FINAL REPORT

The Next Generation Soil Heating Model

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Abstract

Accurately modeling the duration and extent of soil heating from prescribed fires and wildfires is vital to predicting many second-order fire effects, including development of soil hydrophobicity and other biological, chemical, and physical effects. Advancements have been made in the process-based soil heating models that consider soil heating a function of soil characteristics, fuel consumption, and moisture content. Nevertheless, current models of soil heating during fires have not been sufficiently evaluated under a variety of actual burning, soil, or fuel conditions. We assessed Massman's 2015 soil heating model which models soil temperature, soil water potential and soil water vapor under a variety of soil, fuel, and burning conditions with existing field-collected datasets. This complex model better incorporates the physio-chemical processes that describe evaporation of soil moisture and the transport of soil water vapor and liquid water that occur during fires. Improvements to the model were made to stabilize soil moisture estimates. The new version, referred to as Massman's 2018 model, was compared to Campbell's 1995 soil heating model. We tested both soil heating models using standard statistical techniques and several existing soil heating datasets. The results indicate that the Massman's 2018 model is an improvement compared to the Campbell model, showing higher accuracy and less errors when predicting soil temperature and soil moisture for various prescribed fires and pile burns scenarios. We have incorporated Massman's model into the First Order Fire Effects Model (FOFEM 6.6 and greater). This soil heating model has a user-friendly interface and is an improved assessment tool for fire managers.

Background and purpose

Fire is a natural disturbance that occurs in most terrestrial ecosystems and can produce a spectrum of effects on soils. Soil heating during wildfires, broadcast prescribed fires, or slash-pile burns affects the soil and, in some cases, can irreversibly alter the soil. These direct (first-order) fire effects often result in significant long-term biological, chemical, physical, and hydrological effects (second-order fire effects). When using fire as a management tool, it is particularly important to understand and predict the potential first- and second-order effects of soil heating; consequently, it is necessary to improve soil heating modelling capability and prediction.

Since first-order fire-related effects on soils are the direct result of soil heating, this study focused on the critical processes that govern the transport of energy and mass during more extreme fires, with the intent of providing the next generation soil heating model. Soil heating models are complex. The energy generated during ignition and combustion of fuels provide the driving force that is responsible for the changes that occur via heat transfer from radiation, conduction, convections and mass transport, and vaporization and condensation (Neary et al. 2005). Quantifying these different pathways for heat flow in the soil profile requires complex mathematical models. This project developed a soil heating model by simplifying an existing model (Massman 2015) so that it can be integrated into First Order Fire Effects Model (FOFEM 6.6 and greater), a well-used fire effects model.

Most studies of the coupled heat and moisture transport in soils have concentrated primarily on conditions that encompass "normal" ambient environmental conditions, i.e., those involving daily and seasonal variations in radiation, temperature, precipitation, etc. (Novak 2010; Smits et al. 2011). A few studies have examined these processes under more extreme conditions, such as those occurring during wildfires and prescribed burns (Aston and Gill 1976; Campbell et al. 1995; Durany et al. 2010). Broadly speaking, the physical principles and the basic equations of all these models are much the same, but the impacts of various model components vary in the different modeling regimes (i.e., normal vs extreme conditions). Models developed for the soil heating in normal conditions tend to focus on the movement of soil moisture and evaporation; whereas models developed to describe the extreme conditions of fire emphasize soil temperatures and the duration of the soil heating.

The magnitude and duration of soil heating, which in a modeling context are determined by the thermal boundary condition at the soil surface and the initial distribution of soil moisture, determine the depth of heat penetration. There are well-established critical temperature thresholds for specific secondary fire effects on soil. In general, soil temperatures in the range of 60-80°C for short periods of time are lethal to plant seeds, plant roots, and plant tissue in general and at temperatures approaching the range of 120-160°C, microbial life is extinguished (Choczynska and Johnson 2009). At higher temperatures, often irreversible physical, chemical, mineral, and hydrologic changes begin to occur to the soil (DeBano et al. 1998; Neary et al. 2005; Massman et al. 2010). Temperature thresholds have been identified for numerous physical, chemical and biological properties (Neary et al. 2005), such as the formation of water repellent soils that reduce infiltration potential between 175-280°C (DeBano 1976; Robichaud and Hungerford 2000), but being able to predict these temperatures for a given fire or a particular soil depth have been elusive. By improving our ability to model soil heating, secondary fire effects can then be addressed; for instance, by predicting threshold temperatures and their duration.

Several modeling studies have focused solely on soil temperatures and the associated heat flow during extreme events (Steward et al. 1990). However, modeling heat and moisture transport simultaneously is a much more difficult task. Although such models (Aston and Gill 1976; Campbell et al. 1995; Durany et al. 2010; Massman 2012) have had some success modeling soil temperatures during severe heating events, they have yielded somewhat disappointing simulations of the coupled soil moisture dynamics. For example, Albini et al. (1996) review the models of Aston and Gill (1976) and Campbell et al. (1995) and found that the earlier model was prone to instabilities and that the later model did not provide an adequate simulation of soil moisture content. Similar conclusions were reached by Campbell et al. (1995) themselves. Likewise, the model of Durany et al. (2010) provides reasonable model performance when simulating soil temperatures, but the model "retained" soil volumetric moisture contents as high as 0.15 despite heating the soils to over 500 °C. Massman (2012), using Campbell et al. (1995) as a modeling template, found that all evaporated soil moisture just re-condensed and accumulated ahead of the dry zone and that no moisture actually escaped the soil. Massman (2015) has developed a model based on non-equilibrium evaporation that does seem to circumvent many of the problems the previous researchers and models have encountered. This approach is unique in that all other models referenced above assume equilibrium evaporation, which must necessarily fail when the soil becomes very dry as one might anticipate during soil heating by wildfires.

Project objectives and hypotheses

The goal of the proposed research was to improve our understanding and predictive ability of soil heating models that can be incorporated into fire behavior models and be used for predicting the secondary fire effects of soil heating from various fire scenarios. To achieve this goal, we addressed four primary objectives:

1) Develop a simplified version of Massman's 2015 soil heating model.

2) Evaluate Massman's 2015 and Campbell's 1995 soil heating model performance with existing field-collected independent data sets under various fuel and moisture conditions.

3) Publish and archive independent soil heating datasets from various fuel and moisture conditions. The final datasets will be publicly available on the Forest Service (FS) Rocky Mountain Research Station web page.

4) Package the simplified soil heating model to be useable with other modules such as the First Order Fire Effects Model (FOFEM).

Our hypotheses were:

1) The proposed simplified soil heating model will simulate soil temperature during fire as effectively as Massman's 2015 model which simulate soil temperature, soil water potential and soil water vapor.

2) The simplified soil heating model will fit, with acceptable statistical accuracy, the soil heating profile data sets from various fuel and moisture conditions.

Material and methods

Study design

Massman's 2015 non-equilibrium soil heating model has three model variables (soil temperature, soil water potential, and soil water vapor) and several supporting relationships that describe soil thermal conductivity, the soil water retention curve, hydraulic conductivity functions for water transport, and the non-equilibrium evaporative source term as functions of these three variables. When the boundary conditions and soil physical properties are included, the number of input parameters to this model is about 35. In contrast, his 2012 equilibrium model has only two model variables, soil temperature and soil water potential, and about half as many input parameters. However, the 2015 model is more realistic than the 2012 model, principally because the newer model incorporates the physical processes and models the heat pulse better than the old model.

We attempted to simplify his soil heating model based on the non-equilibrium model, however it proved impractical and this plan was abandoned in favor of implementing the full 2015 model. There were two principal steps involved in simplifying the 2015 model: 1) reducing the size of the input parameter set by a model sensitivity analysis to a small subset of critical parameters and then, 2) reducing the number of independent dynamic variables from three to one (temperature). To do so, we attempted to parameterize the evaporative energy flux in terms of temperature only (and not in terms of soil moisture or soil water vapor as is presently done in the 2015 model). Such a parameterization directly partitions total heat flow into conductive and latent heat (evaporative) fluxes. Once the evaporative flux was determined, the change in soil moisture and vapor was attempted by updating algebraically rather than using the dynamics described by partial differential equations as employed in Massman's 2015 model. The change proved impractical and this plan was abandoned in favor of implementing the full model Massman's 2015 model.

