Application of the Extended Force-restore Model to Estimating Soil-frost Depth in the Tokachi District of Hokkaido, Japan

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Abstract

In the present study, we tested the applicability of the extended force-restore model (eFRM) to estimating soil-frost depth in the Tokachi district where the soil is a type of volcanic ash. The optimal thermal conductivity of the snow (TC-S) in each cold period varied from 0.074 to 0.172 W m⁻¹ K⁻¹, with root-mean-square errors (RMSEs) ranging from 0.020 to 0.039 m. The difference between observed and estimated maximum soil frost depth (SFDmax) was less than 0.03 m. The fixed TC-S through the six cold periods from 2001 to 2007 was optimized as the value of 0.173 W m⁻¹ K⁻¹ with minimum RMSE of 0.043 m. When this optimal value of TC-S was used to estimate SFD max, the difference between the observed and estimated values was 0.04 m at most, with the exception of 2003-2004 and 2004-2005, when little soil-frost developed. Our results showed that even though we considered the TC-S to be invariant over time, the eFRM was able to estimate soil-frost depth with an accuracy of a few centimeters using only mean daily air temperature and snow depth as inputs.

Key words: Extended force-restore model, Soil-frost depth, Volcanic ash.

1. Introduction

Variation in the soil-frost depth plays a crucial role during agricultural operations in spring because frost affects the permeability of the soil to snowmelt water (Gray et al., 2001) and delays the annual increase in soil temperature. The soil-frost depth is decreasing in cold regions around the world as a result of climate warming (e.g., Cutforth et al., 2004; Frauenfeld et al., 2004; Hirota et al., 2006). However, precise monitoring of the soil-frost depth is commonly difficult without special instruments (e.g., frost tubes) due to the complexity of various subsurface phenomena.

The extended force-restore model (Hirota et al., 2002; hereafter referred to as eFRM) has been validated using data from a Canadian farm whose soils were characterized as fine-textured chernozems, and in that study, the model successfully estimated the soil temperature profile from only mean air temperature and snow depth data. In the present study, we tested the applicability of the eFRM to estimating soil-frost depth in the Tokachi district of Hokkaido, Japan, an area where the soil freezes seasonally and the annual maximum frost depth has decreased significantly in the last 20 years (Hirota et al., 2006).

From history of soil-frost study, it was recognized that snow-depth and air temperature were most correlated to the soil-frost depth (e.g., Lunadini, 1981; Fukuda, 1982; Tsuchiya, 1985; Yamazaki et al., 1998). F20 (e.g., Fukuda, 1982; Tsuchiya, 1985), which is one of the semi-experimental indices and is widely used in variety of research and industrial field, use the accumulative air temperature below 0°C until snow-depth reaching 0.2 m. That is, snow cover is the most influential to developing of soil-frost. In this context, we greatly focused on the thermal conductivity of the snow which is the snow-associated parameter of physical model of eFRM.

2. Material and Methods

The study was conducted at an experimental plot operated by the National Agricultural Research Center for Hokkaido Region in the town of Memuro in the central part of Tokachi District, Hokkaido, Japan.
(42°53' N, 143°03' E; Fig. 1). The 1979-2000 mean annual precipitation and mean annual air temperature, recorded at the Memuro meteorological station, which is located 2.5 km west of the site, are 970 mm and 6 °C, respectively (JMA, 2008). The soil of the study site is derived from volcanic ash, which accumulated between 10000 and 1000 years ago (Kikuchi, 1981) and which covers roughly two-thirds of the Tokachi district, and is classified as Typic Hapludands (Iwata et al., 2008).

We continuously monitored snow depth, using an ultrasonic snow-depth gage (Kaijo, SL-340), and air temperature at 1.9 m above the ground (Vaisala, HMP45A) from November 2001. Frost depth was measured manually once or twice a week using a frost tube consisting of a 25-mm outside diameter acrylic tube filled with 0.03 °C methylene blue solution, which has a dark blue color in the unfrozen condition and turns colorless upon freezing. The frost depth was indicated by the boundary between the blue and colorless parts of the tube (e.g., Kinoshita et al., 1967). The acrylic tube was suspended in a 38-mm outside diameter PVC casing installed in the soil. Snow density was measured once or twice a week using a 50 mm diameter aluminum snow survey tube.

