模擬森林火災下における地温変化の解析

Analysis of temperature changes in soil under simulated wildfire

○ 小渕敦子・溝口勝・西村拓・井本博美・宮崎毅
東京大学大学院農学生命科学研究科

Abstract

黒ぼく土を用いて模擬森林火災実験下における地温分布変化を測定した。表層土の地温は100℃で温度が停滞した後、急激に温度上昇した。100℃を超える深さは体積含水率が小さいほど深く、燃焼時間の平方根に比例した。相変化を伴う移動境界値問題とみなして、凍土の分野で知られているNeuman解を用いて熱解析したところ、適切な熱物性値を与えれば地温の時間変化は良好に予測できるが、温度分布の形状は完全には再現できないことが分かった。より厳密に現象を予測するためには遷移領域における水分移動を考慮したモデル化が必要である。

1. はじめに

インドネシア、シベリアなど世界各地で森林火災が発生。
燃焼中の土壌温度を知ることは、植生回復を考える上で重要。
しかし・・・
燃焼時の土壌温度に関する詳細な研究報告は見当たらない。
そこで・・・
模擬森林火災時の地温分布変化を測定。
移動境界値問題として熱解析。

2. 実験方法[1)]

試料： 黒ぼく土
初期体積含水率： 0.15, 0.32, 0.39, 0.45 m^3/m^3
乾燥密度： 0.75 Mg/m^3
カラム： 内径 15 cm 高さ 30 cm
熱電対を深さ0, 1, 2, 4, 6, 8, 10, 15, 20, 25, 30 cm に挿入
炭火を用いてカラムの土壌表面を6 時間加熱
⇨ 地温分布変化を測定

3. 測定結果

(1)地温の時間変化（θ=0.32の場合：Fig.1）

表面温度はいずれの試料でも600～700℃に上昇。各深さの地温は100℃付近で温度が停滞した後、急激な温度上昇。
100℃を超える深さは初期θが小さいほど深く、燃焼時間の平方根に比例（Fig. 2）。その比例定数と初期体積含水率の関係をFig. 3に示す。

(2)地温分布（θ=0.32の場合：Fig.4）

地温は100℃を境にして100℃以上の高温領域、ほぼ100℃の遷移領域、100℃以下の低温領域の3領域に分かれた変化パターンを示した。
6時間での温度分布をみると、高温領域は初期水分量が小さい方が厚くなったが、10cm以下の温度分布は初期水分量には依存しなかった。

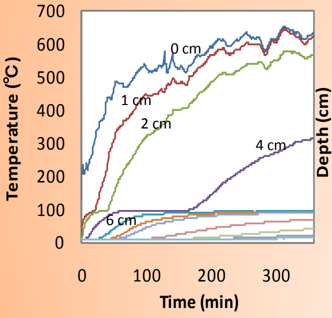

Fig.1 Temperature change (θ=0.32)

