# An empirical expression to relate aerodynamic and surface temperatures for use within single-source energy balance models

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# Context

- Single source energy balance models are commonly used to retrieve Latent Heat flux LE from surface temperature $T_{surf}$ data acquired in the TIR domain
- Most methods derive LE as a residual of the surface energy balance :

$$LE=Rn(T_{surf})-H(T_{surf})-G(T_{surf})$$

- However, the temperature source of sensible heat flux H is not the surface temperature but the aerodynamic temperature $T_{aero}$:

$$H = \rho c_p \frac{T_{aero} - T_{air}}{r_a}$$

- The link between $T_{aero}$ and $T_{surf}$ is often parameterized as an excess resistance :

$$H = \rho c_p \frac{T_{surf} - T_{air}}{r_a + B_{radio}^{-1} / u_*}$$

- Or a $\beta$ function: $$\beta = \frac{T_{aero} - T_{air}}{T_{surf} - T_{air}} \quad \Rightarrow \quad H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_a}$$

- $\beta$ mostly depends on the vegetation extent (Leaf Area Index LAI)

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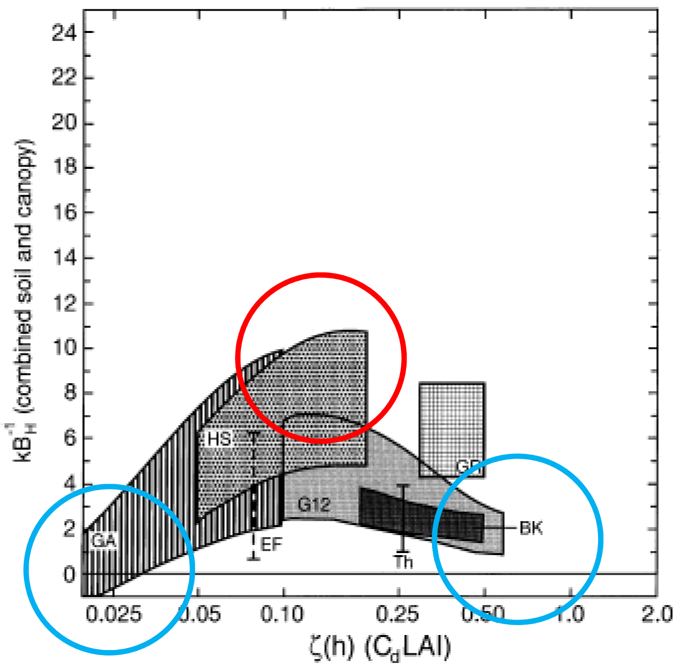
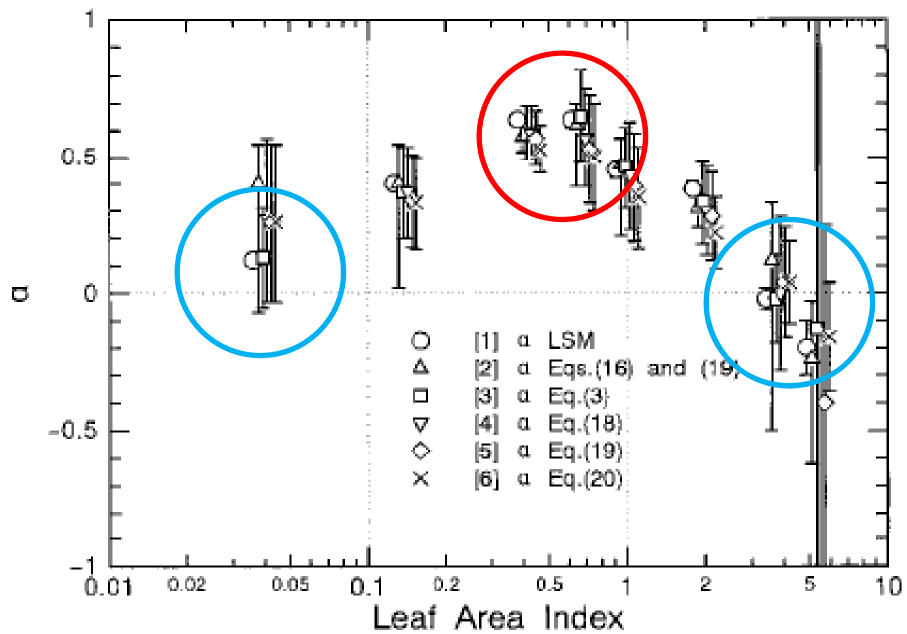
# β(LAI) function




