9th International Conference on Urban Climate, Toulouse, France
22 July 2015

Numerical Evaluation of Heat Budget in Tree Crown Considering the Detailed Structure

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Background

Planting trees: One of the countermeasures to UHI

- Cooling effect by the transpiration
- Sunlight cover effect

Understanding the performance of heat exchange between the individual plant and the atmosphere.

Apply to the effective design for comfortable outdoor space

Important to establish the prediction model of heat transfer around the plant foliage

Heat budget of isolated plant unit is numerically evaluated with thermal plant model including radiation transfer model for net radiation and transpiration model for latent heat transfer.

Heat budget of isolated plant

$$\boxed{Rn = H + lE + G}$$

Rn	**Net radiation**
H	**Sensible heat**
lE	**Latent heat**
G	**Conductive heat**

Predict from circumferential environment

Heat budget of plant

$$\boxed{Rn = H + lE + G \fallingdotseq H + lE}$$

Temperature difference between front and back surface of a leaf is assumed to be small.

Conductive heat flux in a leaf is neglected.

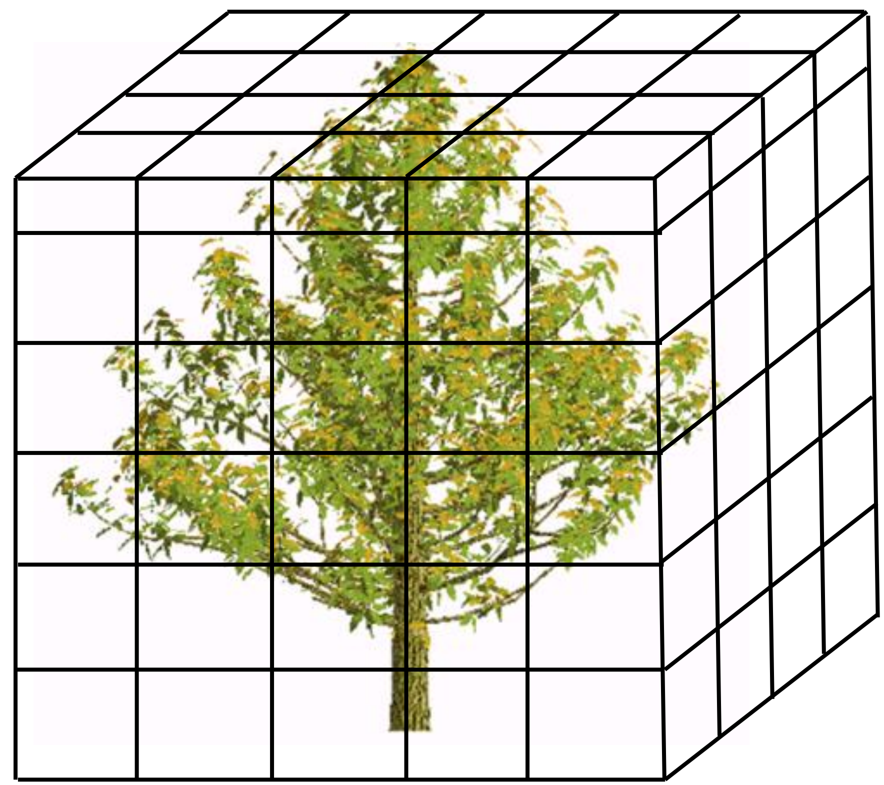
Net radiation absorbed in leaves ***Rn*** and latent heat transfer from leaves ***lE*** are identically evaluated, and sensible heat transfer ***H*** is evaluated as the heat budget is satisfied.

Modelling of tree foliage

Computer graphics model with software AMAP is applied to modelling of tree crown.

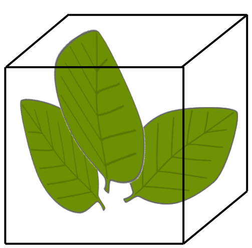
AMAP: tree characteristics such as shape of tree crown, a leaf and leafing arrangement on a branch

Polygon data of leaves included in a control volume is transformed into foliage structure parameters.



