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A MATHEMATICAL MODEL OF SUN DRYING OF RICE

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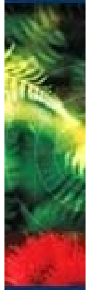


Introduction

- As mentioned in previous paper, sun drying of rice still most widely used & economical

Sun drying of rice

- A complicated and poorly controlled process of heat transfer from sun to grains and mass transfer from grains to air

Objective of this paper

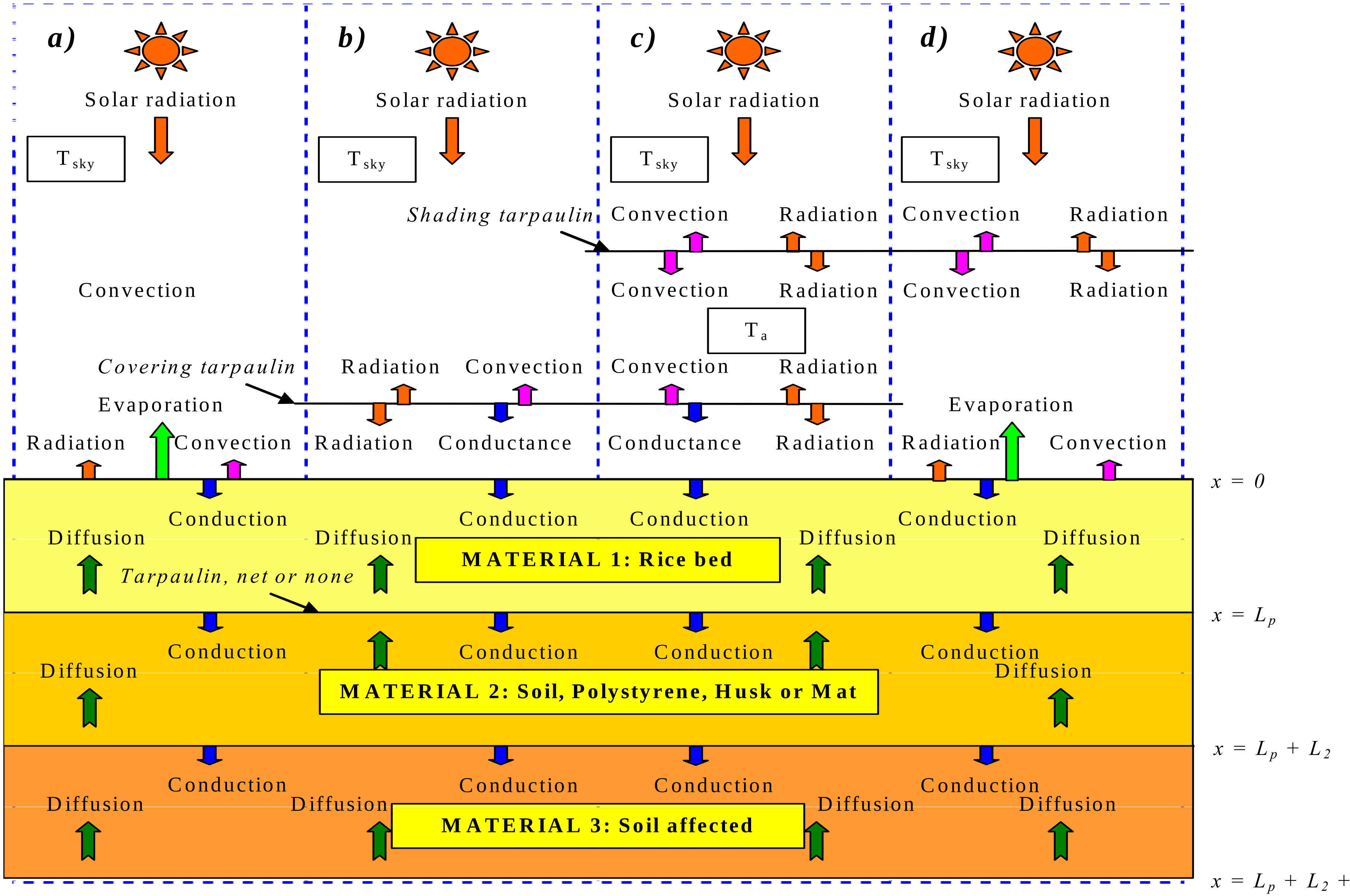
- Formulate math model to predict drying of rice during sun drying
- Solve model for various input parameters
- Validate results against experimental measurements

Process Description

- Conversion of radiation from sun to thermal heat in bed
- Transfer moisture from centre of grain kernel to surface
- Transfer moisture from surface of kernel to air between grains
- Transfer moisture from between grains to bed surface
- Transfer moisture from bed surface to surrounding air

Four scenarios modelled

- Direct radiation onto bed
- Direct radiation onto tarpaulin covering bed
- Direct radiation onto cover above bed
- Direct radiation onto cover above bed with another tarpaulin directly on bed



a)

Solar radiation

T_{sky}

Convection

Covering tarpaulin

Evaporation

Radiation

Convection

b)

Solar radiation

T_{sky}

Shading tarpaulin

Radiation

Convection

Radiation

Conductance

c)

Solar radiation

T_{sky}

Convection

Radiation

Convection

Radiation

T_a

Convection

Radiation

Conductance

Radiation

d)