Massman JH 1999

$$\alpha = 1 - \beta = 1 - \frac{1}{1 + kB_{radio}^{-1} / r_a k u_*}$$




Matsushima JMSJ 2005

Proposed relationship: $$\beta = 1 - \frac{a}{LAI * b * \sqrt{2\pi}} \cdot e^{\frac{(ln(LAI) - c)^2}{2 * b^2}}$$

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# Objectives

- to retrieve $\beta$ variations against Leaf Area Index for 9 experimental agricultural plots where seasonal evolution of micrometeorological conditions is available and LAI values range from 0 to above 2.
- to compare several formula, including the new one, of $\beta$(LAI) against observed trends.
- to compare the model performances in computing sensible heat flux from observed surface temperature.

# Published $B^{-1}_{radio}$(LAI) and β(LAI) relationships

| Author | Formula for $B^{-1}$ or β |
|---|---|
| Lhomme et al. | $B^{-1} = 8.6347 + 24.33LAI - 40.969LAI^2 + 26.121LAI^3 - 8.5759LAI^4 + 1.4378LAI^5 - 0.0972LAI^6$; |
| Matsushima | $\beta = [0.88\ \ 0.6\ \ 0.36\ \ 0.36\ \ 0.55\ \ 0.62\ \ 1.02\ \ 1.2]$ if $LAI = [0.04\ \ 0.14\ \ 0.42\ \ 0.68\ \ 1\ \ 2\ \ 3.8\ \ 5.4]$; |
| Blümel | $kB^{-1}(f_c) = \frac{C(f_c)}{ln(z_{eff}/z_{omeff})} - ln\left(\frac{z_{eff}}{z_{omeff}}\right)$ where<br>$f_c = 1 - e^{-0.5LAI}$;<br>$C(f_c) = \left(\frac{C_s - C_c}{1 - e^{-2.6(10h/z)^{0.355}}}\right) e^{-2.6(10h/z)^{0.355} f_c} + C_s - \left(\frac{C_s - C_c}{1 - e^{-2.6(10h/z)^{0.355}}}\right)$;<br>$C_s = ln\left(\frac{z}{z_{oms}}\right)\left[ln\left(\frac{z}{z_{oms}}\right) + kB_s^{-1}\right]; kB_s^{-1} = 2.46(z_{oms}u_*/\nu)^{0.25} - ln(7.4)$;<br>$C_c = ln\left(\frac{z-d}{z_{om}}\right)\left[ln\left(\frac{z-d}{z_{om}}\right) + kB_c^{-1}\right]$;<br>$kB_c^{-1} = 16.4(\sigma_\alpha LAI^3)^{-0.25}\left[0.05u \Big/ ln\left(\frac{z-d}{z_{om}}\right)\right]^{0.5}$;<br>$\sigma_\alpha = 1 - \frac{0.5}{0.5 + LAI} e^{-LAI^2/8}; z_{eff} = z - f_c d$;<br>$z_{omeff} = z_{eff} e^{-k \Big/ \sqrt{g(f_c)\left[\frac{k}{ln(\{z-d\}/z_{om})}\right]^2 + (1-g(f_c))\left[\frac{k}{ln(z/z_{oms})}\right]^2}}; g(f_c) = \sqrt{f_c} + f_c(1-f_c)$;<br>$Z_{oms}$=0.005; |
| Su/Massman | $B^{-1}(f_c) = \frac{1}{2\frac{u_*}{u(h)}\left(1 - e^{-0.1LAI\left(\frac{u_*}{u(h)}\right)^{-2}}\right)} f_c^2 + \frac{2\frac{u_*}{u(h)}\frac{z_{om}}{h}}{1.25(z_{oms}u_*/\nu)^{-0.5}} f_c(1-f_c) + B_s^{-1}(1-f_c)^2$<br>where *u(h)* is the wind speed at the top of the canopy |

