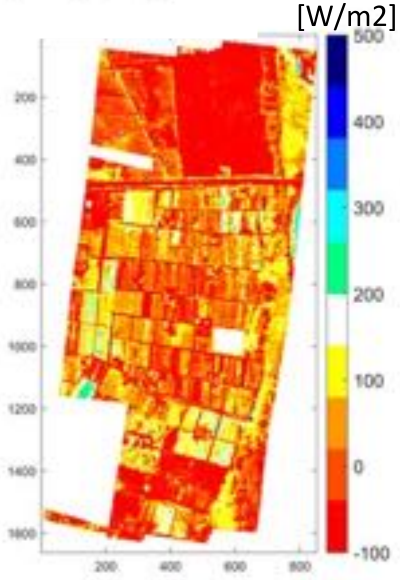


STIC



Over the 7 flights

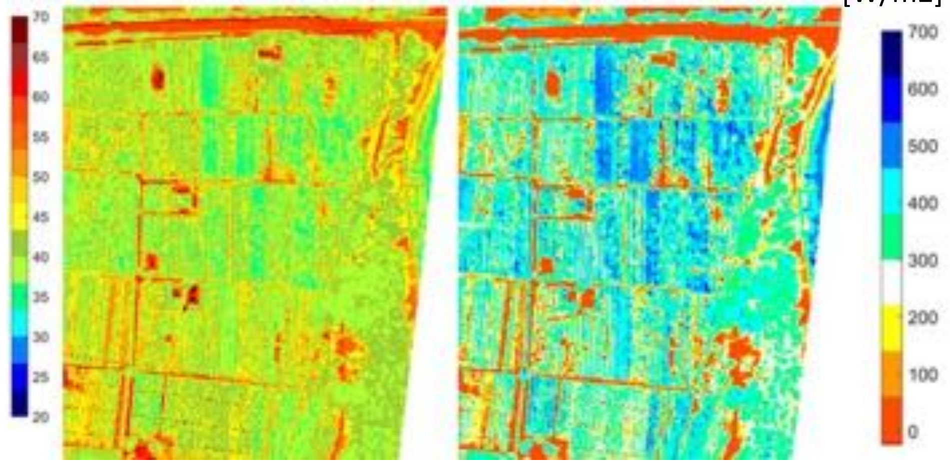
Mean abs (pixel diff)
=152.3 W/m2
Mean (pixel diff)
=10.5 W/m2



LE RMSE
FESTresidual 39.1 W/m2
STIC 190.7 W/m2

Effect of irrigation on the water and energy fluxes

[°C] Airborne LST (1m) FESTresidual LE (1m) [W/m2]



LST vegetated=40,9 °C
LST bare soil/grass=46,8 °C

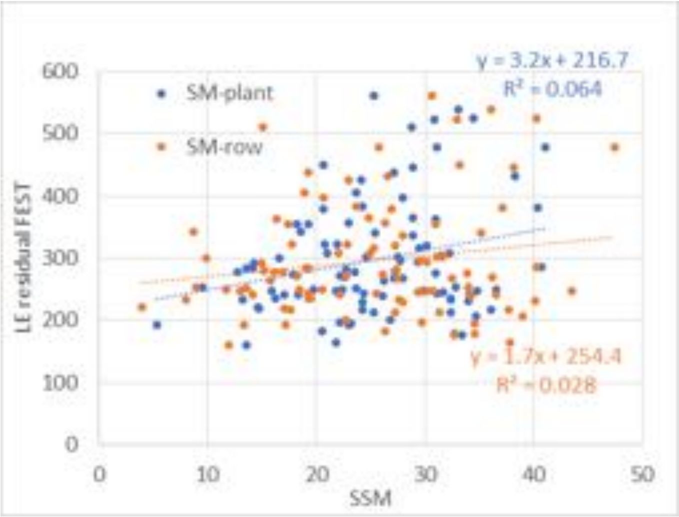
6°C difference

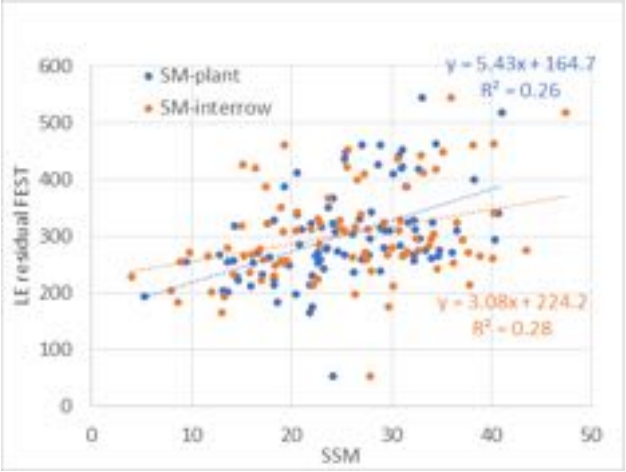
LE vegetated=330 W/m2
LE bare soil/grass=93,2 W/m2