$a(x)$ Leaf area density

$g(x,\hat{r})$ Configuration function of PDF of leaf surface direction vectors



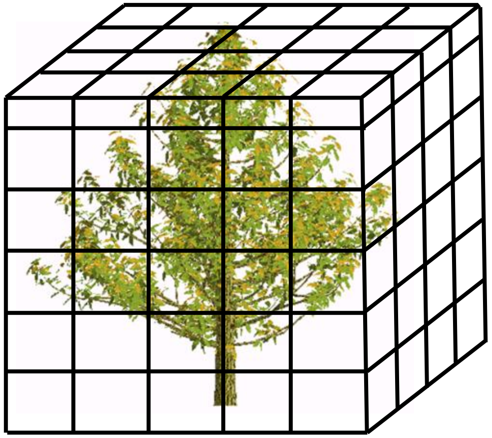
Radiative heat transfer model for foliage

Ross's radiative heat transfer model

Short wavelength radiation

$$i(x,\hat{r}) = i_d(x,\hat{r}) + I(x,\hat{r})$$

Separate radiation intensity into direct and diffuse solar radiation components



Direct solar radiation of PAR and NIR

$$r_j \frac{\partial i_d(x,\hat{r})}{\partial x_j} = -a(x)G(x,\hat{r})i_d(x,\hat{r})$$

Diffuse solar radiation of PAR and NIR

$$r_j \frac{\partial I(x,\hat{r})}{\partial x_j} = -a(x)G(x,\hat{r})I(x,\hat{r}) + a(x)\int_{4\pi}\Gamma(x,\hat{r},\hat{r}')I(x,\hat{r}')d\omega' + a(x)e(x,\hat{r})$$

Long wavelength radiation Thermal radiation of atmosphere and leaf surface

$$r_j \frac{\partial i_{ir}(x,r)}{\partial x_j} = -a(x)G(x,r)i_{ir}(x,r) + \frac{1-\varepsilon}{\pi}a(x)\int_{4\pi}\Gamma_R(x,r,r')i_{ir}(x,r')d\omega'$$

$$+\frac{\varepsilon}{\pi}a(x)G(x,r)\sigma\left(T_L + 273.15\right)^4$$

Transpiration model

Prediction of transpiration rate of a leaf surface

$$J_p = \frac{g_b g_s (\rho_l - \rho_c)}{g_b + g_s}$$

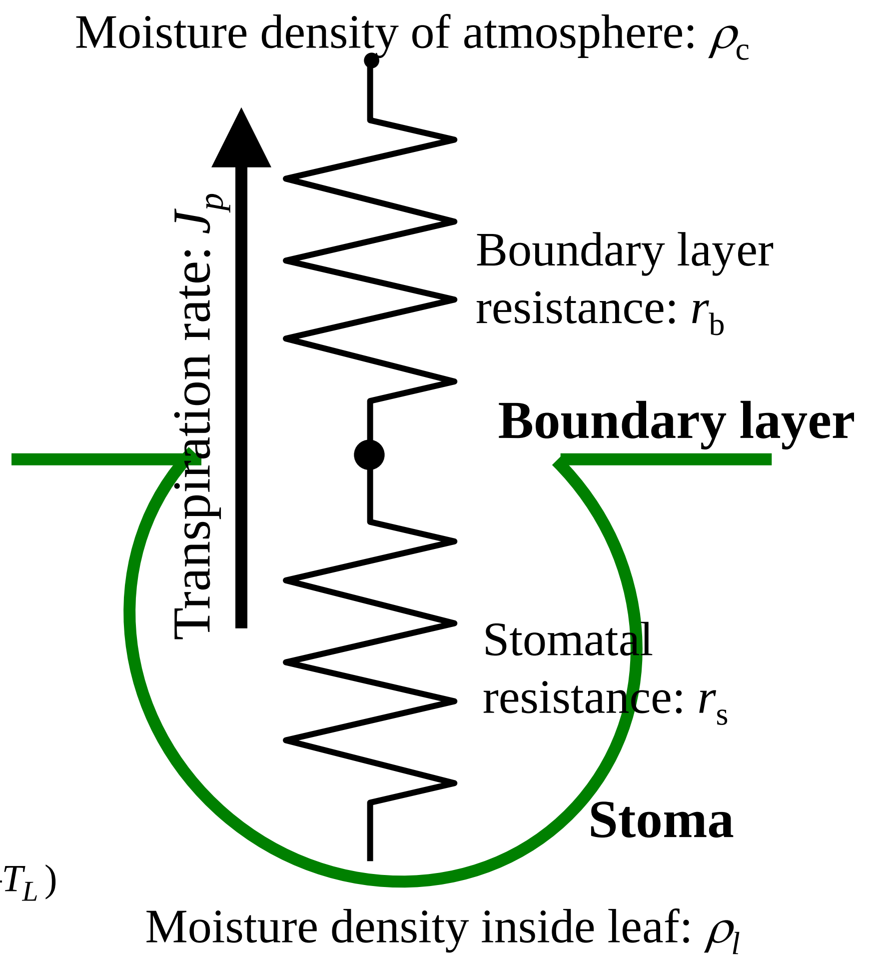
Jarvis model

$$g_s = g_{s,\max} f_1(Q) f_2(D) f_3(T_l)$$

$$f_1(Q) = \frac{g_{s,\max} \cdot Q}{Q + g_{s,\max} / a}$$

$$f_2(D) = 1 - bD$$

$$f_3(T_l) = \left(\frac{T_l - T_L}{T_0 - T_L} \right) \left(\frac{T_H - T_l}{T_H - T_0} \right)^{(T_H - T_0)/(T_0 - T_L)}$$