Solar radiation

T_{sky}

Convection

Radiation

Convection

Radiation

Evaporation

Radiation

Convection

$x = 0$

Diffusion

Conduction

Tarpaulin, net or none

Diffusion

Conduction

Conduction

Diffusion

Conduction

Diffusion

MATERIAL 1: Rice bed

$x = L_p$

Diffusion

Conduction

Conduction

Conduction

Conduction

Diffusion

MATERIAL 2: Soil, Polystyrene, Husk or Mat

$x = L_p + L_2$

Diffusion

Conduction

Diffusion

Conduction

Conduction

Diffusion

Conduction

Diffusion

MATERIAL 3: Soil affected

$x = L_p + L_2 + L_3$

Soil not affected

Physical Basis

- Temperature and moisture gradients develop through bed depth
- The solid (rice kernels) and gaseous phases in bed considered as continua with interaction over adjacent interfaces
- Moisture diffusivity and thermal conductivity treated as effective properties of porous rice bed
- Rate of moisture leaving bed depends on vapor pressure difference between kernel and surrounding air

Model Formulation

- To account for simultaneous changes in material conditions with locations and time,
- Heat (temperature) and mass (MC and RH) balances formulated in form of Partial Differential Equations (PDEs).

Within the kernel

Heat transfer

$$\rho_m . c_{pm} \frac{\partial T}{\partial t} = \lambda_m \frac{\partial^2 T}{\partial x^2} - D_{vm.eff} . \varepsilon_m . h_g \frac{\partial^2 C}{\partial x^2}$$

for $0 < x < L_p$, (m=1)
$L_p < x < L_p + L_2$, (m=2)
$L_p + L_2 < x < L_p + L_2 + L_3$, ($m$=3) and
$t > 0$.

Energy balance at surface

$$
\begin{aligned}
&\left(1 - S_1\right)\left(1 - S_2\right)\beta_p .A_{top} .I + S_1\left(1 - S_2\right)\beta_p .A_{top} .I_{sh} \\
&+ S_1\left(1 - S_2\right)F_{A1} .\in_{tarp} .\in_p .A_{top} .\sigma\left[\left(T_{sh} + 273.15\right)^4 - \left(T_{x=0} + 273.15\right)^4\right] \\
&+ S_2 .F_{A2} .\frac{1}{\left(\dfrac{1}{\in_{tarp}} + \dfrac{1}{\in_p}\right) - 1} .A_{top} .\sigma\left[\left(T_{cov} + 273.15\right)^4 - \left(T_{x=0} + 273.15\right)^4\right] \\
&+ S_2 .A .U_{tarp/p}\left(T_{cov} - T_{x=0}\right) - D_{vp.eff} .\varepsilon_p .h_{gin} .A\frac{\partial C}{\partial x} \\
= &\left(1 - S_1\right)\left(1 - S_2\right)\in_p .A_{top} .\sigma\left[\left(T_{x=0} + 273.15\right)^4 - \left(T_{sky} + 273.15\right)^4\right] \\
&+ S_1\left(1 - S_2\right)\in_p .A_{top} .\sigma\left[\left(T_{x=0} + 273.15\right)^4 - \left(T_a + 273.15\right)^4\right] \\
&- \left(1 - S_2\right)k_y .h_{gout} .A\left(C_1 - C_a\right) + \left(1 - S_2\right)h .A_{top}\left(T_{x=0} - T_a\right) - \lambda_p .A\frac{\partial T}{\partial x}
\end{aligned}
$$