Micro-sprinkler irrigation

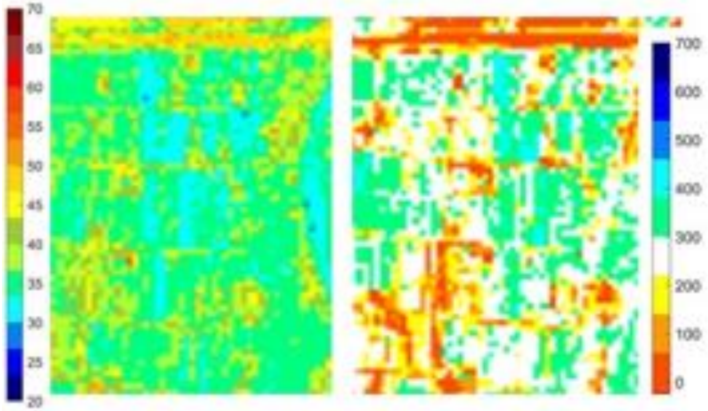
Irrigation is almost uniform

14 July @ 14:06 UTC





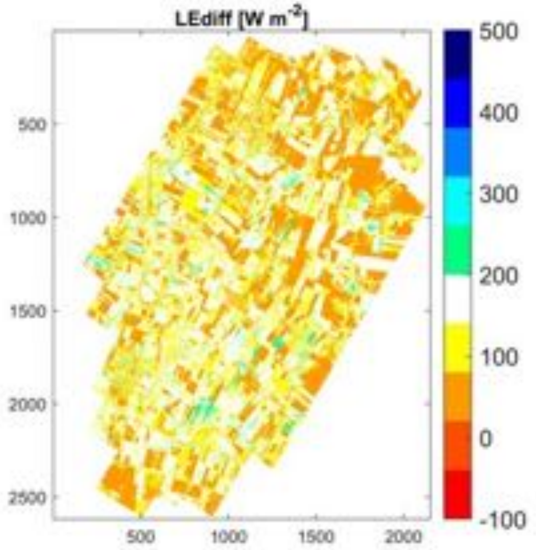
Airborne LST (4m) FESTresidual LE (4m)



Difference of ET estimates for Concordia 4m

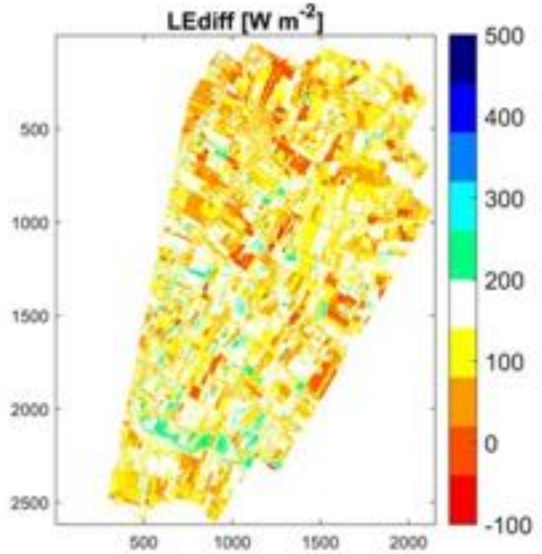
Average over the 7 flights

FESTresidual-STIC



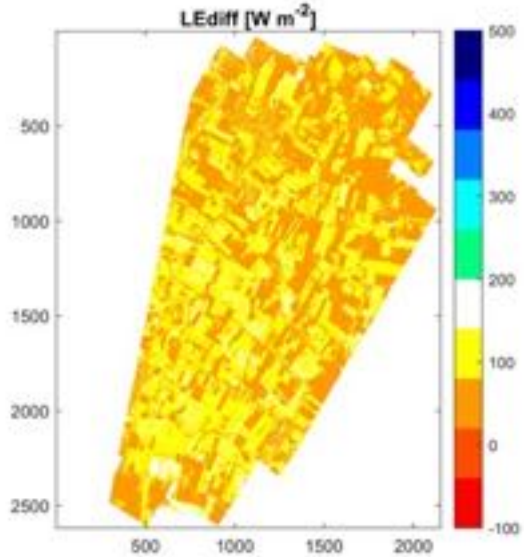
Mean abs (pixel diff) =135.8 W/m2
Mean (pixel diff) =96.3 W/m2