$$\boxed{T_l = 0.882 T_a + 0.0036 S + 1.86}$$

Leaf temperature: predict with linear function of global solar radiation and air temperature.

Assumption in numerical analysis

- Scattered ray at leaf surface in a volume element does not contribute to another volume.
- Diffuse solar radiation and infrared radiation (long wavelength) are not taken into account.
- Ratios of energy of PAR and NIR to solar radiation are 0.5 and 0.5, respectively.
- Reflectance and transmittance in PAR region of leaf surface are 0.1 and 0.1, and those in NIR are 0.4 and 0.5, respectively.

Measurement of heat budget for foliage

Evaluate the validity of numerical model

Measured object: potted flesh plant of hibiscus

Date and place: 2nd Aug 2012 10:00 – 16:00

Osaka Prefecture University (34.5N, 135.5deg.E)

Measuring items:

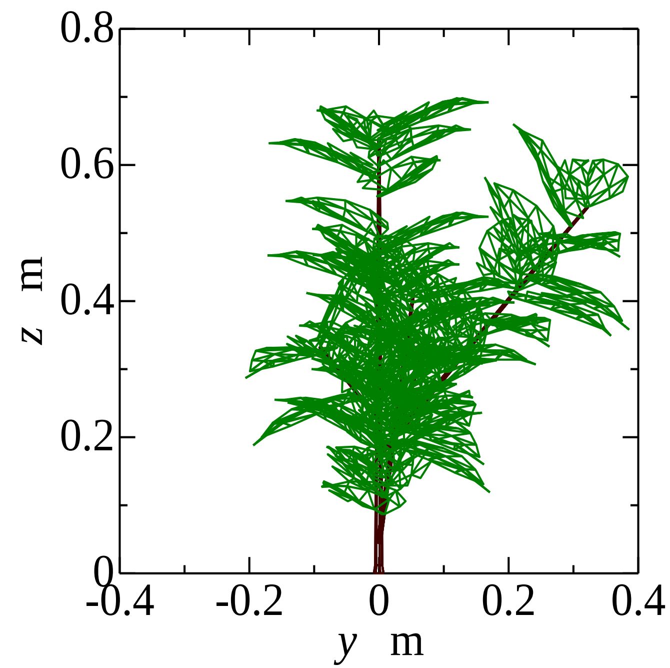
Solar and infrared radiation,
air temperature, relative humidity,
wind velocity, leaf temperature

***Rn*:** consider solar and infrared radiation from sky and soil and floor surfaces and LAI of potted hibiscus

***lE*:** Based on a method of weighting Enough water is poured into the potting, and soil of potting is cover with plastic film.

Numerical conditions

2nd, Aug 2012	10:00	12:00	14:00
Zenith angle (deg.)	32.4	16.9	30.8
Azimuth angle (deg.)	-66.6	3.49	64.2
Global solar rad. (W/m^2)	777	559	820
Air temp. (deg.C)	35.5	33	35.4
Relative humid. (%)	38.1	50.2	41.7
Wind velocity (m/s)	1.9	1.7	1.8