$B^{-1}_{radio}$(LAI) from SVAT simulations

β(LAI) from EC/TIR data on rice paddy

$B^{-1}_{radio}$(LAI) from the theoretical wind profile within the canopy

**$B^{-1}_{radio}$ relationships translated into β:**

$$H = \rho c_p \frac{T_{surf} - T_{air}}{r_a + \frac{B^{-1}_{radio}}{u_*}} \quad \Rightarrow \quad \beta = \frac{1}{1 + \frac{kB^{-1}_{radio}}{r_{a,obs} k u_{*,obs}}}$$

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# Dataset

- 9 agricultural seasons at 3 locations (Toulouse, Avignon, Marrakech)
- Eddy Covariance and std meteorological data
- Destructive + hemispherical photo. LAI
- Longwave emission measured by 2 types of thermoradiometers (small FOV/narrowband and hemispherical/broadband)

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# Rationale to retrieve $\beta_{obs}$(LAI)

- Observed $\beta$ (median values per 0.5 LAI interval) retrieved from observed sensible heat flux, surface temperature and friction velocity (10AM-4PM):

$$\beta_{obs} = \frac{r_{a,obs} H_{obs}}{\rho c_p \left(T_{surf,obs} - T_{air,obs}\right)} \qquad r_{a,obs} = \frac{\left[ ln\left(\frac{z-d}{z_{om} / e^{kB_{aero}^{-1}}}\right) - \Psi_h\left(\frac{z-d}{L_{obs}}\right) + \Psi_h\left(\frac{z_{om} / e^{kB_{aero}^{-1}}}{L_{obs}}\right)\right]}{k u_{*,obs}}$$

- Roughness length $z_{om}$ and displacement height d from Pereira et al. (1999) checked with the help of observed friction velocity $u_{*,obs}$ values
- Vegetation emissivity correction (0.98 ) and $B^{-1}_{aero}$ (~0) adjusted within realistic bounds so that $\beta_{obs}$ tends towards 1 @ max LAI
- Errors on $H_{obs}$, $T_{surf,obs}$, $z_{om}$ and $u_{*,obs}$ produce $\beta_{obs}$ error bars