Existing datasets

Several different independent field data sets were used for model evaluation. These data sets were collected in field experiments during logging slash pile burns and broadcast prescribed fires. Each dataset consists of: pre-fire fuel loads, fuel moisture conditions, forest floor characteristics (amounts, compositions and moisture), soil characteristics (texture, moisture) (Table 1). These datasets and associated metadata are archived and publicly available on the Forest Service Rocky Mountain Research Station web site: https://www.fs.fed.us/rmrs/projects/high-soil-temperature-data-archive.

Table 1. Description of the independent field data sets used for model evaluation.

Dataset/ date	**Location**	**Vegetation type**	**Soil type**	**Depths sampled**	**Number of samples**
Massman 2001-2004	Manitou Experimental Forest, Colorado	Ponderosa pine	Granitic	Surface, duff, 1,2, 3, 4, 5, 6, and 8 cm	2-5 thermologger/burn
Sackett and Hasse (Weiss) 1980-2006	Pacific Southwest Research Station, Arizona and California	Chaparral, pinyon- juniper, various pines	Various	Surface, duff, 2, 4, 10, 20, 30 cm	2-5 thermologger/burn
Busse 1995-2008	Pacific Southwest Research Station, California	Mixed chaparral and forests, mastication	Granitic	Surface, duff, 2.5, 5, 10 cm	1-3 thermologger/burn

i. Massman – pile burn dataset from Manitou Experimental Forest, Colorado. The data (soil temperatures, heat fluxes, moisture, and CO_2 amounts) for the prescribed burns during 2001, 2002, and 2004 at Manitou Experimental Forest and all supporting soil data and metafiles were archived in the RMRS database. These data are described or used in numerous publications.
ii. Sackett and Hasse (retired, data available via D. Weise) – Pacific Southwest Research Station, 60 prescribed fires (Arizona and California) from 1980 to 2006. These complete data sets consist of: 1) soil temperatures profiles (160 total profiles) at different distances from bole and under the canopy, 2) soil moisture contents, taken at approximate thermocouple depth, before and after burn, 3) forest floor moistures samples taken for litter, fermentation and humus layers, and some woody fuel moistures, 4) forest floor consumption measurements, 5) fuel loading, 6) general weather observations, and 7) DBH of trees being monitored.
iii. Busse – California, various pile burns, broadcast prescribed fires some with mastication treatments. These data have been used in several publications.

Selection of the input data

In Table 2 the data for each fire used for running the model are provided. The heating curve parameters were obtained using the First Order Fire Effects Model (FOFEM) where the model parameters consist of inputs related to the environmental conditions during fires.

Table 2. Heating curve parameters: maximum intensity (Qmax), time until maximum intensity (tmax) and duration of the fire (burn time); and model parameters for each type of fire and case.

Cases		Manitou 04 Center	Manitou 04 Edge	Busse05R2 10	Busse05R310 (Western US01)	Weise90_5 101	Weise90_5301 (Western US01)
Fire type		Pile burning	Pile burning	Broadcast burning	Broadcast burning	Broadcast burning	Broadcast burning
Heating curve	Qmax (kW)	16	13	22	16.2	8	6.7
	tmax (h)	13.5	6.2	0.8	0.8	10	3.1
	Burn time (h)	35	12	4.25	4.5	28	18
Model parameters	Depth (cm)	40	40	60	60	60	60
	Grid size (dz; mm)	2	2	2	2	2	2
	Soil density (kg/m^3)	1,300	1,300	920	920	1,300	1,300
	Particle density (kg/m^3)	2,650	2,650	2,650	2,650	2,650	2,650
	Soil moisture	0.16	0.214	0.05	0.05	0.1143	0.1143
	Soil temperature (ºC)	2.42	2.42	17.1	19	10	13.9
	zlamm	4.42	1.25	4	4.42	15	4.42
	psini	1.45E-03	2.56E-04	4.30E-01	1.40E-01	2.15E-03	1.11E-02

Data analysis and model evaluation

The accuracy of the soil heating model was assessed using standard statistical methods including: The Nash-Sutcliffe Efficiency (NSE) (Eq. 1), the root mean squared difference (RMSD) (Eq. 2), the mean absolute error (MAE) (Eq. 3), the centered pattern RMS (CRMS) (Eq. 4) and the correlation among the data (Corr) (Eq. 5); where *M* is the modelled value and *O* the observed data.

$$NSE = 1 - \frac{\sum_{n=1}^{N}(M_n - O_n)^2}{\sum_{n=1}^{N}(O_n - \overline{O_n})^2} \quad \text{(Eq. 1)}$$

$$RMSD = \sqrt{\frac{\sum_{n=1}^{N}(M_n - O_n)^2}{N}} \quad \text{(Eq. 2)}$$

$$MAE = \frac{\sum_{n=1}^{N}|M_n - O_n|}{N} \quad \text{(Eq. 3)}$$

$$CRMS = \left(\frac{1}{n}\sum_{n=1}^{N}[(M_n - \bar{M}) - (O_n - \bar{O})]\right)^{1/2} \quad \text{(Eq. 4)}$$

$$Corr = \frac{\sum(M - \bar{M})(O - \bar{O})}{\sqrt{\sum(M - \bar{M})^2(O - \bar{O})^2}} \quad \text{(Eq. 5)}$$

Potential NSE values range from -∞ to 1. A NSE of 1 indicates a complete match of the modelled data to the data corresponding to the observations. On the other hand, a NSE of 0 means that the modelled and the observed data are equally accurate. When NSE values are below 0, they indicate that the model is not producing accurate data compared to the measured values. For this reason, the closer the NSE values are to 1, the more accurate the modelled data is (Nash & Sutcliffe, 1971)

The RMSD, which is the square root of the average of squared errors. is used to measure the differences among the modelled and observed data. RMSD values close to 0 indicate a better fit to the data.

The MAE indicates the difference between two continue variables, which in this case are the modelled and observed data.

The correlation coefficient alone does not allow one to determine the amplitude of variation of two patterns, so to accurately quantify the differences in two fields, the CRMS is used. Therefore, the use of the correlation coefficient and the CRMS provides complementary information regarding the correspondence between two patterns (Taylor, 2001).

Project results and key findings

1) Objective: Develop a simplified version of Massman's (2015) soil heating model.

- Prior to the Massman's (2015) model validation, we performed verification procedures to ensure that the model was behaving correctly. New functions were created to provide realistic soil curves that serve as a boundary condition for the models.
- A new function was created in the model to drive the heat flux boundary condition and, where necessary, other boundary conditions. This function is based on the 'BDF' curve used to empirically fit temperatures in fire engineering applications (Barnett, 2002). Although the function was created for temperatures, its Weibull-like shape works well for heat fluxes resulting from wildland or other natural fires.
- A simplified soil heating model was attempted based on the non-equilibrium model, however it proved impractical and this plan was abandoned in favor of implementing Massman's 2015 model.
- For testing the sensitivity of the model to other parameters or of the original exponential curve used for the Massman's 2015 model, a constant heat flux function was encoded in the C++ graphical user interface (GUI). During testing with constant heat flux boundary conditions, an instability was discovered that created a sensitivity of the volumetric moisture content to the time step. When a constant heat flux was applied, a sensitivity to time step became apparent, with time steps less than about 0.9 s causing an increase in soil moisture. The time step issue led to the discovery of an error in the soil hydraulic conductivity model. A new, corrected function was created to model soil hydraulic conductivity. This function was implemented in both the Massman's 2018 Matlab version and the C++ version of the model. The new function has eliminated the instability issue which was an important step to stabilize the model.
- Massman's 2018 model was incorporated into the First Order Fire Effects Model (FOFEM version 6.6 and greater). A simple GUI was developed and used for the model validation runs. A helpful tips menu was also added to the model. The latest version of the model is available from the authors and from https://www.firelab.org/project/fofem.