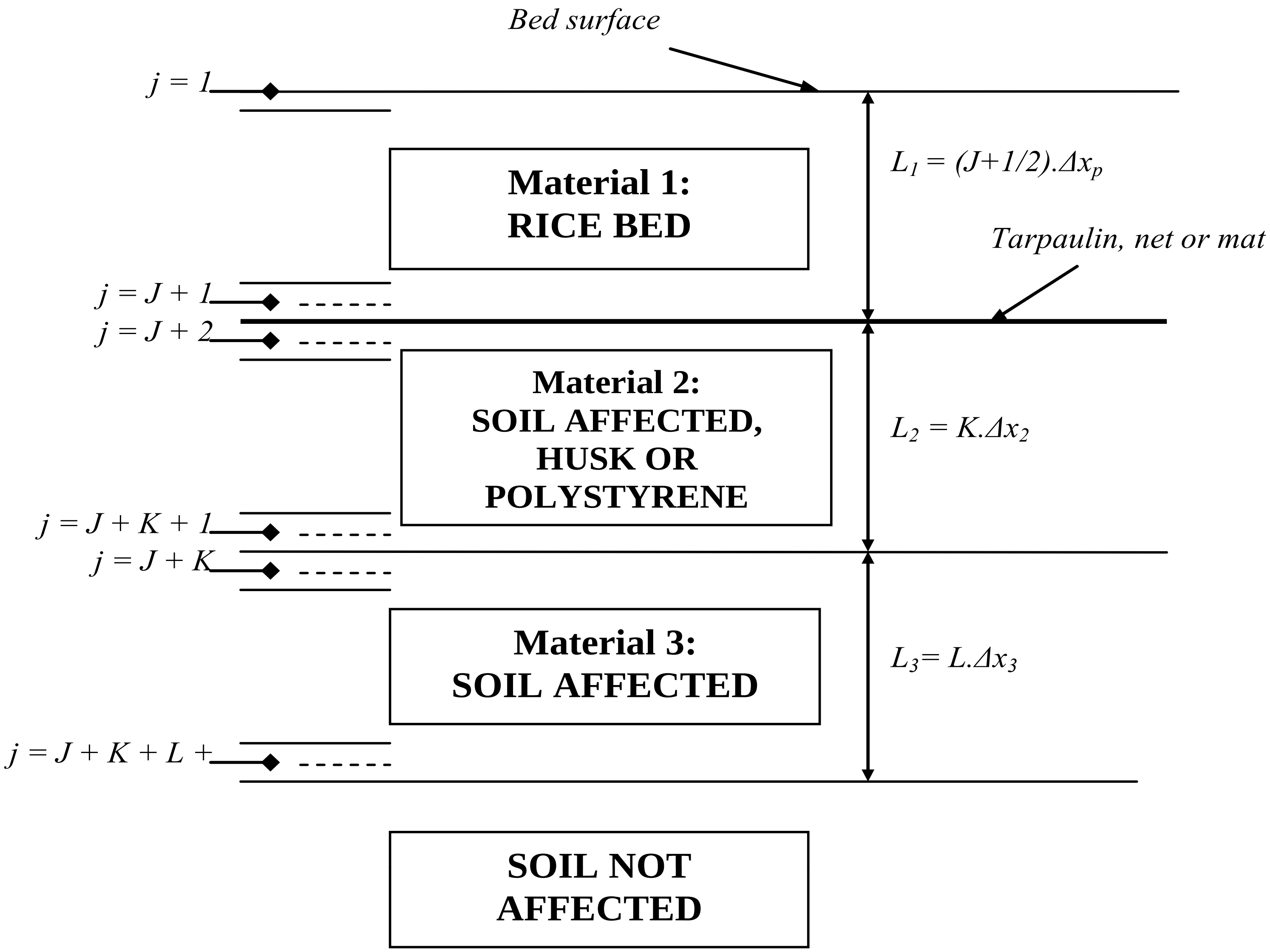
Other equations

- 19 more to complete formulation
- Too many to present here
- Rest of model shown in my thesis and soon to be submitted for publication in journal

Solution

- System has many coupled PDEs describing transport of heat and mass
- Algebraic equations, some non linear
- Analytical solution not possible
- Numerical solution used