To estimate soil frost depth, the eFRM developed by Hirota et al. (2002) was used. The model combines the merits of two traditional methods: the heat conduction equation (e.g., Campbell, 1985) and the force-restore model (e.g., Bhumralkar, 1975). The most useful feature of the eFRM is that it can calculate the daily mean soil temperature at an arbitrary depth without considering deep soil thermometric conditions. Moreover, the model needs only air temperature and snow depth as input data, once the soil parameters are fixed. In this model, the effect of water phase changes on soil temperature is considered by replacing the latent heat of fusion with the apparent heat capacity. The eFRM can include the energy budget at the ground surface. Our primary goal, however, is to estimate the maximum soil-frost depth because this is important information for soil permeability (Iwata et al., 2008), thus we assumed that daily net radiation and latent heat flux at the ground surface during the calculation period both equaled zero for simplicity. In the same sense, heat conduction by water movement which prevailed in the snow melting period after reaching maximum soil frost depth was omitted.

The eFRM also offers the flexibility of setting the maximum calculation depth, the thickness of each layer, and a variety of soil parameters for each layer. We sought general versatility in order to be able to estimate the maximum soil-frost depth over a broad area and/or for further in the past or future than considered in the present study. Therefore, we treated the soil in the model as homogeneous from the ground surface to the maximum calculation depth, which was set as 1.0 m with 70 layers. In the eFRM, we set the following appropriate parameters for volcanic ash. Soil heat capacity for unfrozen and frozen soil was set respectively to 2.29 and 1.50 J m–3 K –1 from the value observed at the study site. Unfrozen and frozen thermal conductivity of soil was estimated as 0.6 and 0.7 W m –1 K –1, respectively, based on Suzuki et al. (2002). Although appropriate parameters were set to the eFRM, the insensitivity of soil thermal parameters like above in the estimation of soil temperature using the force-restore model was confirmed (Hirota et al., 1995). Annual mean soil temperature AMST (°C), which is almost invariant with depth (Hirota, 2000), was calculated from annual mean air temperature AMAT (°C) using the equation (AMST=0.97×AMAT+2.3) of Hirota (2000).

3. Results and Discussion

Figures 2-7 show the model input data (air temperature and snow depth), validation data (observed soil-frost depth), and eFRM outputs of soil-frost depth with different thermal conductivities of the snow.

3.1 Optimization of thermal conductivity of the snow

The values of soil-frost depth estimated by the eFRM showed large fluctuations in response to changes in the
thermal conductivity of the snow (hereafter referred as “TC-S”). The actual TC-S varies as a function of the density of the snow (Kondo, 1994) and the density varies greatly with time and place (Pomeroy and Gray, 2001). However, it is difficult to distinguish the time variation in TC-S. Therefore, we tried to find a constant optimal value of TC-S, which we defined as the value with the smallest root-mean-square error (RMSE) between the eFRM estimate and the corresponding observed value. We defined 0°C as the freezing threshold of the soil and compared the model results with those obtained by observations in the field.

Table 1 shows the results of optimizations in each winter period. The optimal TC-S varied from 0.074 to 0.172 W m⁻¹ K⁻¹, with RMSEs ranging from 0.020 to 0.039 m, with the exception of 2003-2004 and 2004-2005, when little soil-frost developed. The soil-frost depths of 2003-2004 and 2004-2005 were small, 0.04 and 0.05 m respectively, because much snow fell in early December before the air temperature had fallen far enough to cause soil freezing (Figs. 4 and 5). Since most of the soil-frost depths observed in these
periods were zero, optimization with minimum RMSE resulted in minimum TC-S (0.001 W m⁻¹ K⁻¹) and failed. However, the difference between observed and estimated maximum soil frost depth (hereafter referred to as “SFDmax”) was less than 0.03 m. It should be noted that the optimized time-invariant TC-S was an apparent value including time and vertical variation of TC-S and also including that of other fixed parameters such as soil heat capacity, soil thermal conductivity, and so on.