2) Objective: Evaluate Massman's 2018 and Campbell's 1995 soil heating model performance with existing field-collected independent data sets from various fuel and moisture conditions.

The efficiency of the 2018 Massman's model was assessed when predicting data for different scenarios such as pile burnings, broadcast prescribed fires and wildfires. To do so, the modelled data was compared to field temperature measurements and to data predicted by Campbell's 1995 model.

Two validation simulations were conducted for the temperatures reached at the center and edge of a **pile burning** from Manitou04 dataset. Both Massman's and Campbell's models visually compared well to field measurements of soil temperature and moisture (Figure 1). Both models also correlate statistically to the field data, although the Massman's model shows lower errors and greater efficiency than Campbell's (Table 3).

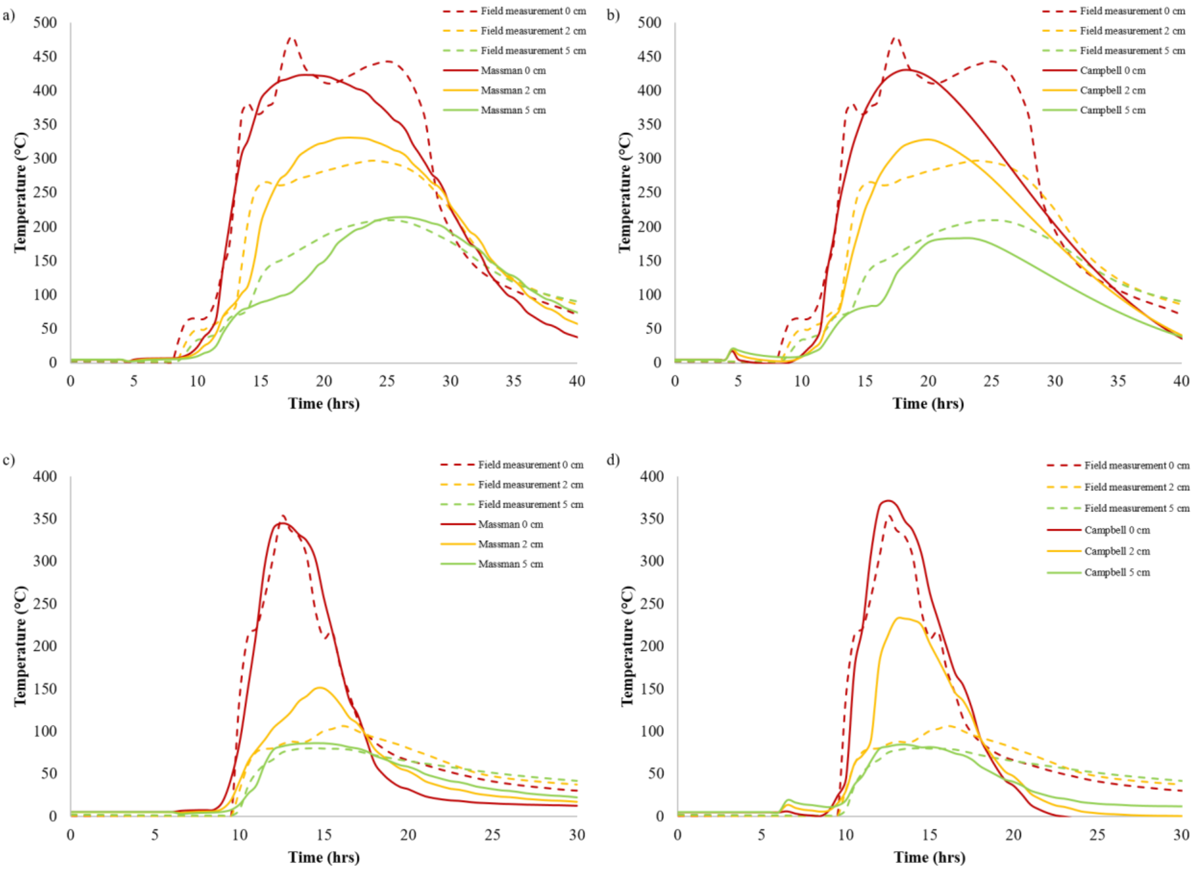

Figure 1. Comparison of Massman's 2018 and Campbell's 1995 model to Manitou04 dataset in the pile center (a, b) and edge (c, d) at 0, 2 and 5 cm depth.

Table 3. Temperature statistical tests results obtained when comparing Massman's 2018 and Campbell's 1995 models to Manitou04 dataset for selected soil depths. Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Difference (RMSD), Mean Absolute Error (MAE), Centered Pattern RMS (CRMS).

	Center of the pile						**Edge of the pile**					
	Massman Model			**Campbell Model**			**Massman Model**			**Campbell Model**		
Soil depth	**0 cm**	**2 cm**	**5 cm**	**0 cm**	**2 cm**	**5 cm**	**0 cm**	**2 cm**	**5 cm**	**0 cm**	**2 cm**	**5 cm**
NSE	0.95	0.93	0.9	0.91	0.9	0.77	0.92	0.37	0.76	0.86	-2.33	0.32
RMSD	36.42	28.28	21.16	51.27	35.11	37.71	28.39	25.59	12.52	39.03	59.61	23.77
MAE	29.09	21.6	15.7	36.07	31.26	33.4	23.98	22.11	10.41	33.65	45.32	19.7
Corr	0.98	0.98	0.96	0.97	0.97	0.95	0.98	0.84	0.92	0.97	0.72	0.73
CRMS	31.36	28.27	19.51	41.34	30.66	22.16	26.13	25.38	10.85	37.02	59.41	19.35

The higher NSE values obtained for the Massman's model indicate that it better predicts the reached temperatures into the soil for both the center and edge of the pile than the Campbell's Model, especially at soil surface. The lower values obtained for the RMSD also show a higher accuracy of the Massman's model as compared to Campbell's model. On the other hand, both Massman's and Campbell's models were similarly correlated to the field data for the temperatures recorded at the center of the pile. Whereas the temperatures at the edge of the pile show a better correlation for the Massman's model. The modelled soil moisture data for the pile burning at the center of the pile is shown in Figure 2 and the statistical analysis results are provided in Table 4. This is the only dataset with continuous soil moisture content measurements.