Finite difference grid



Bed surface

$j = 1$

Material 1:
RICE BED

$L_1 = (J+1/2).\Delta x_p$

Tarpaulin, net or mat

$j = J + 1$

$j = J + 2$

Material 2:
SOIL AFFECTED,
HUSK OR
POLYSTYRENE

$L_2 = K.\Delta x_2$

$j = J + K + 1$

$j = J + K$

Material 3:
SOIL AFFECTED

$L_3 = L.\Delta x_3$

$j = J + K + L +$

SOIL NOT
AFFECTED

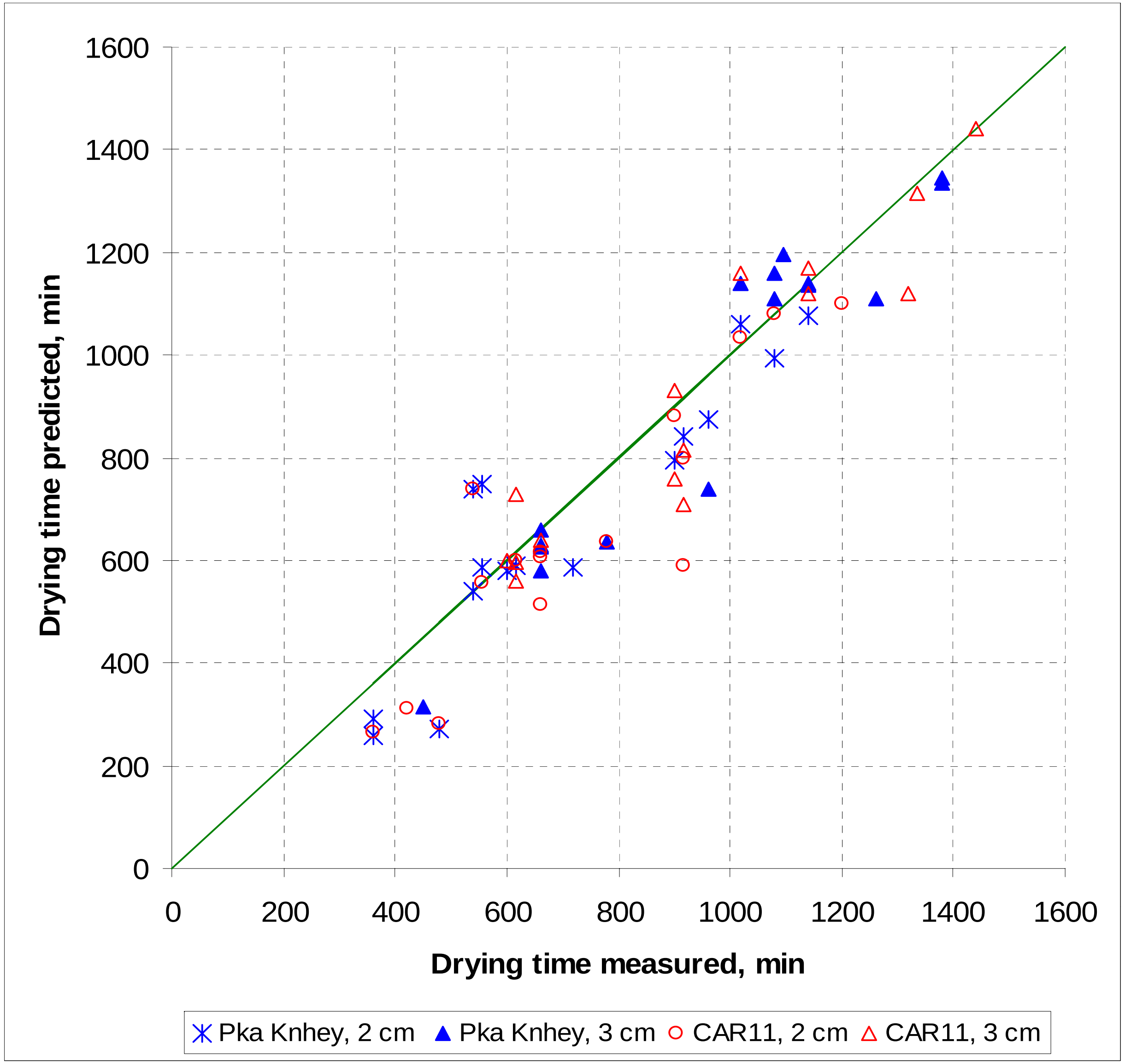
More equations

- 20 more ODEs to describe heat and mass transfer into and out of each node.

Validation

- Validation needed to confirm predictions are working
- 12 drying trials extensively monitored for internal temperatures and RH values
- The experimental method described in detail in another paper
- Drying time for all runs compared to prediction

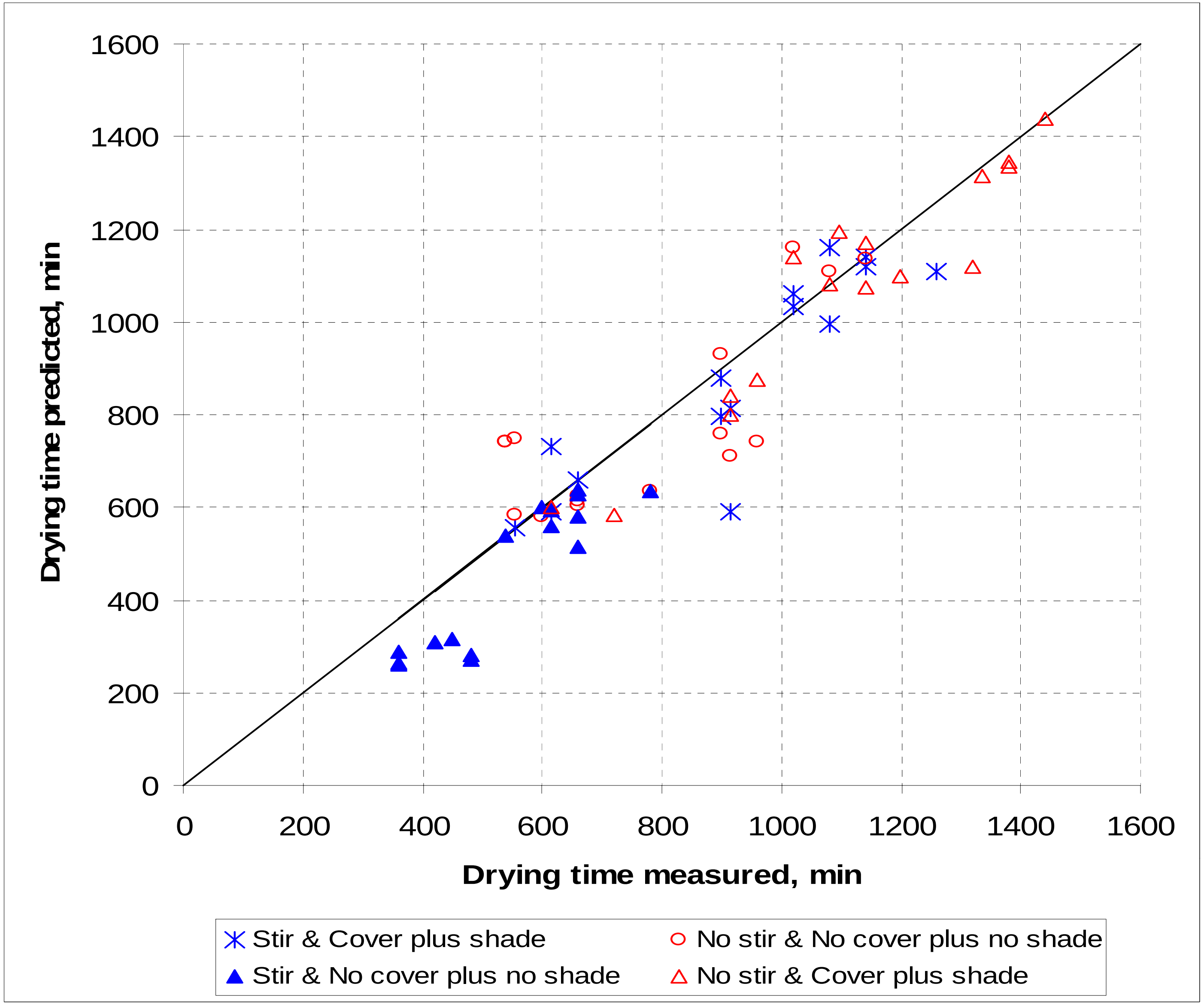
Drying: *variety and depth*



Drying time effects

- The model predicted drying time for all varieties and bed depths equally well
- The Pka Knhey about 20 min longer on average than CAR11
- 2 cm bed depth was predicted on average 50 min shorter than 3 cm