The range of optimized TC-S corresponded to that of general TC-S (0.05-0.4 W m⁻¹ K⁻¹; Kondo 1994, Kondo 2000). The relationship between optimized TC-S and observed snow density at 2001-2002, 2002-2003, and 2005-2006 has roughly positive correlation (Fig. 8, circle). Since higher snow density generally corresponds to higher TC-S (Kondo 1994), our optimized TC-S seemed to represent actual annual variation of TC-S. However, optimized TC-S was lower value in 2006-2007 (0.74 W K⁻¹ m⁻¹), although observed snow density of 2006-2007 had highest in the six year (Fig. 8, triangle). During 2006-2007, rainfall in the late of December, which was unexampled in the past, occurred. This rainfall melted snow cover (Fig. 7) and supply water to below the ground and probably altered actual soil thermal parameters which we assumed fixed value. Therefore, we thought these situation made apparent TC-S lower against the actual higher TC-S.

The fixed TC-S through the six cold periods from 2001 to 2007, except 2003-2004 and 2004-2005, was optimized as the value of 0.173 W m⁻¹ K⁻¹ with minimum RMSE of 0.043 m (Table 1). In the case, we optimized the value of TC-S with only data of Januaries and Februaries, because SFDmax usually occurs during these two months. When this optimal value of TC-S was used to estimate SFDmax, the difference between the observed and estimated values was 0.04 m at most, except for 2003-2004 and 2004-2005 which had large differences of 0.12 and 0.05 m (Figs. 4 and 5; Table 1). Large differences between the observed and estimated values of soil-frost depth at an early stage of the snow-cover period were shown not only in 2003-2004 and 2004-2005 but also in the other years (Fig. 2-7). We thought two reasons of the differences; 1) real TC-S was much smaller than the fixed TC-S because of new-fallen snow, 2) there was few centimeter error of snow-depth between at snow-observing area and at soil-frost observing area because of few meters difference in horizontal space between these observation areas and because of space-patchy snow when the snow depth was low. These two possibilities of the error were

<table>
<thead>
<tr>
<th>Year</th>
<th>Optimized TC-S (W m⁻¹ K⁻¹)</th>
<th>RMSE (m)</th>
<th>SFDmax with optimized TC-S by each year (m)</th>
<th>SFDmax with optimized TC-S over 4 years (*) (TC-S=0.173 W m⁻¹ K⁻¹) (m)</th>
<th>Observed SFDmax (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001-2002</td>
<td>0.129</td>
<td>0.020</td>
<td>0.21</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>2002-2003</td>
<td>0.163</td>
<td>0.030</td>
<td>0.14</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>2003-2004</td>
<td>0.001</td>
<td>0.022</td>
<td>0.07</td>
<td>0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>2004-2005</td>
<td>0.001</td>
<td>0.009</td>
<td>0.08</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>2005-2006</td>
<td>0.172</td>
<td>0.039</td>
<td>0.15</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>2006-2007</td>
<td>0.074</td>
<td>0.028</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>4years (*)</td>
<td>0.173</td>
<td>0.043</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


Fig. 8. Relationship between observed snow density and optimized thermal conductivity (TC-S).
validated as follows. In the case of changing TC-S as new snow to 0.05 W K⁻¹ m⁻¹ (Kondo, 1994; Fig. 9B) in the eFRM, the difference between calculated and observed soil-frost depth decreased against that with the fixed TC-S of 0.173 W K⁻¹ m⁻¹ (Fig. 9A). However, 0.08 m difference of soil-frost depth in the maximum still remains. Therefore, the inconsistency between calculated and observed soil-frost depth could not be explained by only difference in TC-S. In the case of adding 0.02 m of snow-depth to observed one around the early period of snow cover (from November 21st to December 6th) with 0.173 W K⁻¹ m⁻¹ of TC-S (Fig. 9C), the difference of soil-frost depth was 0.06 m in the maximum and smaller than the previous case (Fig. 9B). In the case of mixed those two conditions (TC-S of 0.05 W K⁻¹ m⁻¹ and adding 0.02 m of snow-depth around the early period of snow-cover; Fig. 9D), soil-frost depth did not grow. Model calculation using 0.08 W K⁻¹ m⁻¹ of TC-S with adding 0.02 m of snow-depth around the early period of snow-cover (Fig. 9E) was good corresponded to the observed soil-frost depth well. As described above, we concluded that the inconsistency between calculated and observed soil-frost depth was mainly derived from complex effects both higher TC-S compared to fresh snow cover and from few-centimeter difference of snow-depth. In the case of 2003-2004 and 2004-2005, heavy snow-depth after the large difference occurred seemed to preserve the initial difference until snow melting.