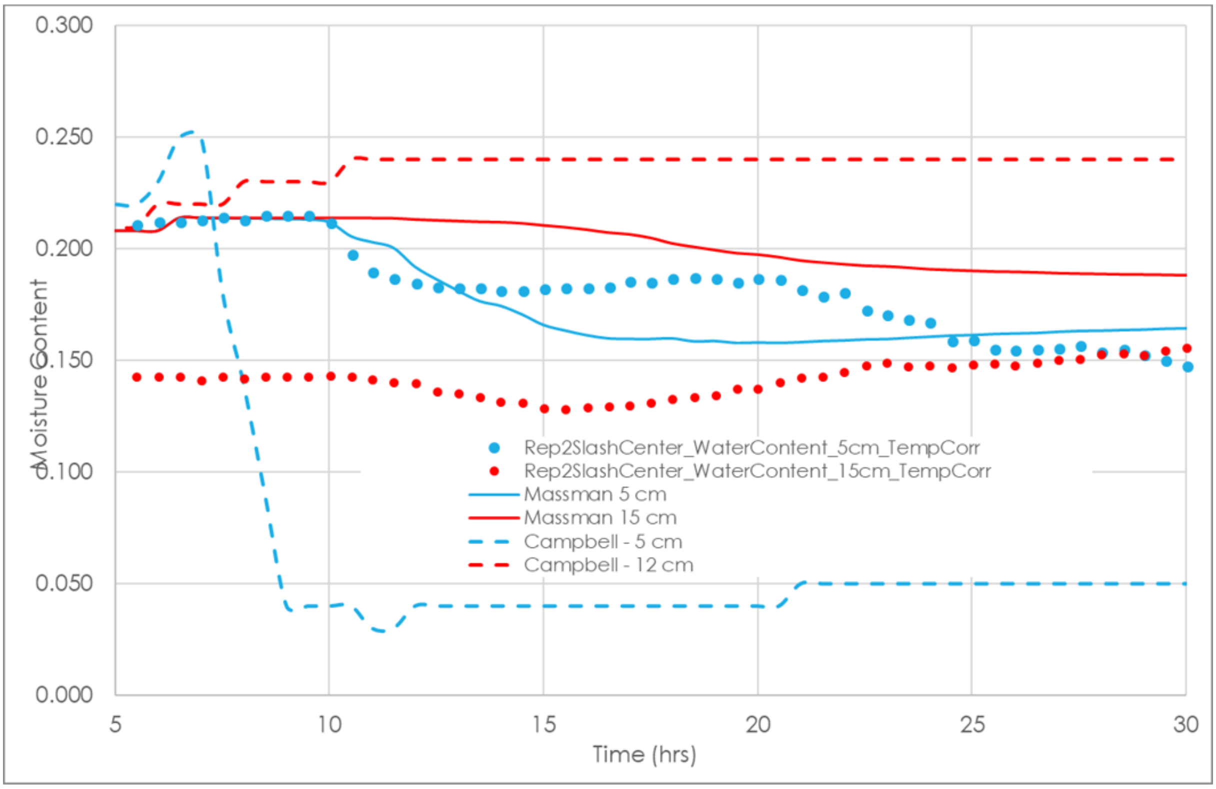

Figure 2. Comparison of Massman's (solid lines) and Campbell's (dashed lines) models of soil moistures at Manitou04 dataset with the soil moistures recorded at the center of the slash pile (dots).

Table 4. Moisture statistics for Manitou04 dataset comparison. Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Difference (RMSD), Mean Absolute Error (MAE), Correlation (Corr) and Centered Pattern RMS (CRMS). The lowest modelled depth of the Campbell model, 12 cm, was used or this comparison. The Campbell model results at 12 cm would not be expected to differ greatly from those at 15 cm.

	Manitou Center of the pile			
	Massman Model		**Campbell Model**	
Soil depth (cm)	**5**	**15**	**5**	**12**
NSE	0.38	-65.65	-0.09	0.00
RMSD	0.02	0.02	0.13	0.10
MAE	0.01	0.06	0.13	0.10
Corr	0.76	-0.66	0.44	-0.05
CRMS	0.01	0.02	0.04	0.01

The obtained statistical analysis for all parameters indicate a better prediction of soil moisture data at 5 cm by the Massman's model.

Four validation simulations were conducted for comparison to soil temperature data from Weise and Busse broadcast prescribed burnings. Simulations for comparison to the Weise90_5101 and Busse05R210 data were run using custom soil models based on Manitou04. A generic soil model, WesternUS01, was used in simulations for comparison to the Weise 90_5301 and Busse05R310 data. Due to constraints in the C++ code, the Campbell's model was limited to results at soil depths above 12 cm. Several measurements in the Weise and Busse data are below 12 cm. Comparisons with the Campbell's model were omitted in those cases. Further simulations were conducted for comparisons to only temperature data from Weise and Busse datasets using custom and generic soil models. The comparisons could only be conducted for temperature data because no moisture data were recorded in the Weise and Busse field experiments.

The graphical comparison among the Busse05R210 field data and the Massman's and Cambell's models are provided in Figures 3a and 3b, respectively. As for the pile burning data, the Massman's model shows lower errors and greater efficiency (Table 5)

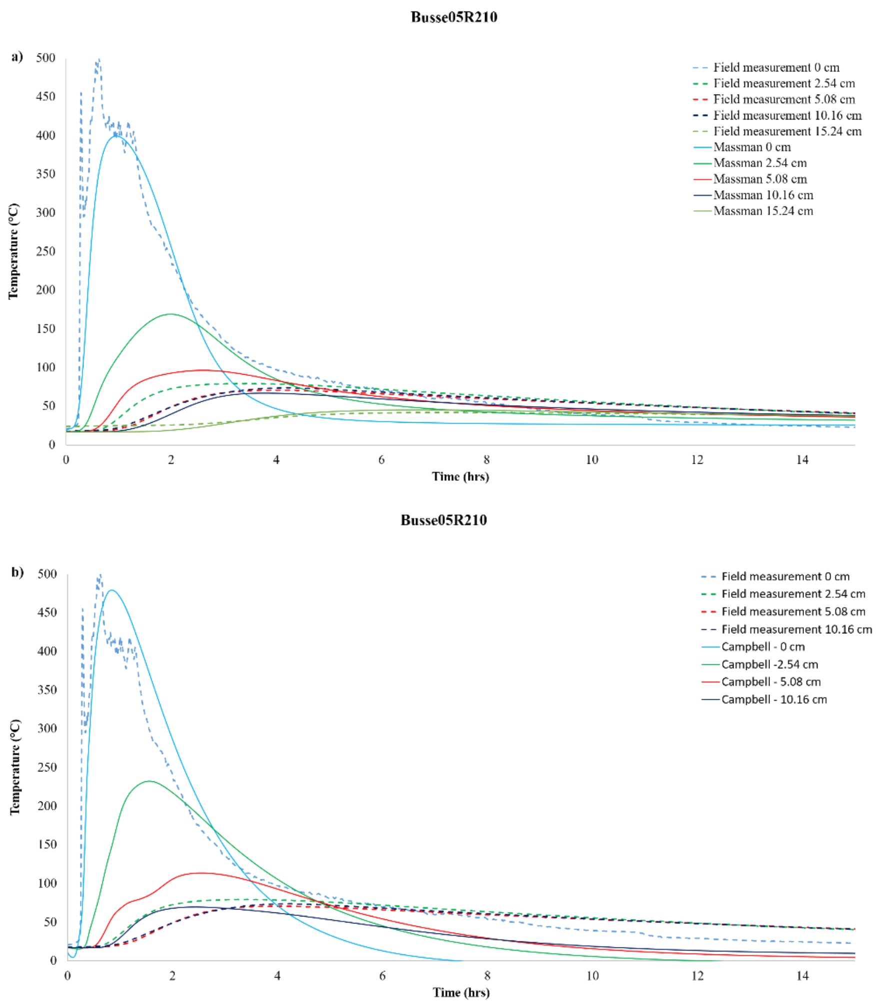

Figure 3. Comparison of Massman's (a) and Cambell's (b) model temperatures with the recorded soil temperatures for Busse05R210 dataset.

Table 5. Statistical tests results obtained when comparing Massman and Campbell models to field-measured data for selected soil depths for Busse05R210 dataset. Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Difference (RMSD), Mean Absolute Error (MAE), Correlation (Corr) and Centered Pattern RMS (CRMS).

Busse05R210									
	Massman Model					**Campbell Model**			
Soil Depth (cm)	**0**	**2.54**	**5.08**	**10.16**	**15.24**	**0**	**2.54**	**5.08**	**10.16**
NSE	0.87	-2.14	-0.10	0.84	0.65	0.79	-10.96	-4.80	-2.44
RMSD	34.77	30.83	14.93	5.93	3.04	44.37	60.14	34.28	27.35
MAE	20.39	19.77	9.63	5.02	2.16	39.63	49.87	32.06	25.57
Corr	0.94	0.58	0.69	0.99	0.99	0.97	0.54	0.57	0.68
CRMS	31.97	30.80	14.87	3.19	3.03	33.00	58.54	29.69	15.10

The Massman's model shows a more accurate prediction of soil temperature than the Campbell's model at soil surface as it can be seen in the NSE values. For intermediate soil depths (2.5 and 5.1 cm) both models show some inaccuracies although Massman's model shows lower errors and higher efficiency than Campbell's model.