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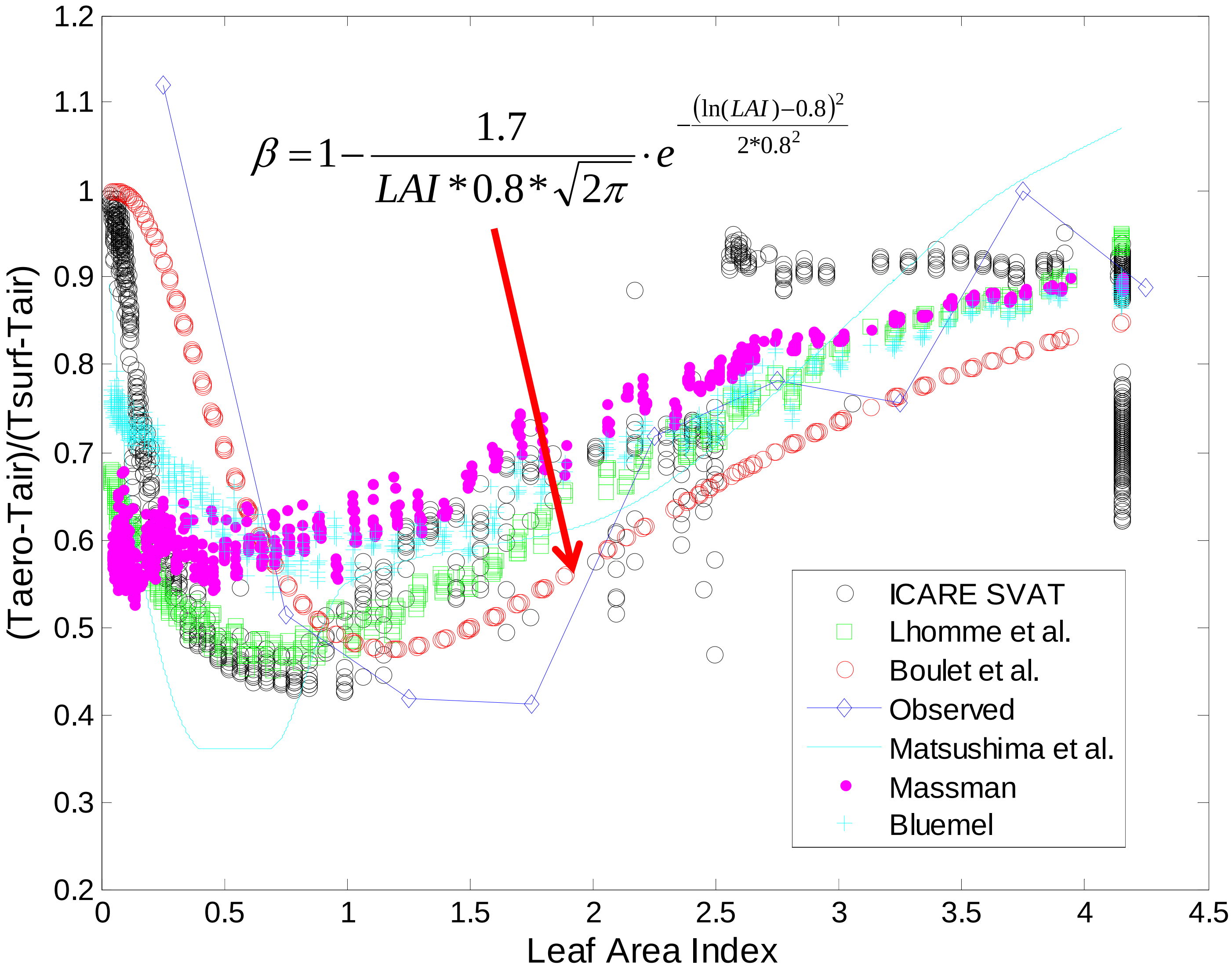
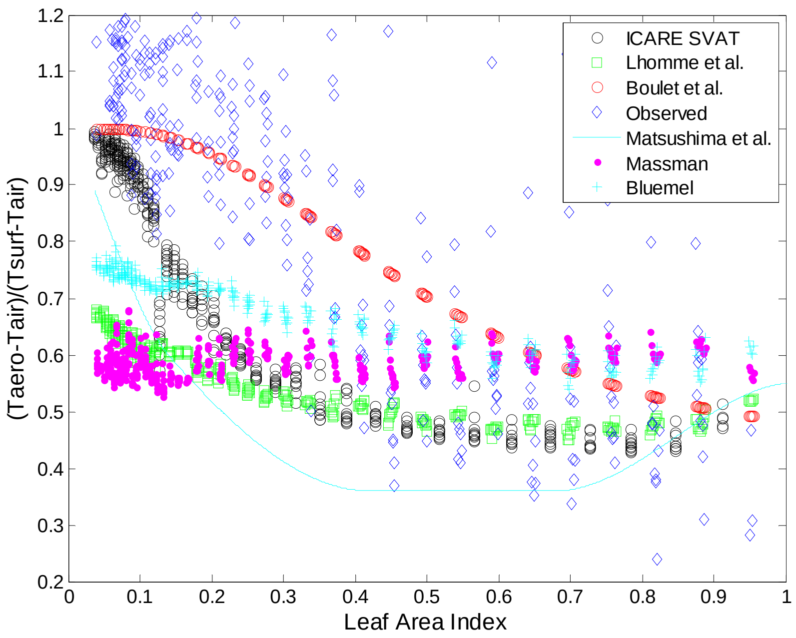
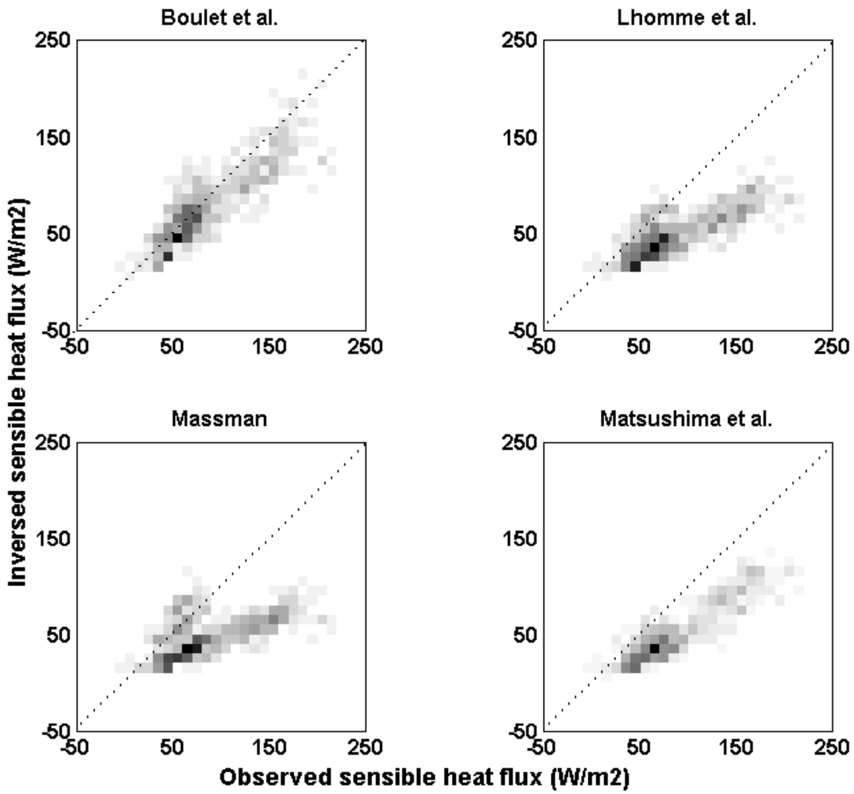
# β retrieval for the R3 wheat site