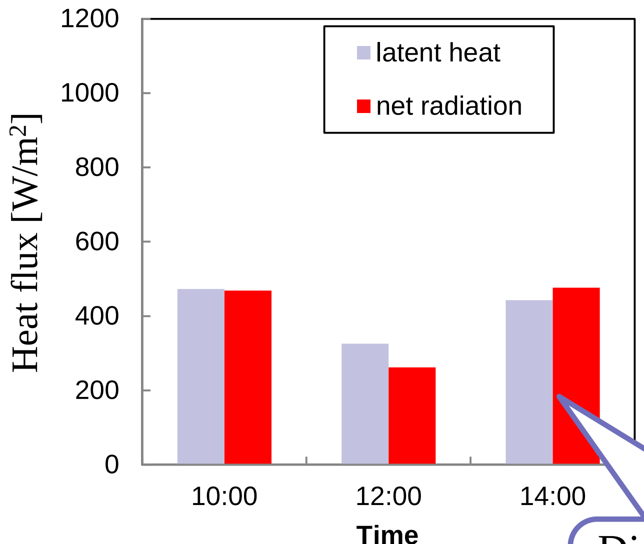


Tree height (m)	**Projected area (m^2)**	**LAI**
0.70	0.12	4.6

Jarvis parameters for hibiscus

$g_{s,max}$ (cm/s)	**a**	**b**
0.807	0.000165	0.226

Comparison of heat budget between numerical and experimental results

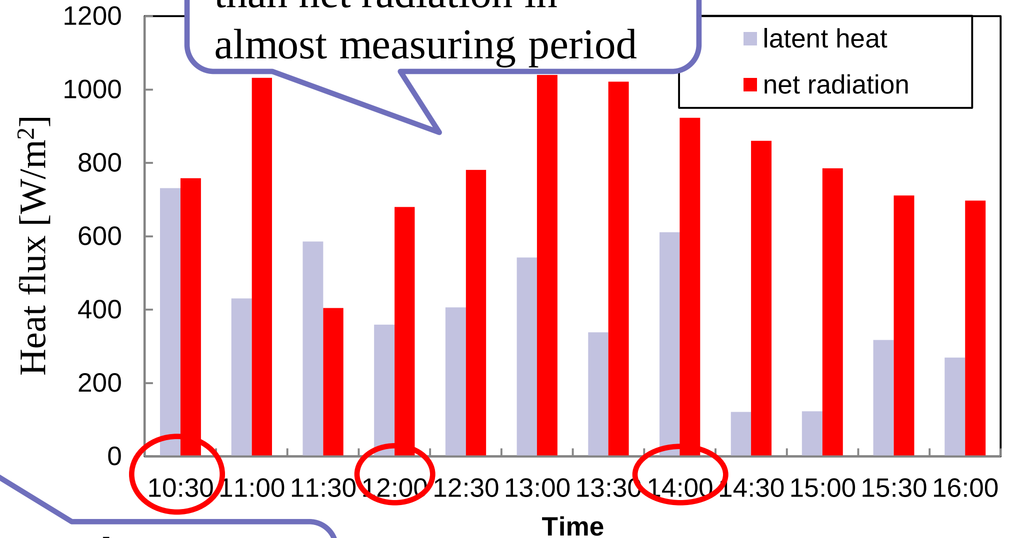


Numerical result

LAI=4.6

Difference between latent heat flux and net radiation is small.