FESTresidual-S-SEBI



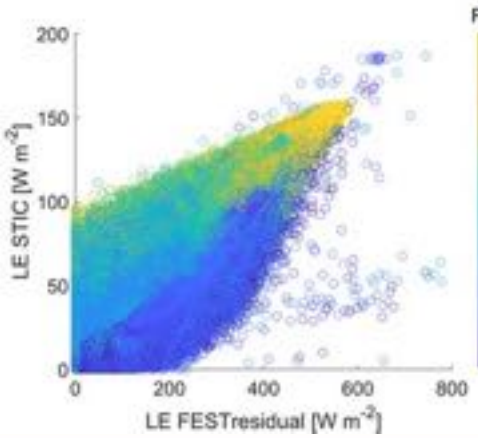
Mean abs (pixel diff) =108,1 W/m2
Mean (pixel diff) =88,5 W/m2

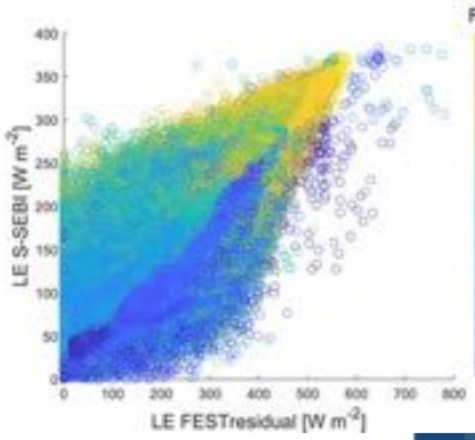
STIC-S-SEBI

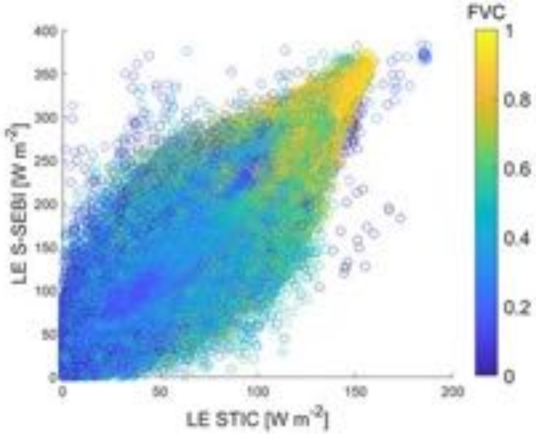


Mean abs (pixel diff) =92,7 W/m2
Mean (pixel diff) =19.3 W/m2

ET estimates and vegetation fraction



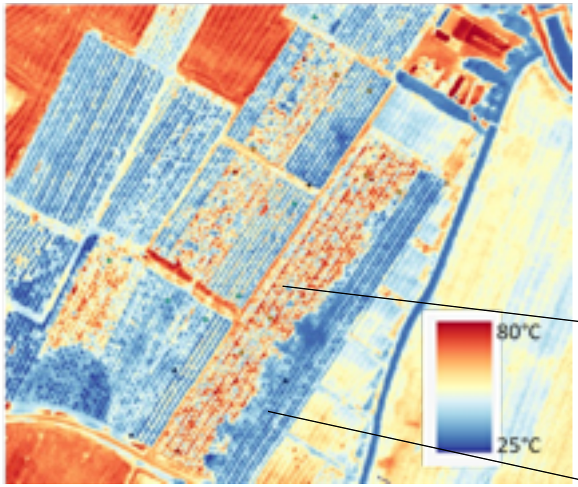




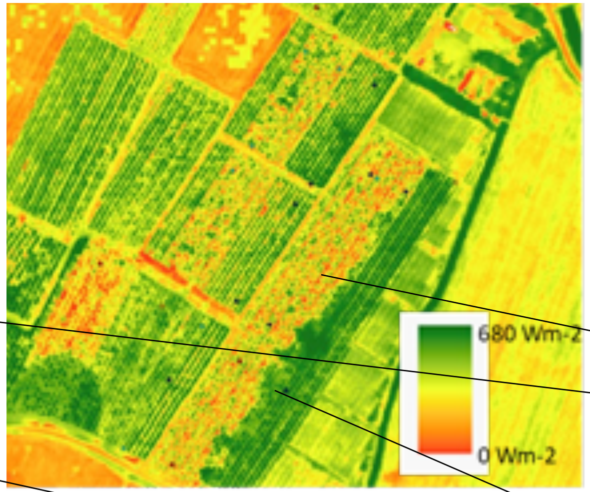
Effect of irrigation on the water and energy fluxes for Mazzoni 1m LST