Although there are no field data of the soil water content variations during burning for Busse05R210, in Figure 4, it can be observed that the Massman's model produced realistic moisture curves than the Campbell model.

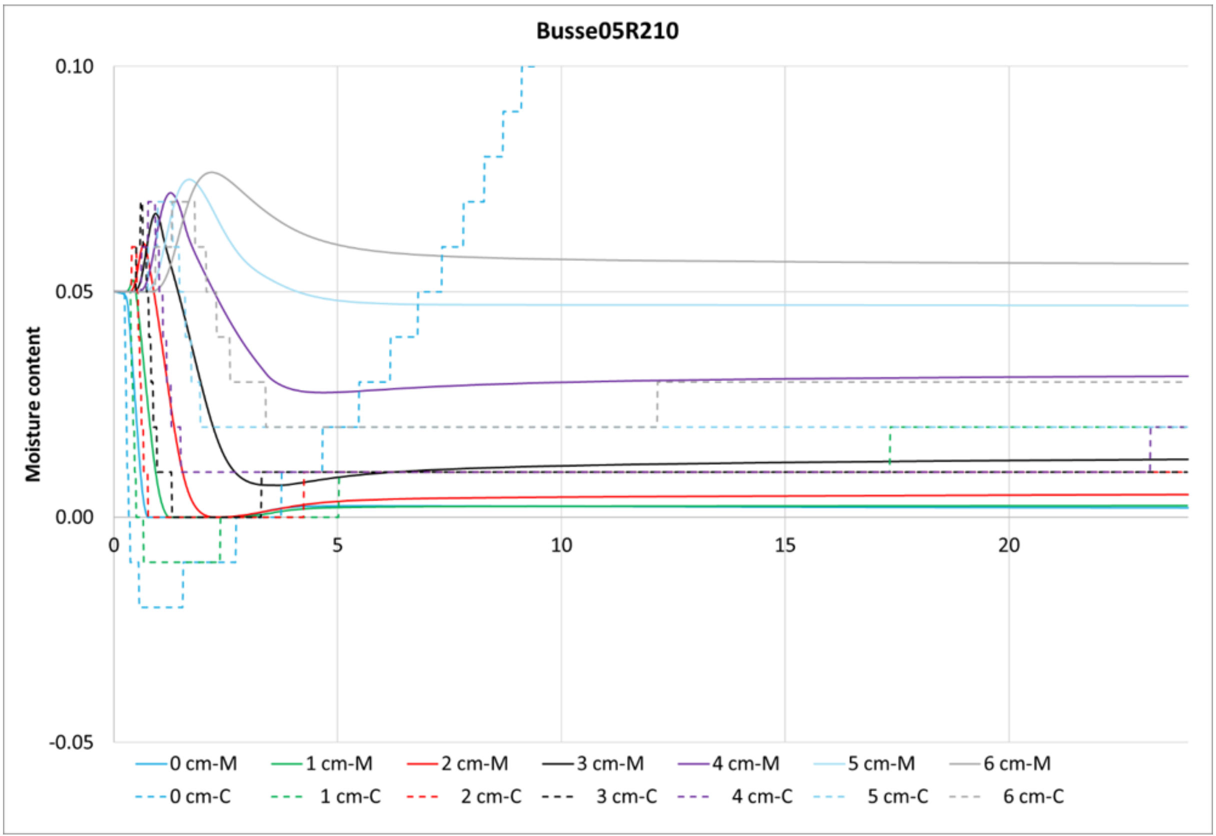

Figure 4. Comparison of simulated soil moistures: Massman's (solid lines) and Campbell's (dashed lines) models for the Busse05R210 dataset.

When using the WesternUS01 soil inputs in Massman's model for the Busse05R310 dataset comparison, the generated temperature data were more accurate (Table 6) than the Campbell's model, as observed in the previous case. Similar results occurred for the soil moisture simulations, the Massman's model was more realistic and accurate than Campbell's model predictions (Figure 5).

Table 6. Temperature statistics. Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Difference (RMSD), Mean Absolute Error (MAE), Correlation (Corr) and Centered RMS for Busse055310 dataset with WesternUS 01 soil).

Busse05R310 (WesternUS 01)									
	Massman Model					**Campbell Model**			
Soil Depth (cm)	**0**	**2.54**	**5.08**	**10.16**	**15.24**	**0**	**2.54**	**5.08**	**10.16**
NSE	0.79	-0.94	-0.40	-0.09	-1.01	0.58	-1.59	-1.44	-5.21
RMSD	43.28	60.69	39.63	13.88	11.41	63.17	80.90	62.23	33.34
MAE	30.13	48.32	32.35	9.23	7.67	55.14	73.56	55.41	31.25
Corr	0.93	0.27	0.35	0.47	0.60	0.95	0.30	0.27	-0.05

CRMS	36.81	55.23	33.20	13.82	8.62	39.30	65.56	44.42	23.51

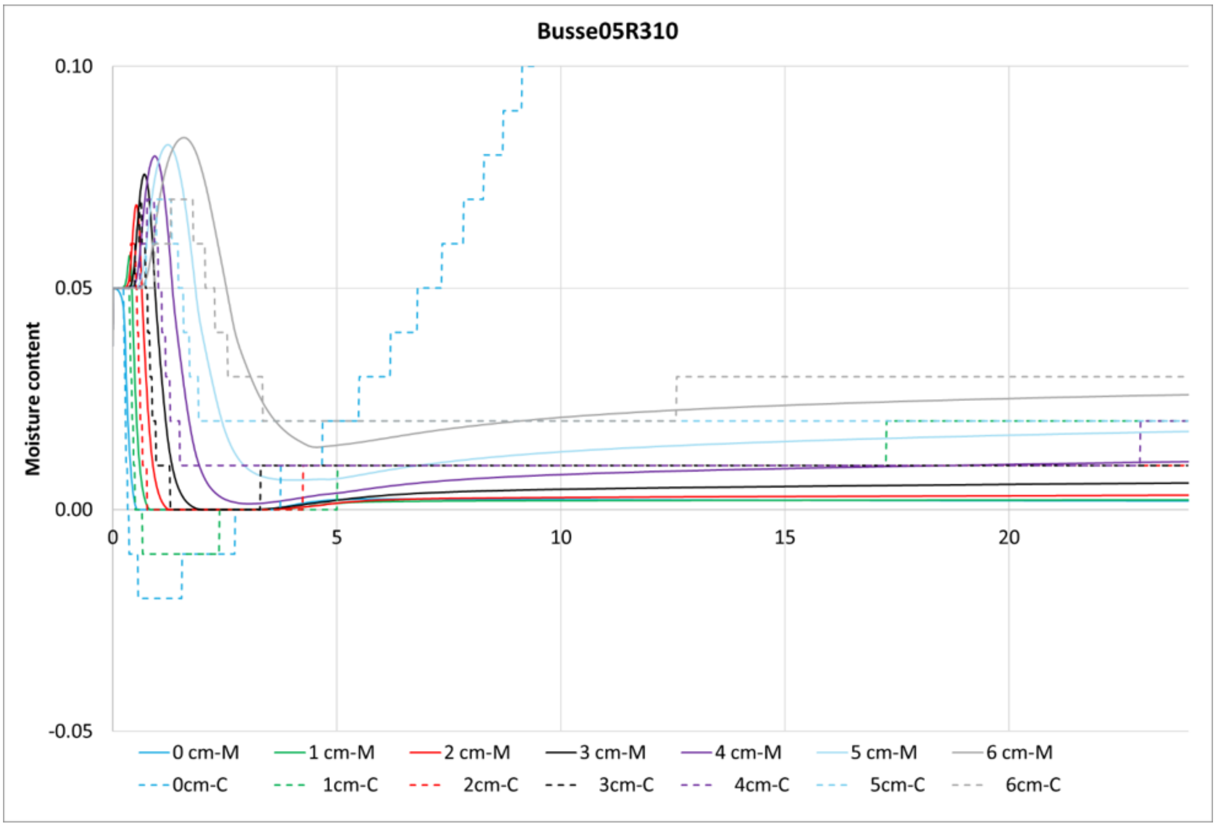

Figure 5. Comparison of simulated soil moistures: Massman's (solid lines) and Campbell's (dashed lines) models for Busse05R310 dataset.