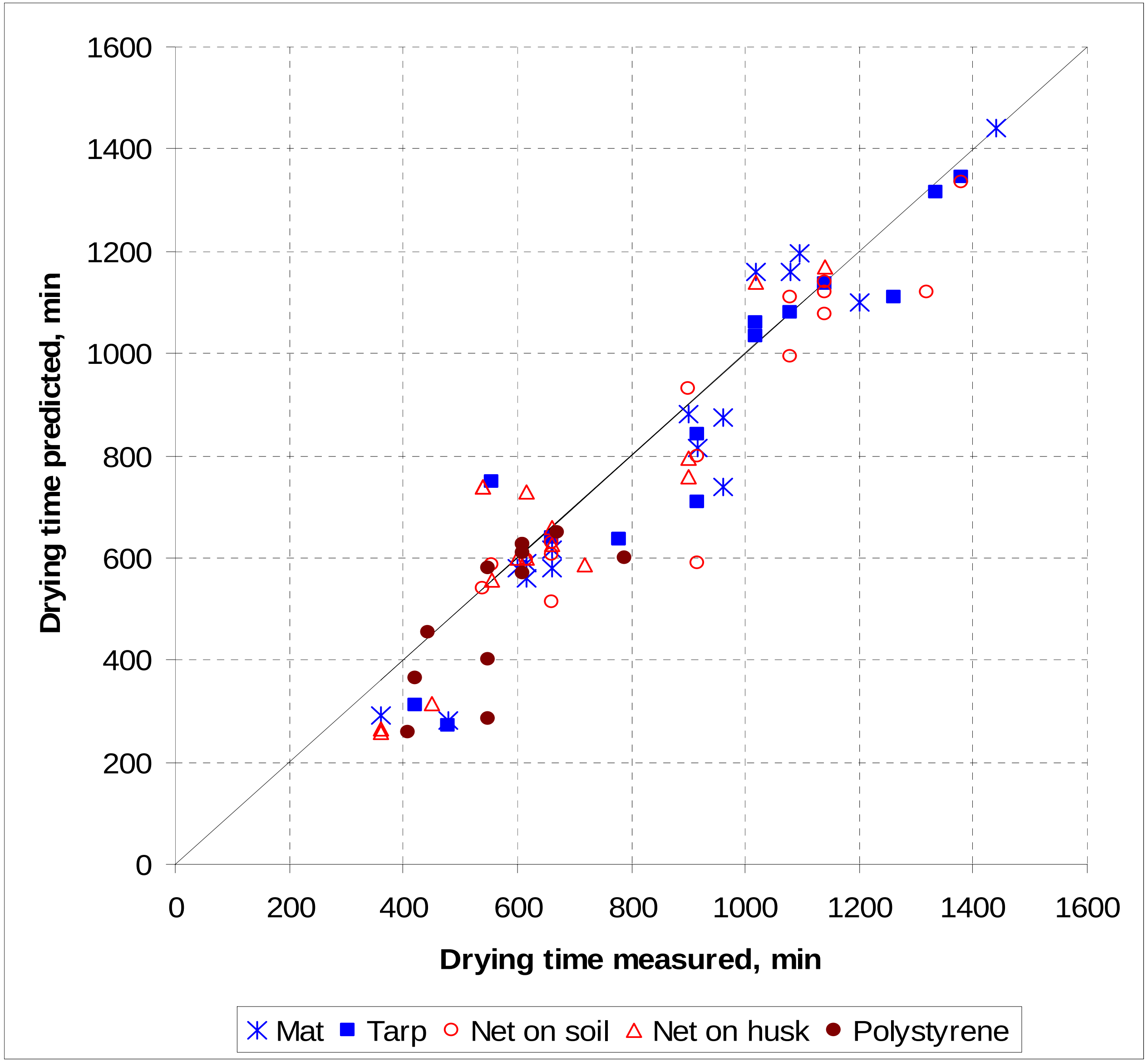
Drying: *stirring and covering*



Drying: stirring and covering

- Stirred and uncovered ⇨shortest drying (455 min)
- Beds not stirred and not covered predicted 776 min
- Stirred and covered 882 min
- Not stirred but covered 1063 min
- This indicates stir helped shorten while cover and shade prolonged drying