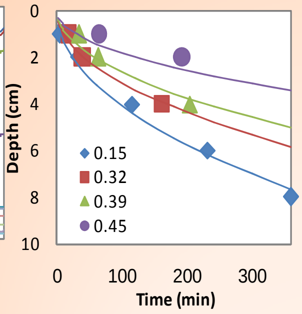

Fig.2 The 100℃-depth vs time

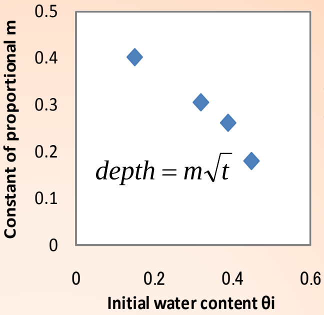

Fig.3 Relationship between m and θi

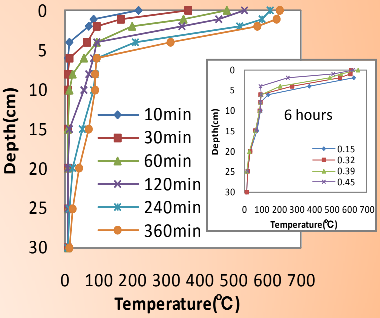

Fig.4 Temperature profile





4. Neuman解による解析

相変化を伴う非定常熱伝導現象とみなして、Neuman解[2)]を適用。

初期温度T_0の半無限の土層の表面がTsになったと仮定。

⇨ 連立熱伝導式 $\frac{\partial T_1}{\partial t} = \alpha_1 \cdot \frac{\partial^2 T_1}{\partial x^2}$ $0 < x < \xi$ ...(1) $\frac{\partial T_2}{\partial t} = \alpha_2 \cdot \frac{\partial^2 T_2}{\partial x^2}$ $x > \xi$ ...(2)

（T：温度 α: 熱拡散率 x: 深さ t: 時間

添字1,2：高温（100℃以上）および低温領域（100℃以下） ξ：境界の位置）

境界における熱収支式： $\frac{d\xi}{dt} = \frac{1}{Q_L \cdot \rho_s \cdot w} \cdot \left| K_1 \cdot \left(\frac{\partial T}{\partial x}\right)_{x=\xi} - K_2 \cdot \left(\frac{\partial T}{\partial x}\right)_{x=\xi} \right|$ ...(3)

（Q_L：蒸発潜熱、K：熱伝導率）

初期条件と境界条件：

$$\begin{aligned} & x > 0, t = 0, T_1 = T_f = \mathrm{const} \\ & x = 0, t \geq 0, T_1 = T_s \\ & x \to \infty, t \geq 0, T_2 \to T_0 = \mathrm{const} \\ & x = \xi, t > 0, T_1 = T_2 = \mathrm{const} = T_f = 100^\circ\mathrm{C} \\ & T_f = \text{evaporating temperature} \end{aligned}$$

解析解： $T_1 = T_s + (T_f - T_s) \cdot \frac{G\left(\frac{x}{2\sqrt{\alpha_1 \cdot t}}\right)}{G\left(\frac{m}{2\sqrt{\alpha_1}}\right)}$ ...(4) $T_2 = T_0 + (T_0 - T_f) \cdot \frac{\left[1 - G\left(\frac{x}{2\sqrt{\alpha_2 \cdot t}}\right)\right]}{\left[1 - G\left(\frac{m}{2\sqrt{\alpha_2}}\right)\right]}$ ...(5) $\xi = m \cdot \sqrt{t}$ ...(6)

ここで、Gは以下の誤差関数

$$G(X) = G(x\eta) = \frac{2}{\sqrt{\pi}} \cdot \int_0^{x\eta} (e^{-\beta^2}) \cdot d\beta$$

Fig.5 は(4)(5)の解析解を用いて計算した地温変化である。
（θ=0.32に対するパラメータ：α_1, α_2 =0.12, 0.18 [cm^2/min], m=0.25（Fig.3の実測値）とした。）

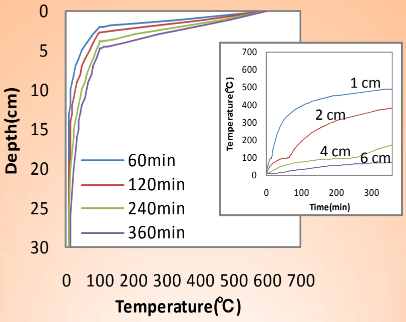

Fig.5 Soil temperature

5. まとめ

解析により以下のことがわかった。
(1)地温はFig.1と同様に100℃で一度停滞した後、急激に上昇。
(2)温度分布は、Fig.4の様な100℃の遷移領域は現れなかった。
(3)この領域で水分移動と蒸発が激しいためと推察される。
(4)より厳密に現象を予測するためにはこの遷移領域をうまくモデル化する必要がある。

参考文献：1) 小渕ら(2007), 農業農村工学会講演要旨集, 1-41, pp.230-231
2) Jumikis, A. R(1996), Thermal Soil Mechanics, Rutgers Univ. Press, New Brunswick, pp.236-246