14 July @ 14:06 UTC

Airborne LST (1m)



FESTresidual LE (1m)



LST vegetated=38.8 °C
LST bare soil/grass=57.3 °C

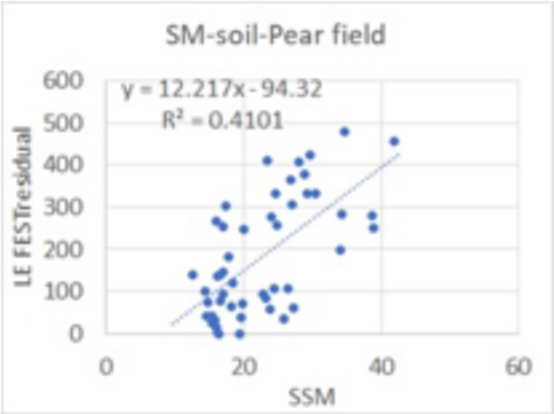
18°C difference

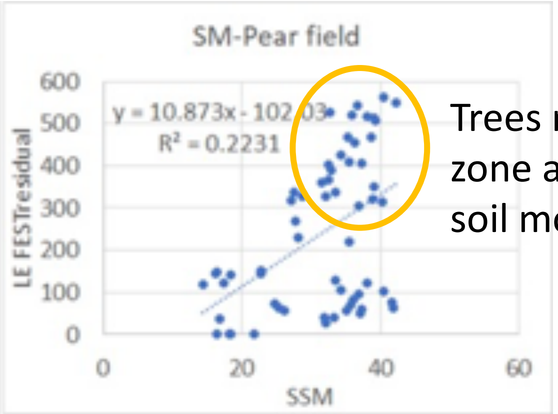
LE vegetated=350 W/m2
LE bare soil/grass=23,2 W/m2

Drip irrigation

Irrigation is provided only to the trees

Flood irrigation!