# Retrieval for 0<LAI<1




$$H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_a}$$

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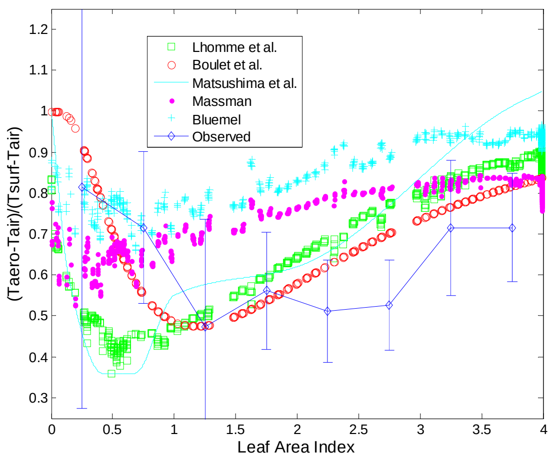
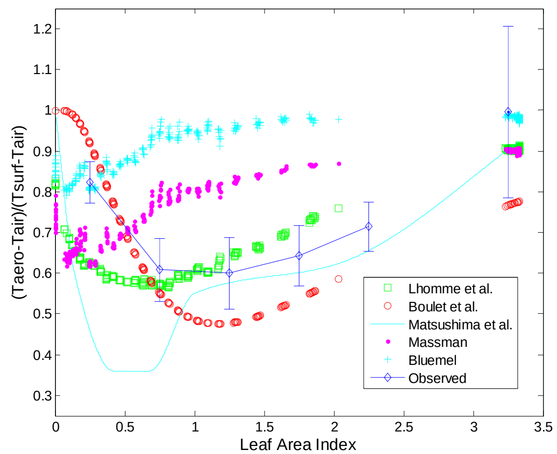
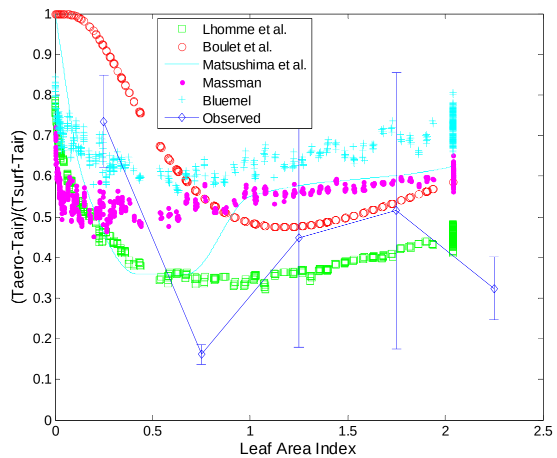
$\beta = (T_{aero} - T_{air}) / (T_{surf} - T_{air})$




Avignon in 2004 (Wheat)