Latent heat flux is smaller than net radiation in almost measuring period



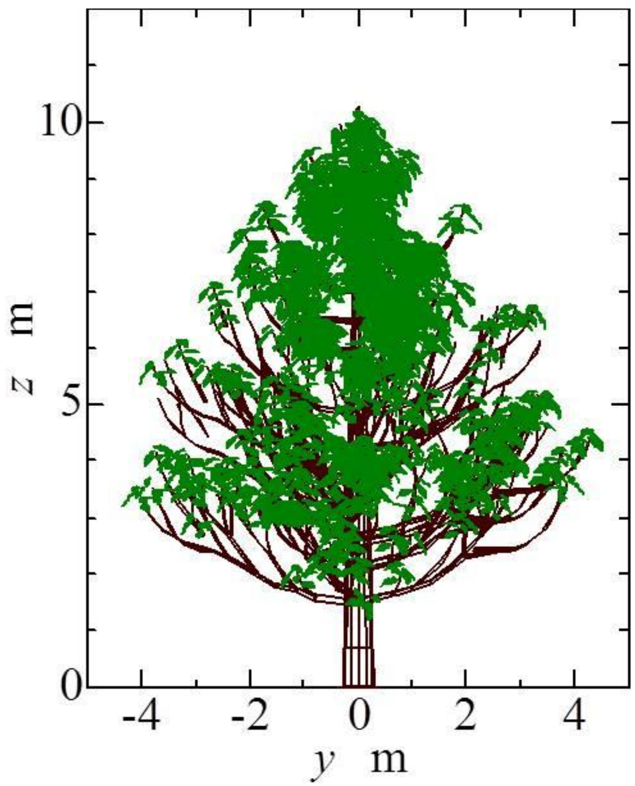
Result of field measurement

LAI=7.3

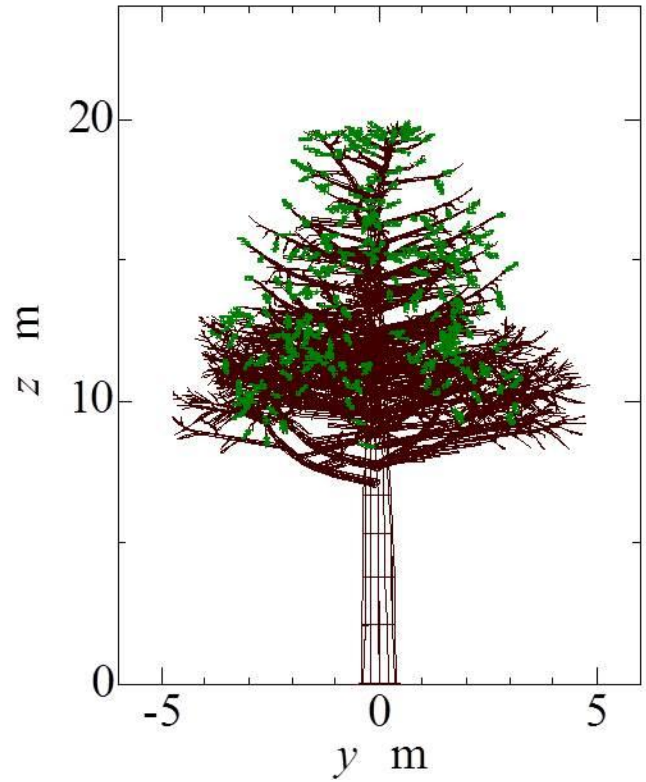
In numerical result, both net radiation and latent heat transfer in numerical analysis is smaller than those in experiment.

It is considered that the difference of LAI leads to the underestimation in numerical analysis.

Numerical analysis of isolated plant



Camphor



Ginkgo

	Height (m)	Projected area (m^2)	LAI	g_{smax} (cm/s)	a	b	T_0
Camphor	10.2	125	3.3	0.75	0.022	0.0026	32.1
Ginkgo	19.7	170	4.6	0.34	0.014	0.011	29.3

Numerical results for isolated tree

	Hibiscus			Camphor			Ginkgo		
Aug. 2nd 2012	10:00	12:00	14:00	10:00	12:00	14:00	10:00	12:00	14:00
Transmission ratio of insolation (%)	43	37	41	38	37	37	57	57	58
Shielding ratio of insolation (%)	57	63	59	62	63	63	43	43	42
Net radiation (W/m^2)	468	262	477	414	260	429	417	253	399
Latent heat flux (W/m^2)	473	326	443	394	331	382	305	277	297

- Net radiation and latent heat flux are almost same value.
- The scattering light from leaf surface is emitted outside of the computation domain without contribution to absorption in tree crown. It is considered that the ratio of scattering is a half of incident solar energy and the assumption not to contribute to absorption in other area in tree crown is overestimate.
- It is important for accurate analysis of heat budget in tree crown to evaluate the effect of the scattering between leaves and thermal radiation from atmosphere and leaves.

Conclusion and future plan

- Heat budget of isolated plant unit was numerically evaluated with thermal plant model including radiation transfer model for net radiation and transpiration model for latent heat transfer, and the numerical results were validated by comparison with that of outdoor measurement for a potted plant.
- By comparison with field measurement of heat budget of hibiscus, both net radiation and latent heat transfer in numerical results were underestimated.
- In numerical results for several kinds of isolated plant, net radiation and latent heat flux were evaluated to be almost same value.
- In a future plan, numerical analysis of heat budget in tree crown will be performed by taking into account the effect of the scattering of solar radiation between leaves and thermal radiation from atmosphere and leaves and evaluate whether the accuracy is improved.

$$e(x,r)=\int_{\omega'=4\pi}\Gamma(x,r,r')i_d(x,r')d\omega'$$

$$G(x,\hat{r})=\frac{1}{2\pi}\int_{4\pi}g(x,\hat{r}_L)\left|(\hat{r}\cdot\hat{r}_L)\right|d\omega_L$$