Drying: Pad type

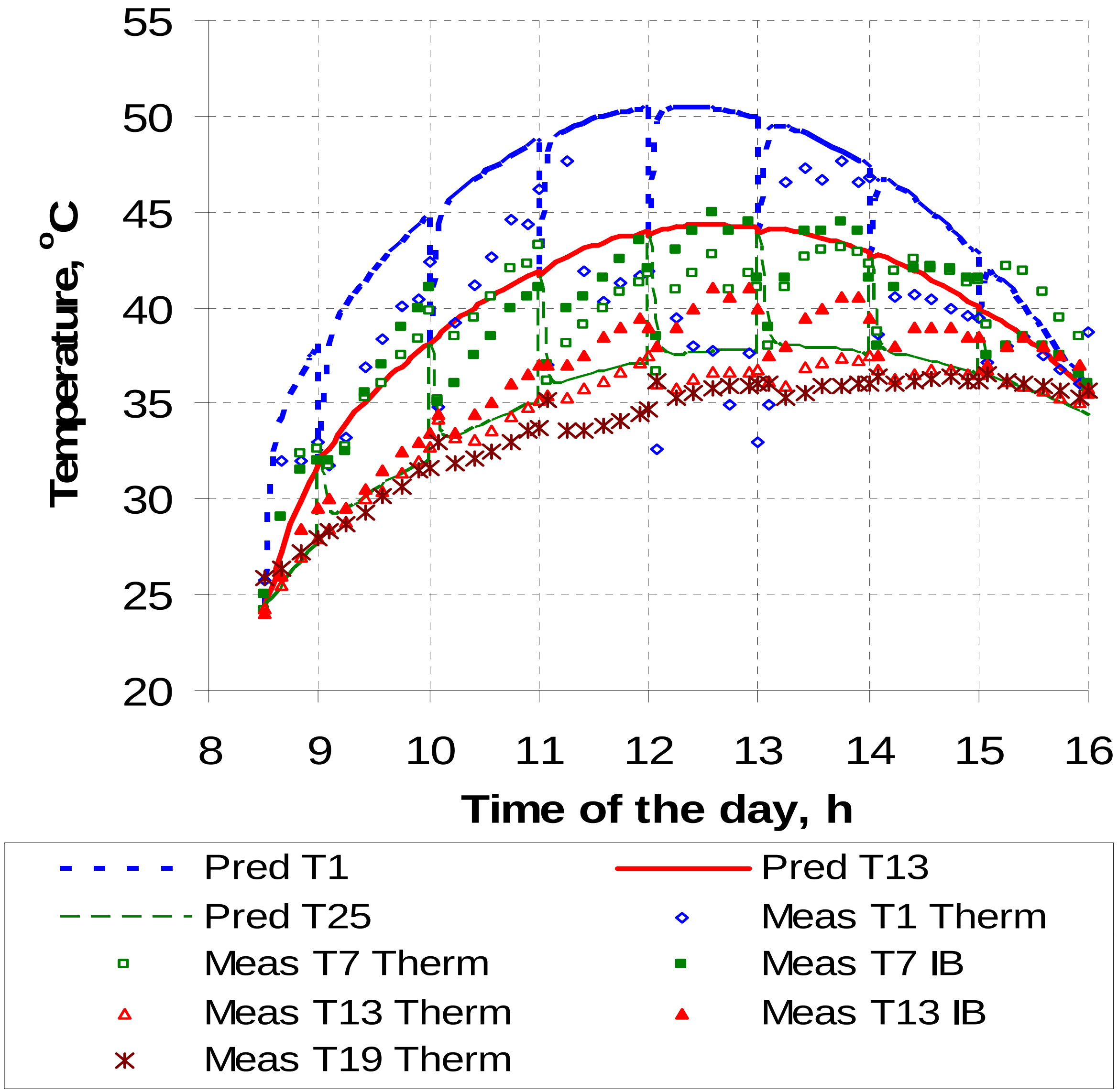


Average drying time

	Net on husk	**Mat on soil**	**Net on soil**	**Tarpaulin on soil**	**Tarpaulin on polystyrene**
Measured	665	848	919	930	602
Predicted	659	804	855	858	502

Temperature

Comparison of the predicted and measured temperatures for CAR11, 2 cm, tarpaulin spread on soil, stirring, no covering, Day One (Dec 10, 2004)