In the case of Weise90_5101 dataset, the predicted temperatures from Massman's model are also more accurate than Campbell's model (Figure 6, Table 7).

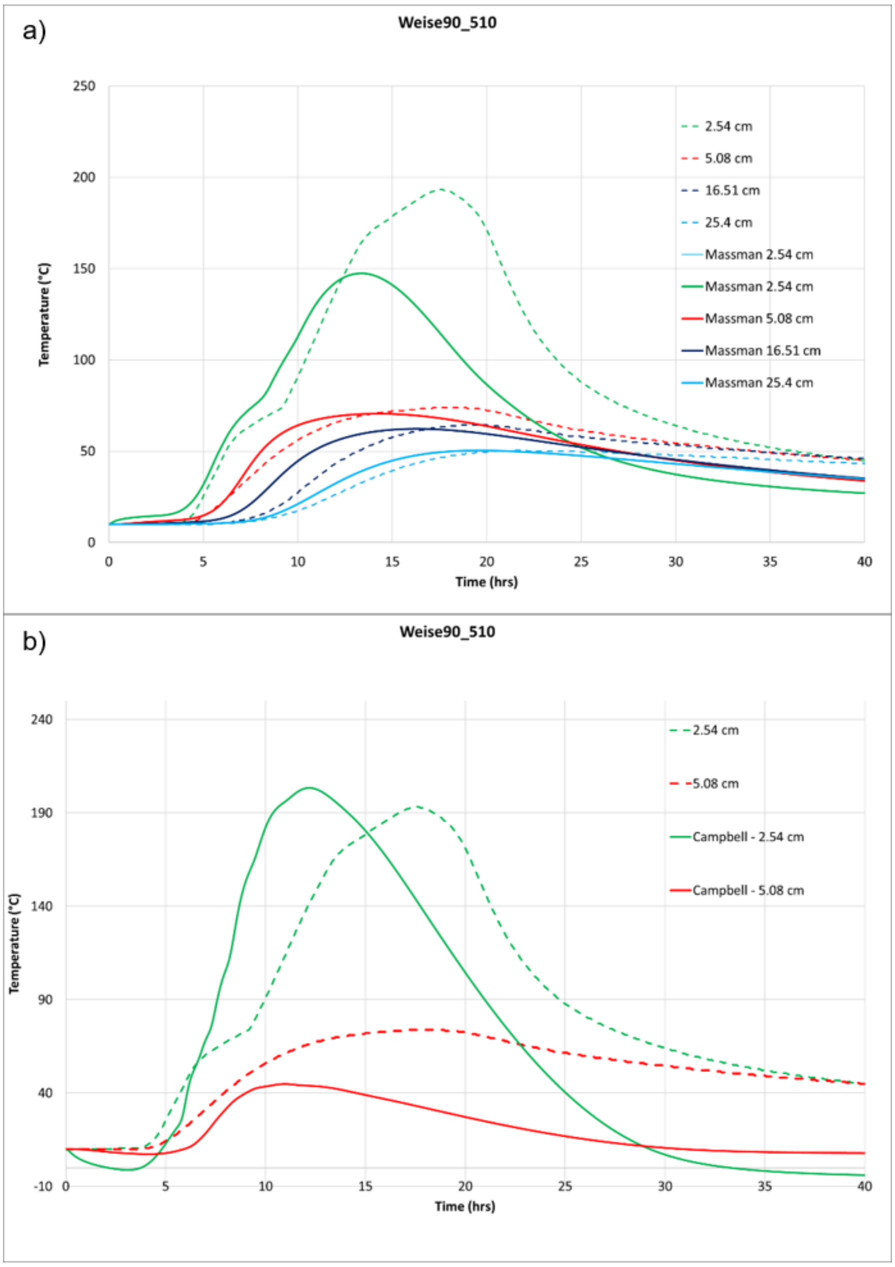

Figure 6. Comparison of Massman's (a) and Campbell's (b) models for temperatures (solid lines) with the observed soil temperatures (dashed lines) for Weise90_5101 dataset.

Table 7. Temperature statistics. Nash-Stcliffe Efficiency (NSE), Root Mean Squared Difference (RMSD), Mean Absolute Error (MAE), Correlation (Corr) and Centered RMS (CRMS) for Weise 90_5101 dataset.

Weise90_5101						
	Massman Model				Campbell	
Depth (cm)	**2.54**	**10.16**	**16.51**	**25.4**	**2.54**	**10.16**
NSE	0.55	0.85	0.83	0.92	0.21	-2.07
RMSD	37.17	7.61	8.00	4.38	49.42	34.66
MAE	29.23	6.64	6.72	3.48	43.98	30.77
Corr	0.86	0.95	0.91	0.96	0.80	0.59
CRMS	28.95	6.28	7.86	4.27	43.94	15.96

The comparisons showed for all depths a higher accuracy of the Massman's model as observed in the NSE values as well as lower errors. The Massman's model also produced more reliable predictions of soil moisture during burning (Figure 7).

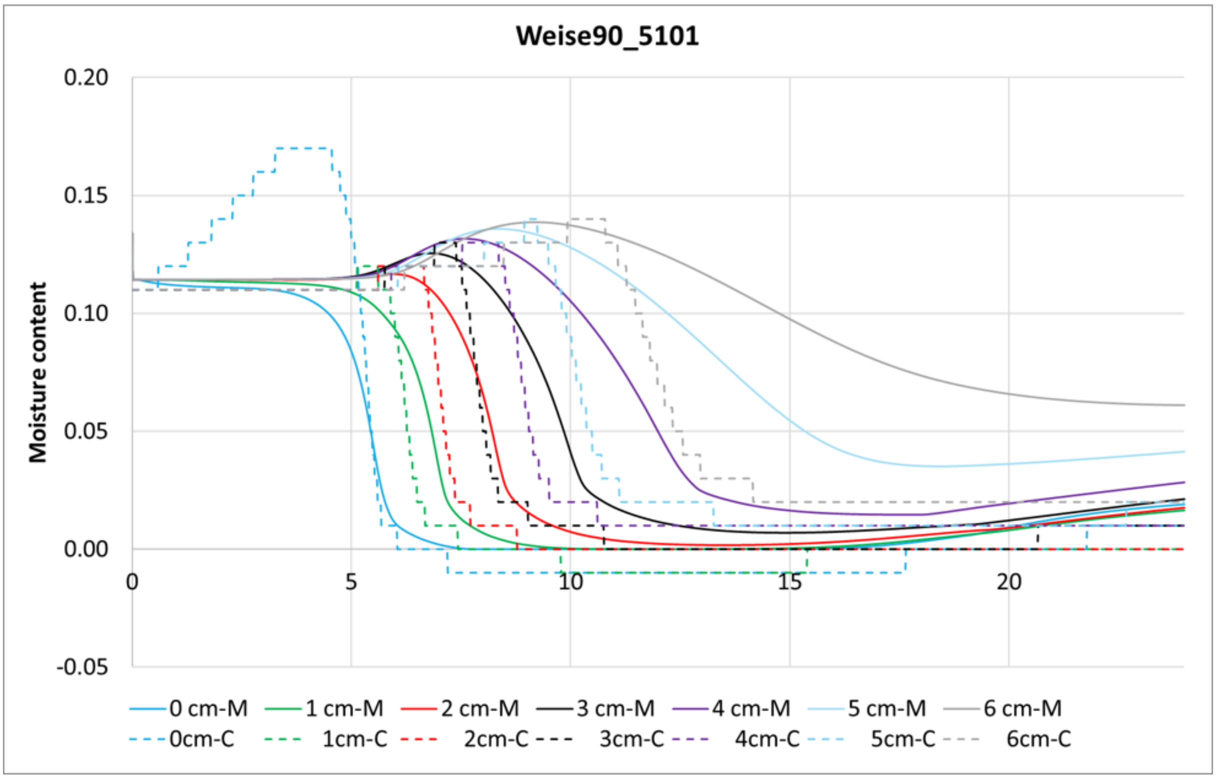

Figure 7. Comparison of simulated soil moistures: Massman's (solid lines) and Campbell's (dashed lines) models for Weisse 90_5101 dataset.