$$\Gamma(x,r,r')=\frac{T}{\pi}\Gamma_T(x,r,r')+\frac{R}{\pi}\Gamma_R(x,r,r')$$

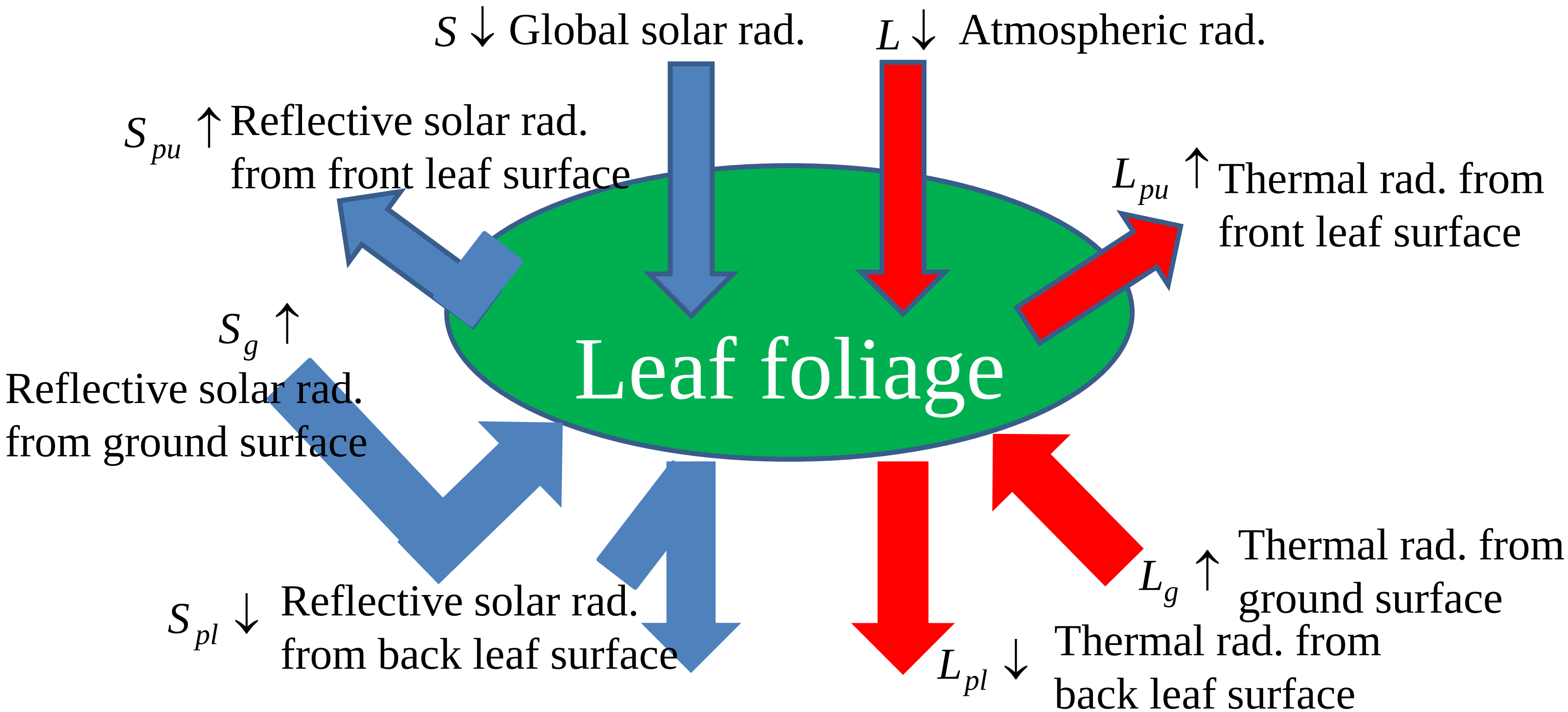
$$\Gamma_T(x,r,r')=\frac{1}{2\pi}\int_{\omega_L=2\pi}g(x,r_L)H\left[(r,r_L)(r',r_L)\right]d\omega_L$$

$$\Gamma_R(x,r,r')=\frac{1}{2\pi}\int_{\omega_L=2\pi}g(x,r_L)H\left[-(r,r_L)(r',r_L)\right]d\omega_L$$

$$H[f]=f \quad if \quad f\geq 0 \qquad H[f]=-f \quad if \quad f<0$$

Net radiation of upper side of foliage

$$Rn = S\downarrow + L\downarrow - S_{pu}\uparrow - L_{pu}\uparrow$$



Net radiation of lower side of foliage

$$Rn = S_g\uparrow + L_g\uparrow - S_{pl}\downarrow - L_{pl}\downarrow$$

Jarvis model

Q: PPFD, D: Vapor pressure deficit, T_l: leaf temperature

$$g_s = g_{smax} f_1(Q) f_2(D) f_3(T_l)$$

$$f_1(Q) = \left(\frac{g_{smax} Q}{Q + g_{smax}/a} \right)$$

$$f_2(D) = 1 - bD$$

$$f_3(T_l) = \left(\frac{T_l - T_L}{T_0 - T_L} \right) \left(\frac{T_H - T_l}{T_H - T_0} \right)^{(T_H - T_0)/(T_0 - T_L)}$$