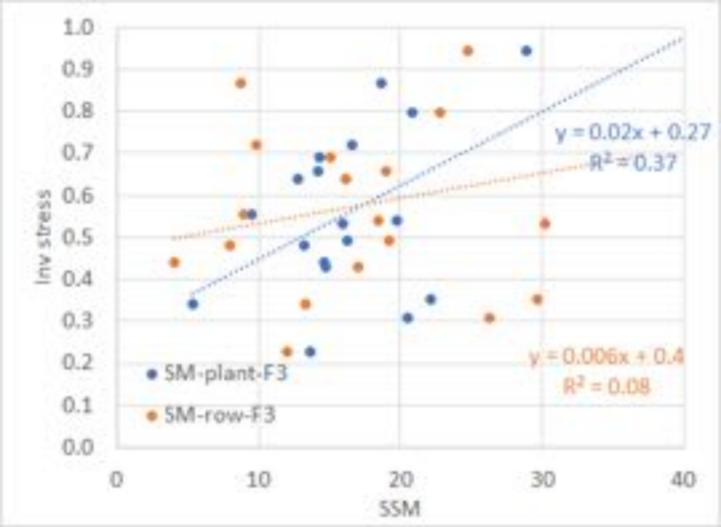


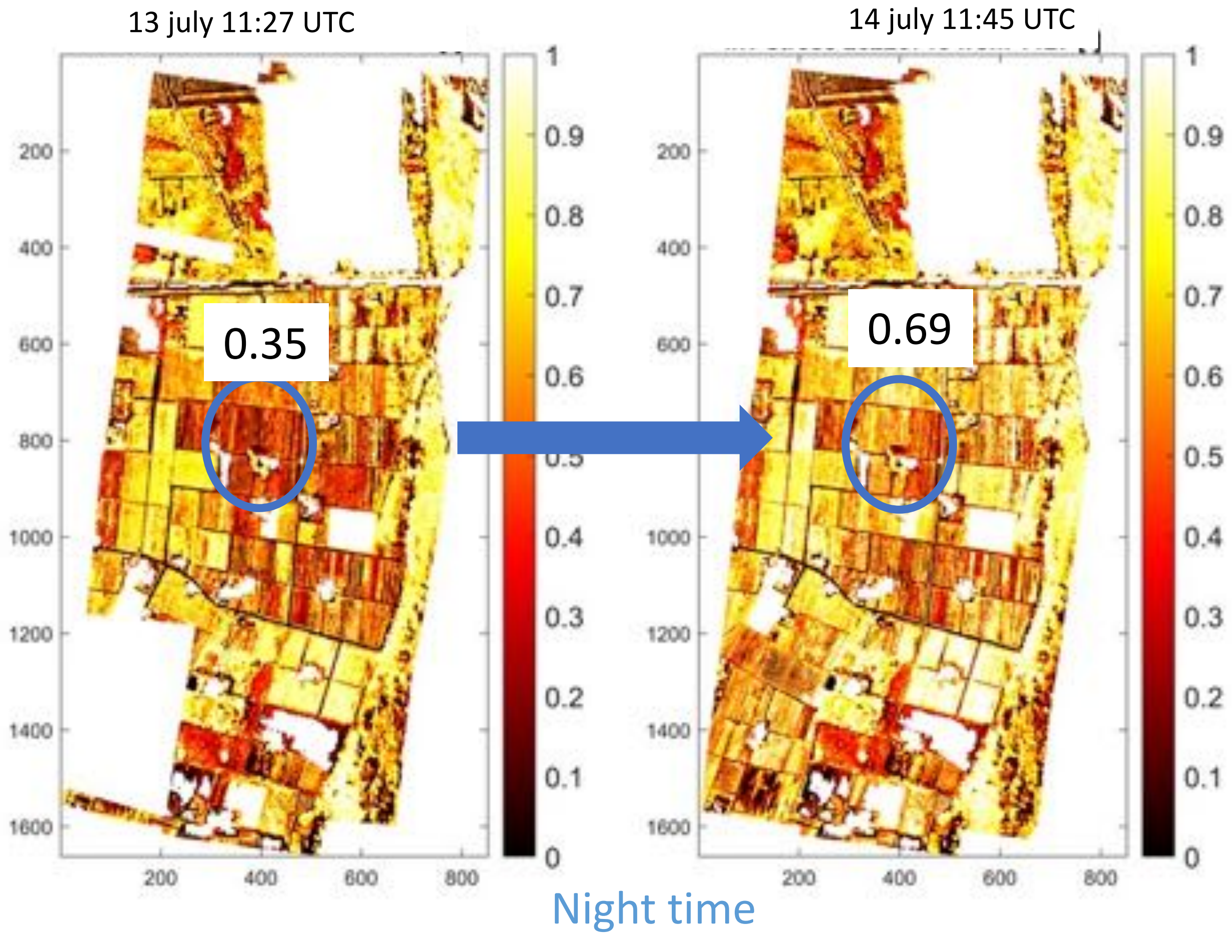
Trees roots zone at higher soil moitsure

Water stress conditions (Diamante 1m)

Water stress metric = fraction of actual ET to Allen et al. (1998) reference ET

0 maximum stress (full stomatal closure)
1 for non-stressed vegetation (fully transpiring).





SM at 7cm = 0.12
SM at 50cm = 0.25

SM at 7cm = 0.16
SM at 50cm = 0.29

Can we estimate SM from satellite LST? → The energy-water balance modeling

It doesn't consider irrigation

FEST-EWB model

Soil moisture dynamic linked to LE (LST)

Soil water balance

$$P_{tot}=R+ET_{eff}+D+(\theta_{t+1}-\theta_t)*Z$$

$$ETeff=\frac{LE}{\rho Cp}$$

Energy balance

$$Rn-G-H-LE=\frac{dS}{dt}$$

The energy water balance system written **as function of LST equilibrium temperature** (that closes the energy balance equation)

FEST-EWB: Flash – flood Event – based Spatially – distributed rainfall – runoff Transformation – including Energy - Water Balance