Analysis of temperature changes in soil under simulated wildfire

○ **Atsuko Obuchi, Masaru Mizoguchi, Taku Nishimura, Tsuyoshi Miyazaki**
Dept. of Global Agricultural Science, The University of Tokyo

Abstract

Soil temperature change under simulated wildfire was measured in Andisol on the condition that the surface temperature was 600-700 ℃. The temperature of top soil became constant at about 100℃ for a while before increasing over 100 ℃. The 100 ℃-depth was proportional to square root of the burning time and was deeper as the initial water content was fewer. This temperature changes can be explained in terms of a moving boundary problem. Then we conducted thermal analysis using Neuman 's theory which is known in the field of frozen soil. As a result of the analysis, we found that if we give appropriate value of thermal properties, soil temperature change can be predicted as a function of time but the shape of soil temperature profile can not be predicted completely. To predict it more properly, we need to consider water movement in the transition zone where evaporation occurs at 100 ℃.

1. Background

Wildfires occur around the world such as Indonesia, Siberia. To know soil temperature during burning is important to consider about plant regeneration. However, there are few studies about the soil temperature during burning. We therefore measured the soil temperature profiles during simulated wildfire and analyzed thermally as a moving boundary problem.

2. Method[1)]

Soil sample: Andisol
Initial water content: 0.15, 0.32, 0.39, 0.45 m^3/m^3
Bulk density: 0.75 Mg/m^3
Column: 15 cm in diameter, 30 cm hight
Thermocoples: 0, 1, 2, 4, 6, 8, 10, 15, 20, 25, 30 cm depths
After heating the surface of soil column with charcoal for 6 hours
⇨ measure soil temperature profiles

3. Results

(1)Soil temperature change（in case of θ=0.32：Fig.1）

The temperature of soil surface rose 600～700℃. The temperature of each depth became constant at around 100℃ before increasing over 100 ℃. The 100℃-depth was deeper as the initial θ was fewer. It was proportional to square root of the burning time（Fig. 2）. The relationship between constant of proportional m and initial θ is shown in Fig. 3.

(2)Temperature profile（in case of θ=0.32：Fig.4）

Temperature change can be divided into 3 zones on reaching 100℃; a high temperature zone which is above 100℃, the transaction zone at almost 100℃, a low temperature zone which is below 100℃.

Comparing the temperature profiles in 6 hours, the high temperature section was thicker as the initial θ was fewer, but the temperature change deeper than 10 cm is not depend on the initial θ .

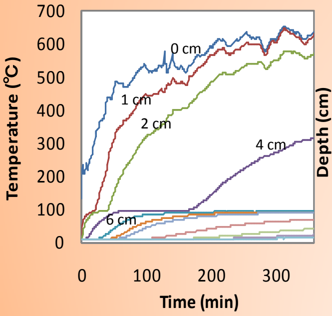

Fig.1 Temperature change (θ=0.32)

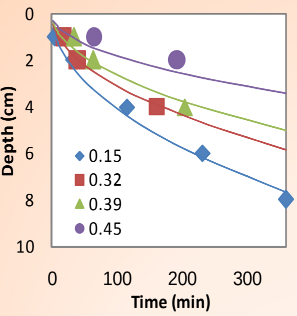

Fig.2 The 100℃-depth vs time

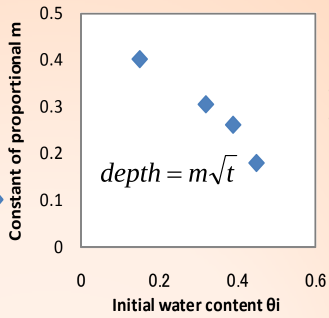

Fig.3 Relationship between m and θi

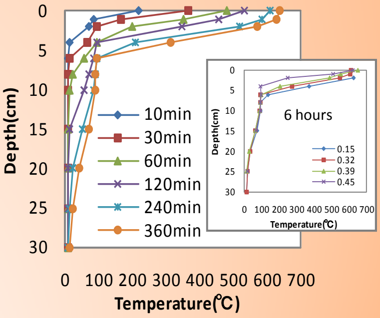

Fig.4 Temperature profile

4. Analysis using Neuman's theory

We applied Neuman's theory[2)] to analyze the phenomena as unsteady heat transfer.