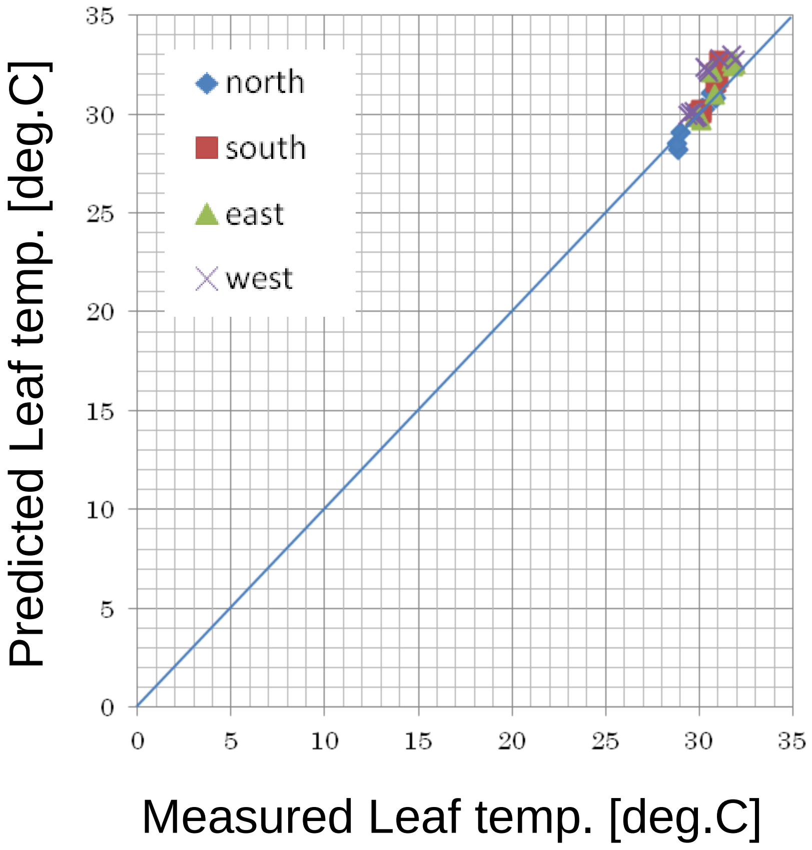
- **g_{smax}: maximum stomatal conductance**
- **a: parameter about stomatal aperture**
- **b: parameter about stoma closing by VPD**
- **T_0: Optimal temperature**
- **T_H: Maximum limit temperature(=45deg.C)**
- **T_L: Minimum limit temperature(=5deg.C)**

In optimization for four parameters (g_{smax},a,T_0,b), nonlinear method of least squares is adopted.

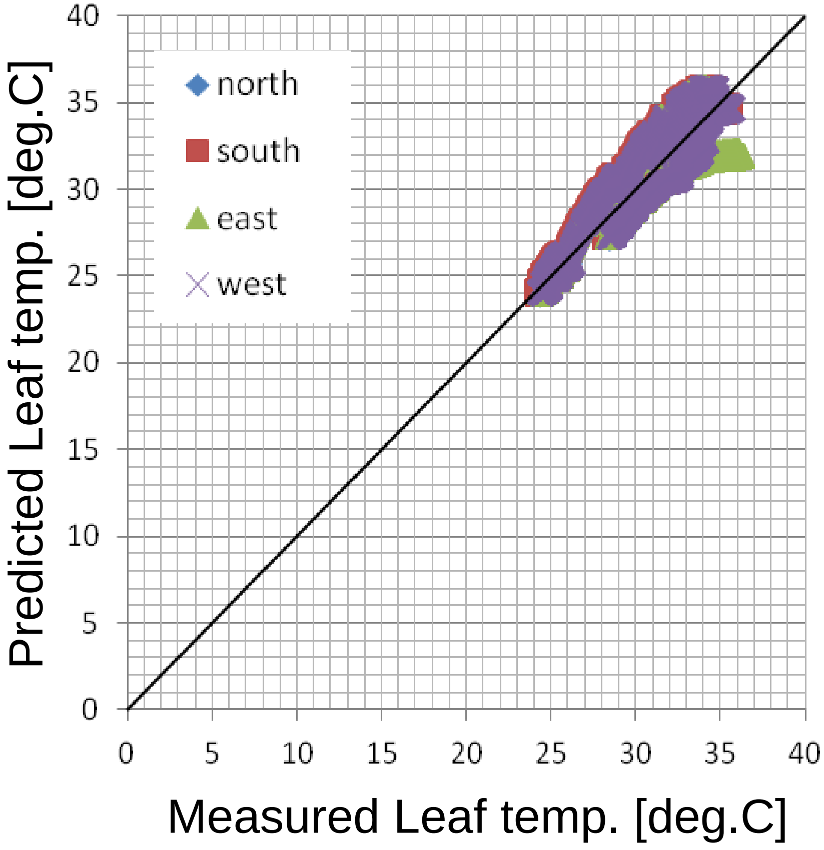
Identification of parameters by measured leaf temperature