Airborne LST «sees» irrigation

FESTresidual

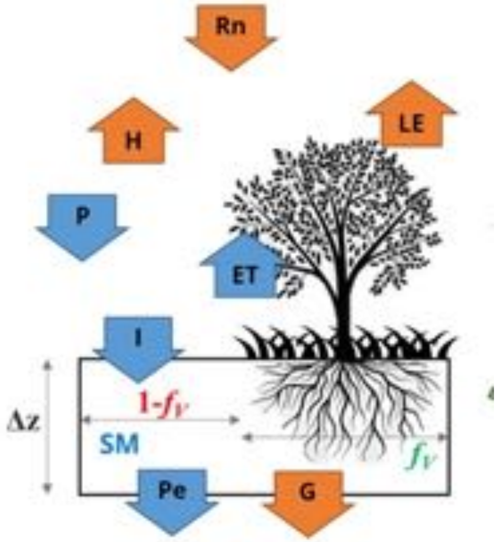
Energy balance

LE=Rn-H-G

LST is an input variable

$LE_{FEST-EWB} = LE_{FESTresidual}$

At a varying soil moisture

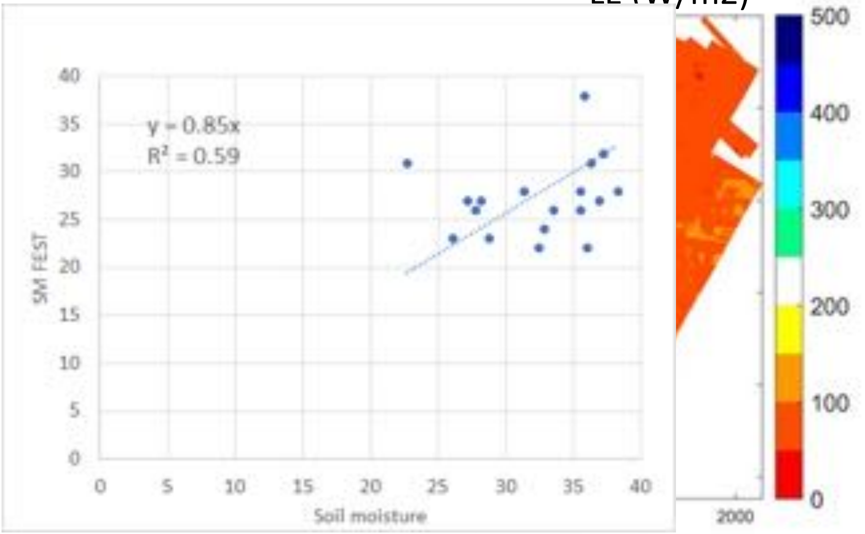


Corbari et al (2011) HYP
Corbari et al., 2015 (Jh)
Corbari & Mancini, 2014 (JHM)
Corbari et al., 2014 (HSJ)

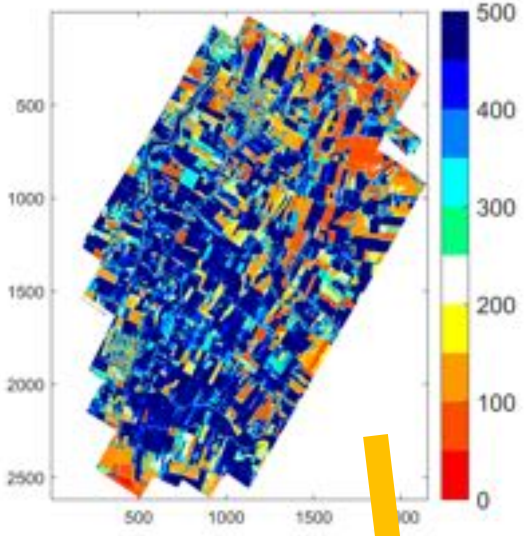
Can we estimate SM from satellite LST and a water-energy balance model? (Concordia 4m)

Unknown SM initial condition (SM residual)

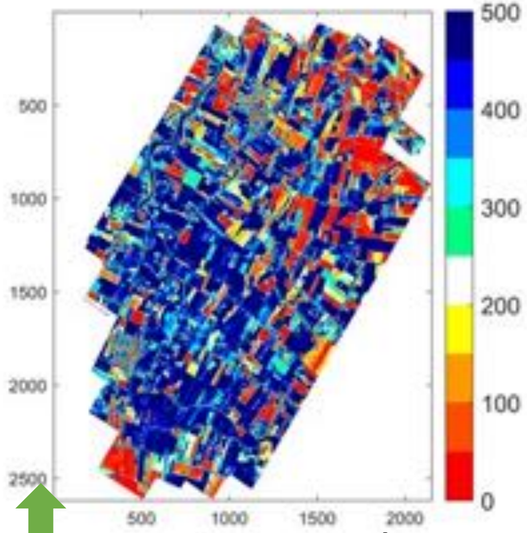
FEST-EWB LE (W/m2)