Assumed that soil surface temperature of semi-infinite soil column which initial temperature is T_0 became Ts.

simultaneous heat conduction equation

⇨ $\frac{\partial T_2}{\partial t} = \alpha_2 \cdot \frac{\partial^2 T_2}{\partial x^2} \quad x > \xi$ …(1) $\qquad \frac{\partial T_1}{\partial t} = \alpha_1 \cdot \frac{\partial^2 T_1}{\partial x^2} \quad 0 < x < \xi$ …(2)

（T：temperature α: thermal diffusivity x: depth t: time

subscript 1,2：high（above 100℃）and low（below 100℃）temperature section ξ：location of boundary）

Heat balance at the boundary：$\frac{d\xi}{dt} = \frac{1}{Q_L \cdot \rho_s \cdot w} \cdot \left[K_1 \cdot \left(\frac{\partial T}{\partial x}\right)_{x=\xi} - K_2 \cdot \left(\frac{\partial T}{\partial x}\right)_{x=\xi} \right]$ …(3)

（Q_L：evaporative latent heat、K：thermal conductivity）

Initial condition and boundary condition：
$x > 0, t = 0, T_1 = T_0 = const$
$x = 0, t \geq 0, T_1 = T_s$
$x \to \infty, t \geq 0, T_2 \to T_c = const$
$x = \xi, t > 0, T_1 = T_2 = const = T_f = 100°C$
T_f = evaporating temperature

Analytical solution：$T_1 = T_s + (T_f - T_s) \cdot \frac{G\left(\frac{x}{2\sqrt{\alpha_1 \cdot t}}\right)}{G\left(\frac{m}{2\sqrt{\alpha_1}}\right)}$ …(4) $\quad T_2 = T_0 + (T_0 - T_f) \cdot \frac{\left[1 - G\left(\frac{x}{2\sqrt{\alpha_2 \cdot t}}\right)\right]}{\left[1 - G\left(\frac{m}{2\sqrt{\alpha_2}}\right)\right]}$ …(5) $\quad \xi = m \cdot \sqrt{t}$ …(6)

G is error function showed below

$$G(X) = G(x\eta) = \frac{2}{\sqrt{\pi}} \cdot \int_0^{x\eta} (e^{-\beta^2}) \cdot d\beta$$

Fig.5 is temperature change calculated by using (4)(5).
（Parameter ：α_1, α_2=0.12, 0.18 [cm^2/min], m=0.25（observed value of Fig.3））

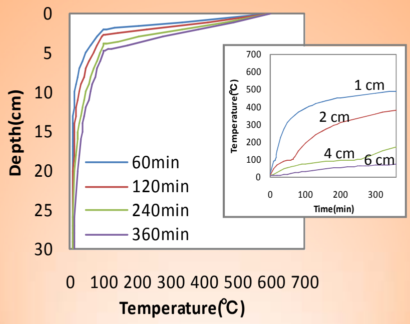

Fig.5 Soil temperature

5. conclusions

(1)Soil temperature became constant at 100℃ before increasing over 100 ℃ as shown in Fig.1.
(2)The transition zone as appeared in Fig.4 was not obtained by this analysis.
(3)This is because water movement and evaporation is active in this zone.
(4)To predict it more properly, we need to model this transition zone.

Reference:

1) Obuchi et. al(2007), Proceedings of JSIDRE, 1-41, pp.230-231
2) Jumikis, A. R(1996), Thermal Soil Mechanics, Rutgers Univ. Press, New Brunswick, pp.236-246

Atsuko Obuchi
Lab. of International Agro-Infomatics
Dept. of Global Agricultural Science
Graduate school of Agricultural and Life Sciences
The University of Tokyo
E-mail: atsuko@iai.ga.a.u-tokyo.ac.jp