The models were also tested using the WesternUS01 Soil Model for the Weise90_5301 dataset. As the previous cases, the Massman's model data showed higher efficiency than the Campbell's model; although the accuracy of the Massman's model decreased with depth, the produced data was still more reliable and presented lower errors than the Campbell's model (Table 8).

Table 8. Temperature statistics. Nash-Sutcliffe Efficiency (NSE), Root Mean Squared Difference (RMSD), Mean Absolute Error (MAE), Correlation (Corr) and Centered RMS (CRMS) for the Weise90_5301 with Western US01 Soil dataset.

Weise90_5301 (Western US01)							
	Massman Model					**Campbell Model**	
Soil Depth (cm)	**1.9**	**2.54**	**20.3**	**28**	**48.3**	**1.9**	**5.54**
NSE	0.92	0.68	-1.93	-1.18	-4.63	-0.02	-0.96
RMSD	13.45	18.73	18.71	15.42	8.39	47.91	46.57
MAE	11.11	15.73	140.7	11.99	7.62	45.76	43.51
Corr	0.97	0.92	0.50	0.60	0.66	0.92	0.82
CRMS	12.79	18.71	12.34	9.68	3.51	19.46	24.02

In Figure 8, it can be observed that the Massman's model provides more realistic and reliable estimate of soil moisture content from the Weise90_5301 dataset using the Soil Model WesternUS01.

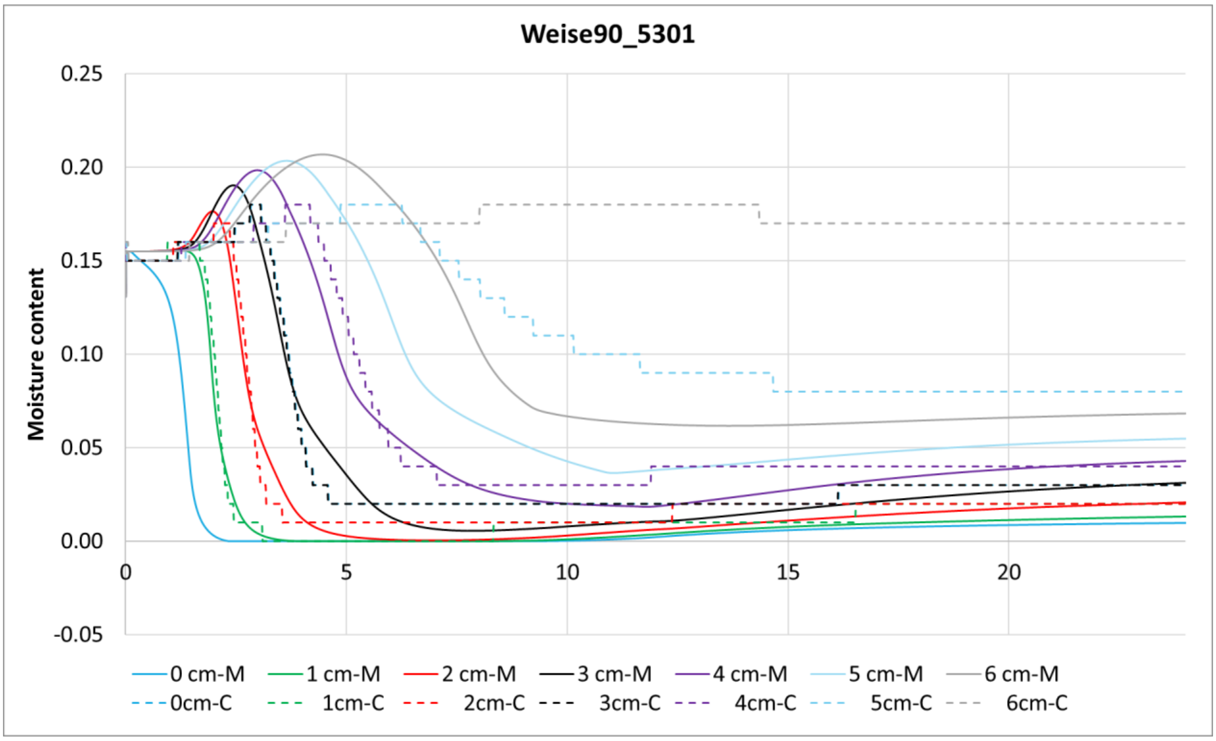

Figure 8. Comparison of simulated soil moistures: Massman (solid lines) and Campbell (dashed lines) for Weise 90_5301.

3) Objective: Publish and archive independent soil heating datasets from various fuel and moisture conditions. The final datasets will be placed in the Forest Service (FS) Rocky Mountain Research Station web page.

We have obtained four independent soil heating datasets (mainly unpublished) from various ecosystems that had different fuel and moisture conditions from several researchers in the Western US. These datasets have been organized, formatted, and made publicly available on Rocky Mountain Research Station website. These files include readme text, soil temperature graphs, metadata and time stamped temperature data. These data sets were collected in field experiments during logging slash pile burns and broadcast prescribed fires. Each dataset consists of: pre-fire fuel loads, fuel moisture conditions, forest floor characteristics (amounts, compositions and moisture), soil characteristics (texture, moisture) (Table 9). These datasets and associated metadata are archived and publicly available on the Forest Service Rocky Mountain Research Station web site: https://www.fs.fed.us/rmrs/projects/high-soil-temperature-data-archive.

Table 9. Description of existing independently collected data sets.

Dataset/ date	Location	Vegetation type	Soil type	Depths sampled	Number of samples
Massman 2001-2004	Manitou Experimental Forest, Colorado	Ponderosa pine	Granitic	Surface, duff, 1,2, 3, 4, 5, 6, and 8 cm	2-5 thermologger/burn
Dumroese 2013-2014	Lubrecht Experimental Forest, Montana	Lodgepole pine, mixed	Belt series	Surface, duff, 1, 2, 3, 6, 8, 10 cm	2-4 thermologger/burn

Sackett and Hasse (Weiss) 1980-2006	Pacific Southwest Research Station, Arizona and California	Chaparral, pinyon- juniper, various pines	Various	Surface, duff, 2, 4, 10, 20, 30 cm	2-5 thermologger/burn
Busse 1995-2008	Pacific Southwest Research Station, California	Mixed chaparral and forests, mastication	Granitic	Surface, duff, 2.5, 5, 10 cm	1-3 thermologger/burn

i. Massman – pile burn dataset from Manitou Experimental Forest, Colorado. The data (soil temperatures, heat fluxes, moisture, and CO_2 amounts) for the prescribed burns during 2001, 2002, and 2004 at Manitou Experimental Forest and all supporting soil data and metafiles are archived in the RMRS database and are available at: http://www.fs.usda.gov/rds/archive/Product/RDS-2007-0002/. These data were used in several publications.

ii. Dumroese – pile burn dataset from Lubrecht Experimental Forest, University of Montana. Two pile burns were conducted in the spring of 2013 and two pile burns were conducted in the fall of 2013. This data was previously unpublished.

iii. Sackett and Hasse (retired, data available via D. Weise) – Pacific Southwest Research Station, 60 prescribed fires (Arizona and California) from 1980 to 2006. These complete data sets consist of: 1) soil temperatures profiles (160 total profiles) at different distances from bole and under the canopy, 2) soil moisture contents, taken at approximate thermocouple depth, before and after burn, 3) forest floor moistures samples taken for litter, fermentation and humus layers, and some woody fuel moistures, 4) forest floor consumption measurements, 5) fuel loading, 6) general weather observations, and 7) DBH of trees being monitored. This data was previously unpublished.

iv. Busse – California, various pile burns, broadcast prescribed fires some with mastication treatments. These data were used in several publications, however the complete datasets were previously unpublished.