FEST-EWB Optimized LE

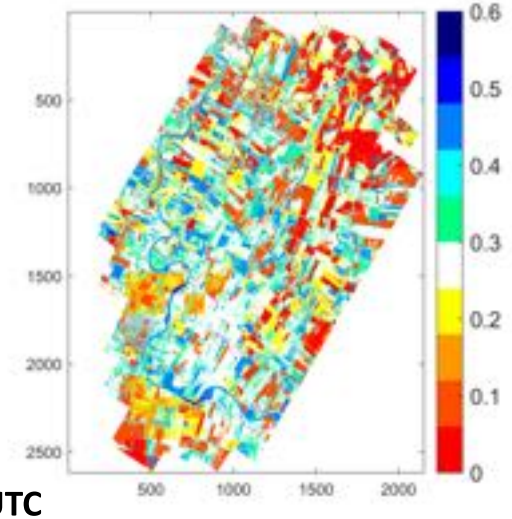


FESTresidual

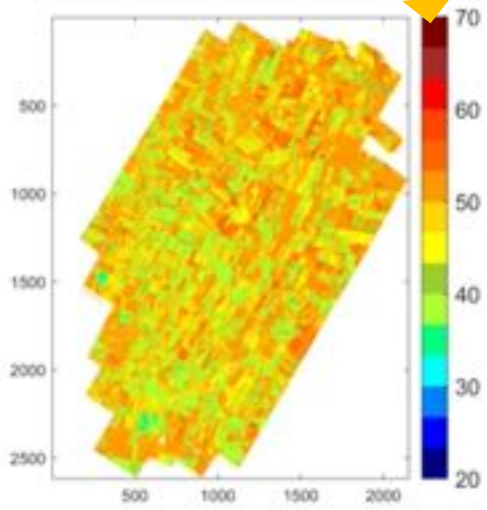


Mean spatial LE difference=14.5 Wm2 [abs 20.2 W/m2]

Optimzed SM moisture

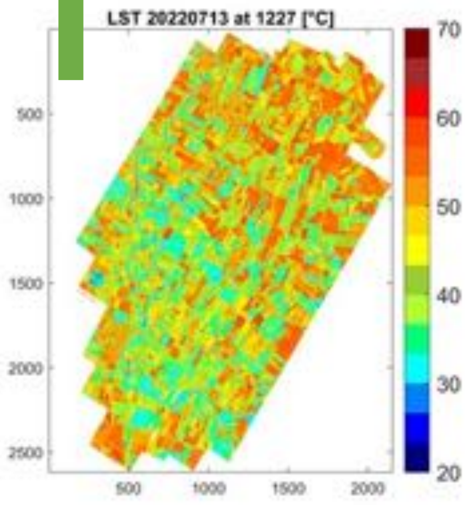


Optimzed LST



input

Airborne LST



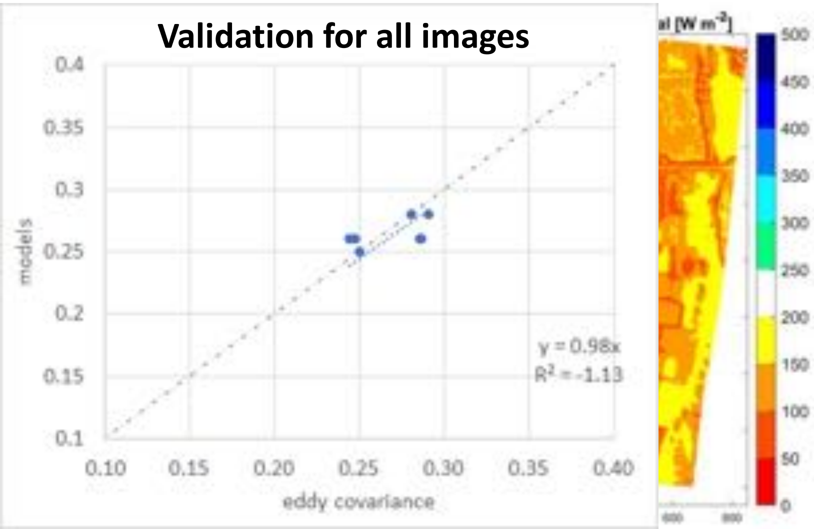
Mean spatial LST difference=-1.8 °C [abs 3.4 °C]