Fig. 9. Results of model calculation with different TC-S and with or without snow-depth addition around the early period of snow cover in 2003-2004 (gray bar). In the upper graph, solid line and bar mean respectively air temperature and snow depth as model inputs.

Fig. 10. Results of sensitivity analysis of (a) thermal conductivity of the snow (TC-S) and (b) annual mean soil temperature (AMST) to maximum soil-frost depth (SFD_max). Vertical lines in both plots indicate the optimal value for TC-S and the site-specific value in the study site for AMST, respectively. In (a), the abscissa axis shows the difference from optimized TC-S in each year.
### 3.2 Sensitivity of TC-S to SFDmax

Sensitivity analysis of two eFRM parameters, TC-S and annual mean soil temperature (AMST), to SFD$_{\text{max}}$ was performed. The relationship between TC-S and SFD$_{\text{max}}$ showed a positive correlation (Fig. 10a) due to higher TC-S enhanced cooling of soil. A 0.05-W m$^{-1}$ K$^{-1}$ increase (decrease) of TC-S generally leads to a 0.04-m increase (decrease) of SFD$_{\text{max}}$.

AMST and SFD$_{\text{max}}$ showed an exponentially negative relationship (Fig. 10b). A 2°C increase and decrease of AMST approximately corresponded to a 0.02-m decrease and 0.03-m increase of SFD$_{\text{max}}$, respectively.

### 4. Conclusion

Our results showed that even though we considered the optimized thermal conductivity for the snow to be invariant over time, the eFRM could estimate soil-frost depth with an accuracy of a few centimeters for a volcanic ash soil in the Tokachi district using only mean daily air temperature and snow depth as inputs. In the case of using 6-year fixed TC-S, there was a slightly larger difference between estimated and observed SFD$_{\text{max}}$ in the periods of little SFD$_{\text{max}}$ (2003-2004 and 2004-2005). However, for agricultural operations, poor estimation of SFD$_{\text{max}}$ in the case of SFD$_{\text{max}}$ lower than about 0.1 m was thought to be not a problem, because the threshold of SFD$_{\text{max}}$ if snowmelt water infiltrates deeper soil or runs off the ground surface is about 0.2 m (Iwata et al., 2008), and the frozen soil in the year of small SFD$_{\text{max}}$ immediately thaws after the snow has melted.

In order to estimate SFD$_{\text{max}}$s over broader areas and for a long time, it is necessary to consider the temporal and spatial distribution of AMST, which can be taken from annual mean temperature, due to the dependency of SFD$_{\text{max}}$ on AMST (Fig. 8b).

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拡張フォースレストアモデルを用いた北海道十勝地方における土壌凍結深推定の試み

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要 約

本研究では拡張フォースレストアモデルを用いて、火山灰土壌の北海道十勝地方における土壌凍結深の推定を試みた。実測の土壌凍結深と拡張フォースレストアモデルによって計算される値の二乗平均平方根誤差 (RMSE) が最小となるように、各寒候期毎に一定の雪の熱伝導率を求めた (2001–2007)。その結果、各年毎の雪の熱伝導率は 0.074 から 0.172 Wm⁻¹ K⁻¹ の範囲で最適化された (RMSE = 0.20 〜 0.39 m)。年最大土壌凍結深は最大で 0.03 m の差で推定することができた。また、全ての年で一定として最適化した雪の熱伝導率は 0.173 Wm⁻¹ K⁻¹ (RMSE = 0.043 m) で、土壌凍結深が小さい年 (2003-2004, 2004-2005) を除けば、年最大土壌凍結深は最大 0.04 m の誤差で推定することが出来た。拡張フォースレストアモデルを用いたことで、気温と積雪深データのみから、固定した雪の熱伝導率を用いた場合でも、数 cm の精度で最大土壌凍結深を推定することができるようになった。

キーワード: 拡張フォースレストアモデル, 火山灰土壌, 土壌凍結深