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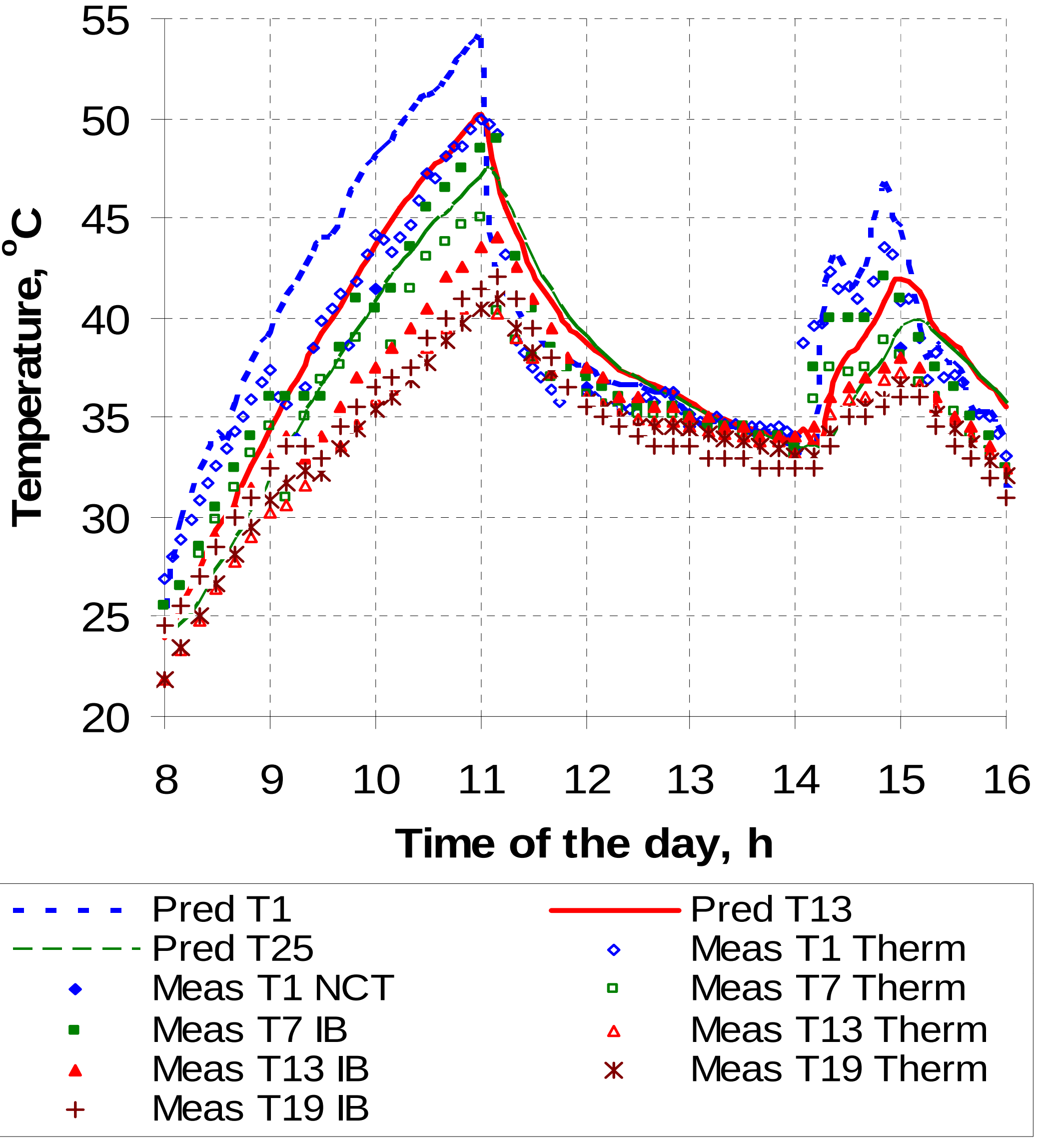
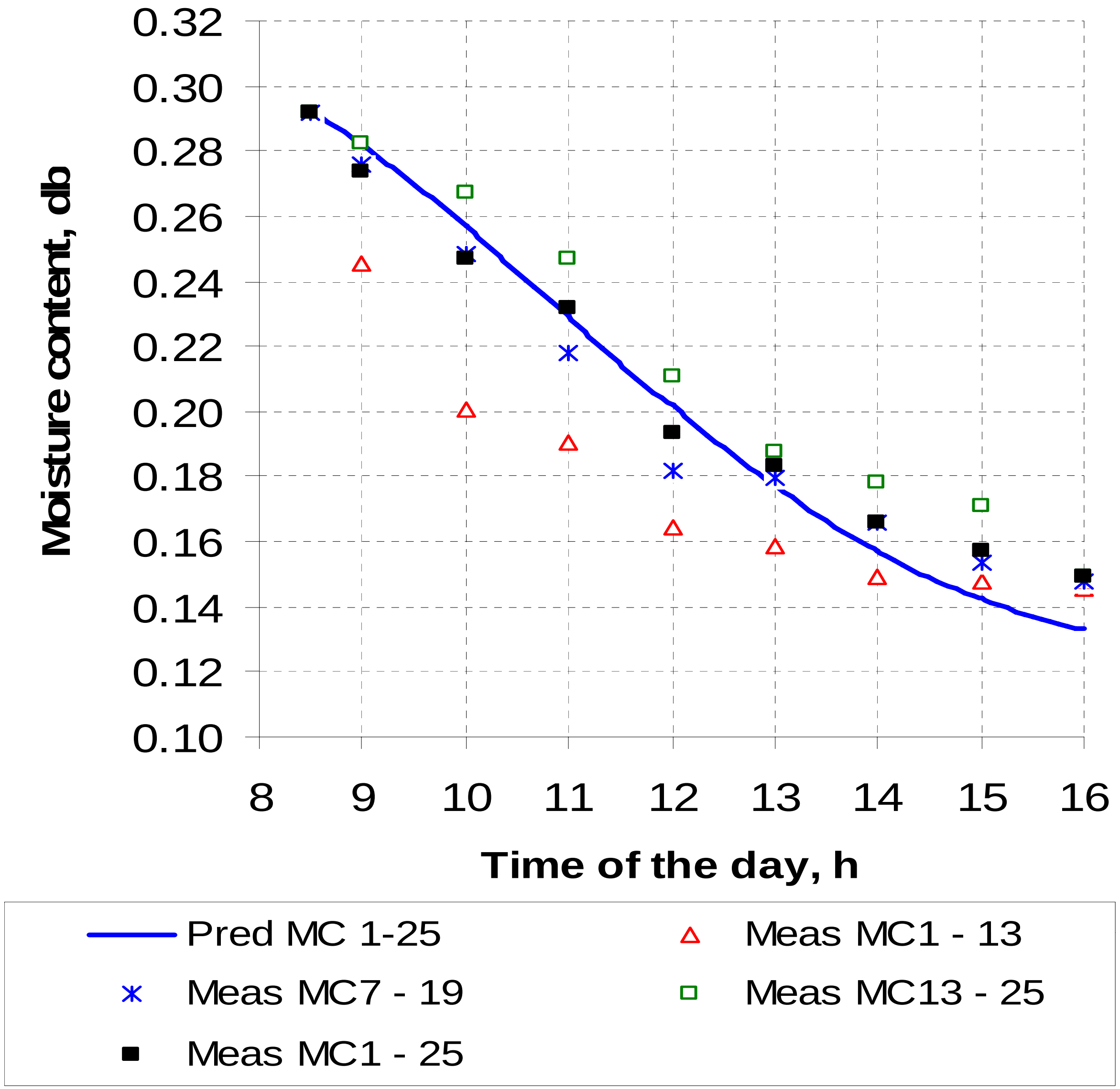
Temperature