Example 13 july @ 12:27 UTC

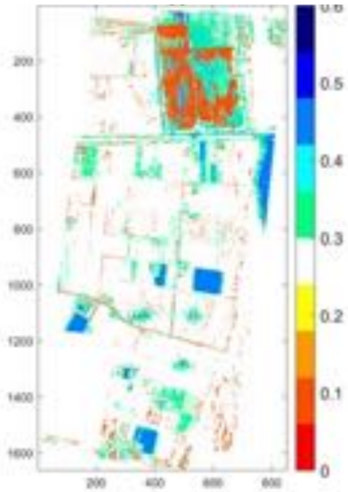
Can we estimate SM from satellite LST and a water-energy balance model? (Diamante 1m)

Unknown SM initial condition (SM residual)

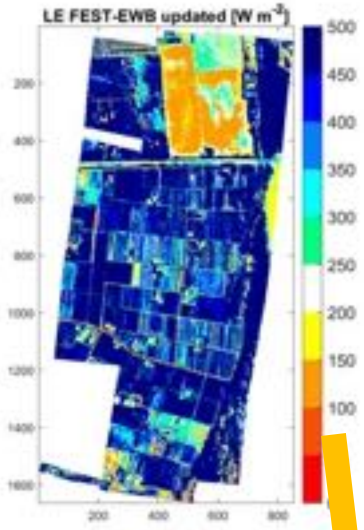
FEST-EWB
LE (W/m2)



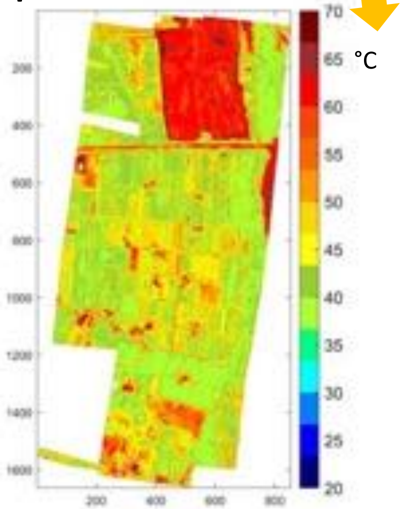
Optimzed SM moisture



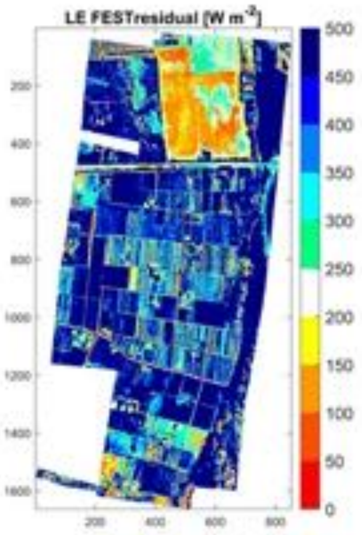
FEST-EWB
Optimized LE



Optimzed LST



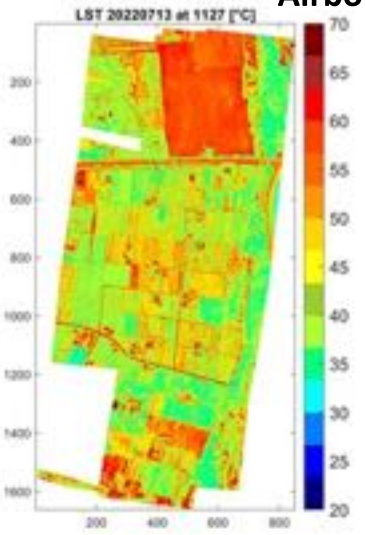
FESTresidual



Mean spatial LE difference=-19.5 Wm2 [abs 27.6 W/m2]

input

Airborne LST



Mean spatial LST difference=-0.9 °C [abs 2.8 °C]

Example 13 july @ 11:27 UTC

Conclusions

- We investigated the diurnal and spatial patterns of evapotranspiration variability with three numerical models based on different modelling hypothesis

- Differences and similarities in ET estimates have been analysed for different SM conditions and crop vegetation fraction, and have been compared to eddy covariance measurements for accuracy evaluation considering instantaneous estimates: different impact factors influencing the model performances were investigated, including SWC (irrigated/not irrigated), land cover cover, and FVC

- We show the influence of irrigation technique on LST and ET flux dynamic and spatial variability as well as on the impact on the water stress evolution

- The potentiality of estimating soil moisture at high spatial resolution by integrating airborne LST data into a coupled water-energy balance model