$$T_l = 1.068T_a + 0.00044S - 2.71$$

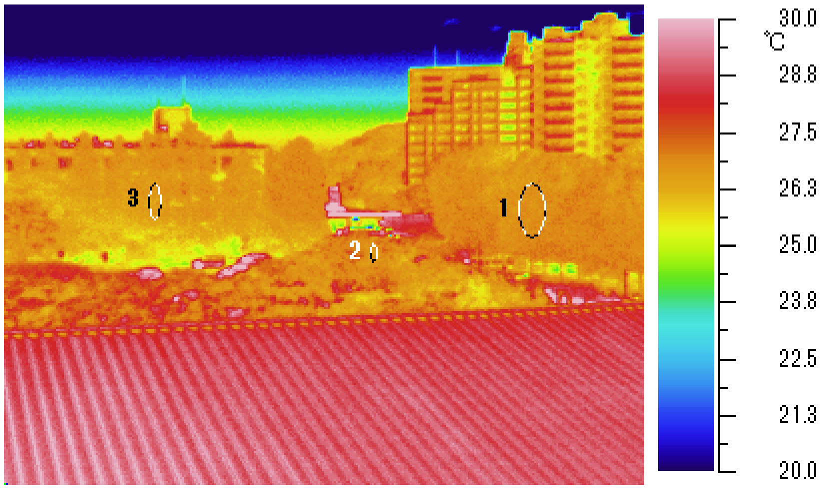
Ta : Air temp.
S : Solar rad.



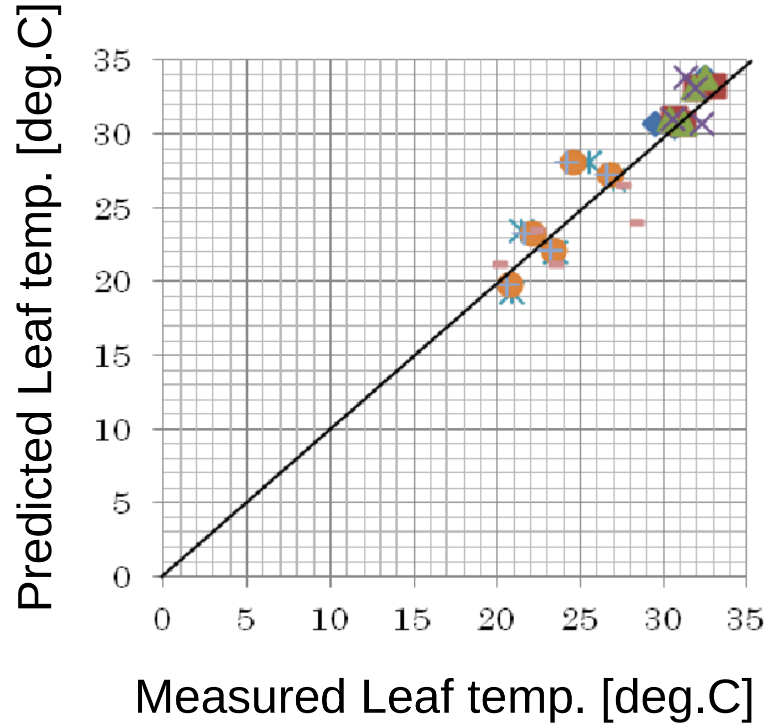
Measured with leaf porometer



Measured with thermocouple



Measured with thermography



	a地点領域1		b地点領域1		b地点領域2		b地点領域3	
2011/8/7	分散	標準偏差	分散	標準偏差	分散	標準偏差	分散	標準偏差
9時	0.0469702	0.216726	0.013918	0.117976	0.025471	0.159595	0.022186	0.148948
12時	0.0464938	0.215624	0.081695	0.285823	0.045299	0.212835	0.058902	0.242698
15時	0.0980376	0.313109	0.031373	0.177124	0.036364	0.190693	0.018691	0.136716
18時	0.037077	0.192554	0.034388	0.185441	0.027487	0.165792	0.022029	0.148423