Comparison of the predicted and measured temperatures for Pka Knhey, 2 cm, net spread on husk, no stirring, covering plus shading, Day One (Dec 24, 2004).



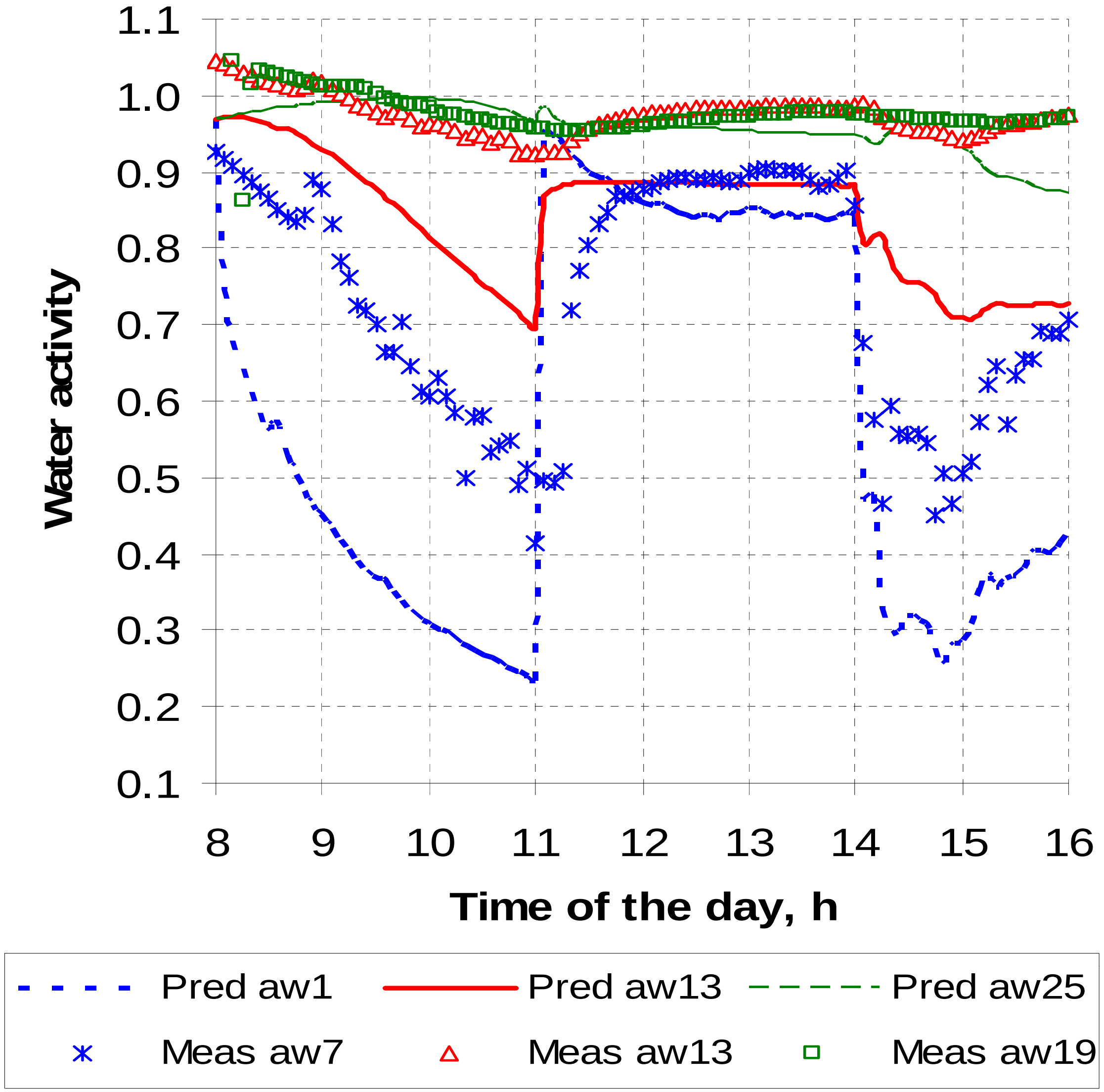
Moisture Content

Comparison of the predicted and measured MCs for CAR11, 2 cm, tarpaulin spread on soil, stirring, no covering, Day One (Dec 10, 2004)



RH of air in Bed

Comparison of the predicted and measured water activities for Pka Knhey, 2-cm, net spread on husk, no stirring, covering plus shading, Day One (Dec 24, 2004)



Conclusions

- Model accurately predicted drying time, temperature and MC within bed during drying except for polystyrene pad
- It did not predict experimental water activity (relative humidity) consistently well

Acknowledgements

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