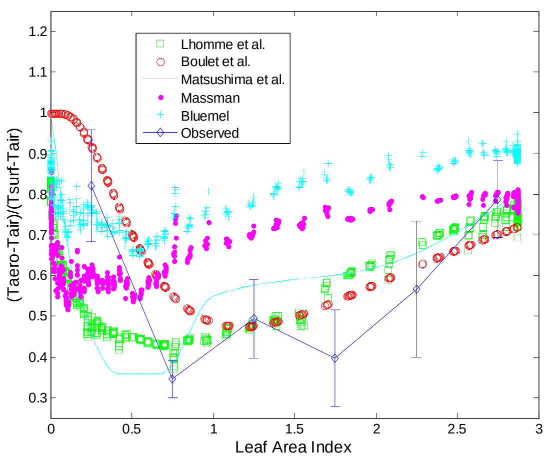



Lamasquère in 2006 (Corn)

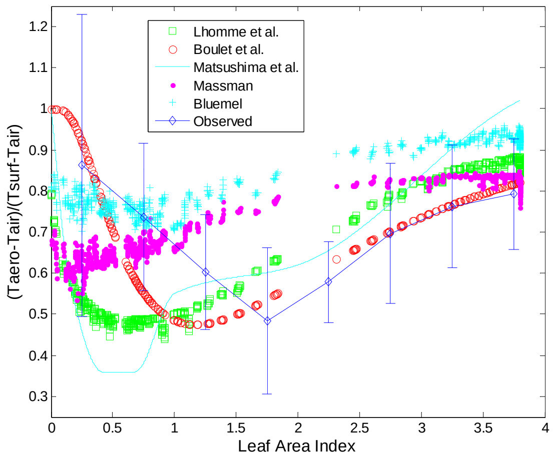



Auradé in 2007 (Sunflower)

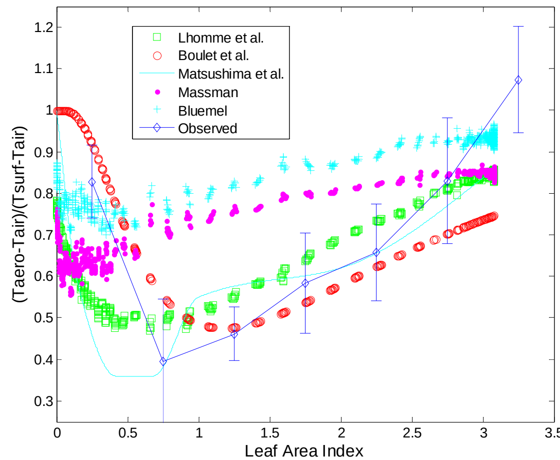
**New formulation: a=1.7, b=c=0.8 (cal. on R3 dataset) kept for all datasets**




Avignon in 2005 (Peas)




Auradé in 2006 (Wheat)




Avignon in 2007 (Sorghum)

**Leaf Area Index**

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# Sensible heat flux retrieval

$$H = \rho c_p \beta \frac{T_{surf} - T_{air}}{r_a}$$

| | **Boulet et al.** | **Lhomme et al.** | **Matsushima** | **Su/Massman** | **Blümel** |
|---|---|---|---|---|---|
| **Wheat R3 2004** | 52 | **62** | **76** | **61** | 57 |
| **Wheat Avignon 2004** | *45* | *46* | 52 | 50 | *47* |
| **Peas Avignon 2005** | 55 | 53 | 50 | 53 | 53 |
| **Wheat Avignon 2006** | *41* | **-*** | *47* | *45* | *40* |
| **Sorghum Avignon 2007** | 52 | 54 | **66** | 54 | **68** |
| **Wheat Auradé 2006** | *45* | *49* | **66** | *47* | 54 |
| **Sunflower Auradé 2007** | **72** | **61** | *45* | **65** | 59 |
| **Corn Lamasquère 2006** | **78** | **88** | **95** | **86** | **76** |
| **Wheat Lamasquère 2007** | *45* | **60** | 51 | *48* | 50 |

(RMSE in W/m$^2$ with modelled aerodynamic resistance)

LAI values beyond interval of validity of the empirical regression

# Conclusion

- A simple 2 parameter expression of the link between aerodynamic and surface temperatures is proposed
- This expression matches fairly well the observed variations along LAI values
- Its performance in estimating sensible heat flux with calibrated values on the R3 site is at least comparable to, and often better than, the previously published relationships
- Need to reassess impact of geometry for vegetation with strong geometric features, as well as roughness length for heat exchange ($kB_{aero}^{-1}$)

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