4) Objective: Package the simplified soil heating model to be useable with other modules such as the First Order Fire Effects Model (FOFEM).

We package the Massman's 2018 soil heating model in a user-friendly interface within the First Order Fire Effects Model (FOFEM 6.6 or greater). FOFEM is a commonly used fire effect model used within the Interagency Fuels Treatment Decision Support System (IFTDSS) framework or standalone. For the implementation of the soil heating model in the First Order Fire Effects Model (FOFEM 6.6 or greater) interface, a simple GUI was developed (Figure 9).

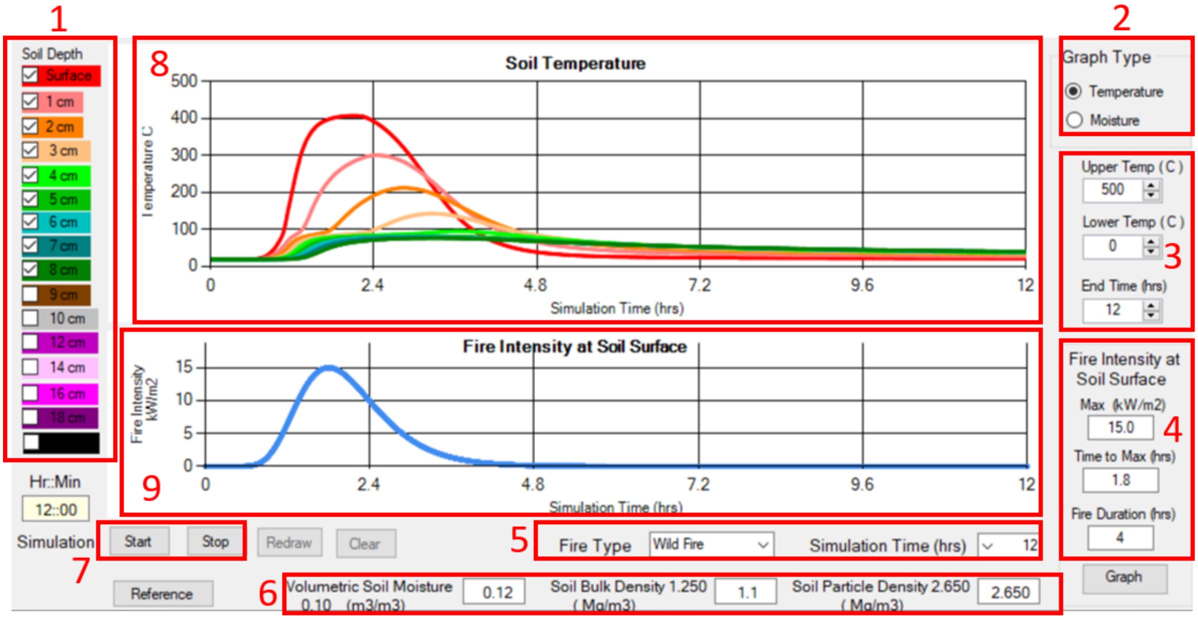

Figure 9, Graphical User Interface (GUI) developed for running the soil temperature and moisture content simulation with the Massman's 2018 Model.

The GUI (Figure 9) can run with inputs from FOFEM or run independently. The user can: 1) select the soil depths for which the temperatures are displayed; 2) switch between the temperature and moisture graphs that is displayed in (8); 3) select the upper and lower temperature limits as well as the end time of x-axis graph (8); 4) input the maximum fire intensity at the soil surface, time until the maximum temperature and duration of the fire which is shown in (9); in 5), select the fire type that is going to be modelled (wildfire, broadcast prescribed burning, pile burning or burnup model, when burnup model is selected the input parameters from FOFEM are used); in 6), input the soil characteristics such as the volumetric soil moisture, soil bulk density and soil particle density; in (7) allows the user to start and stop the model run. Additionally, when the model run is complete, a CSV file containing the modelled data for soil temperature and moisture is created.

Conclusions, implications for management/policy and future research

Soil heating and soil moisture movement can now be simulated with Massman's 2018 Soil Heating Model. Improvements to the model include addressed instability in the volumetric soil moisture and the soil hydraulic conductivity transport. Using previously collected datasets, the validation study indicated that Massman's 2018 model performs better than the Campbell's 1995 model in simulating soil temperature and soil moisture transport for a different fuel and moisture condition from various Western US ecoregions. Massman's 2018 model better performance is likely due to more in-depth numerical calculations of the heat and vapor transport than Campbell's 1995 model and is, accordingly, more computationally expensive. The soil moisture content modeling during fires is a marked improvement in understanding fire's impact on the soil properties. The user-friendly interface allows for easy use of the model, and the model's graphical output displays the heat and soil moisture pulse at different soil depths of interest. Incorporation of the Massman's 2018 model into the First Order Fire Effects Model (FOFEM ver 6.6 or greater) allows users direct access to the improved soil heating model and ease of comparing various fuel loadings and timing of the fire. Fire managers who are interested in secondary fire effects of the heat flux into the soil profile can use this model to address numerous impacts. For example, understanding the effects of various fire intensities on sterilizing the soil or killing tree seeds during pile burns can be simulated. Additionally, during prescribed fires the effects of the spring vs fall timing of the burns can be examined by the heat generated under various moisture conditions. Heat pulses into the soil profile can also affect the soil's nitrogen flux which can move nitrogen in and out of the plant's root zone affecting plant growth.

The next steps for the use of the improved soil heating model is to integrate the model directly with other post-fire models. The suite of post-fire erosion prediction technologies (Elliot and Hall 2010, Robichaud et al. 2014) will likely benefit from these results. Soil heating and water vapor movement often enhances soil water repellency, yet previously we did not have methodology to predict soil temperatures and soil moisture content in the soil profile. Massman's 2018 model will allow for predicting heat pulse in the soil profile from wildfires and prescribed fires, thus a user can compare the likely formation of water repellent soil conditions. This will have important implications for watershed managers and public water supply purveyors. Recent large wildfires in municipal watersheds (i.e. High Park Fire in Colorado, Rim Fire in California) indicate wildfires can affect drinking water, yet the potential effects from prescribed fires have not been modelled for these sensitive watersheds. Integrating these models for watershed managers is the next step to address watershed management options and their effects. These modeling efforts will help managers directly compare fire effects from prescribed fire verses wildfires.

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Appendix B: List of completed/planned Scientific/technical publications/science delivery products.

17-22 April 2016 European Geosciences Union General Assembly, Vienna, Austria. A non-equilibrium model for soil heating and moisture transport during extreme surface heating, W. Massman, P. Robichaud. Presentation with Abstract (Robichaud presented, 60 participants).

21-25 August 2017. 6th International Meeting on Fire Effects on Soil Properties (FESP6), Skukuza, South Africa. Modeling Soil Heating and Moisture Transport During Fires. P. Robichaud, W. Massman, A. Bova. Presentation with Abstract. Invited (38 participants).

27-Nov- 1 Dec 2017. 8th International Fire Ecology and Management Congress, Orlando, Florida. Modeling Soil Temperatures During Fires Requires Modeling Unresolved Aspects of Soil Moisture and Water Vapor Dynamics. William J Massman; AS Bova Pete Robichaud; Larry Gangi. Abstract (Massman presented remotely, Robichaud in attendance, 40 participants)

18-21 Feb 2019. 7th International Meeting on Fire Effects on Soil Properties (FESP7), Modeling Soil Heating and Moisture Flux During Prescribed Fires and Wildfires, Peter R. Robichaud, William J. Massman, Anthony Bova, Antonio Girona García. Invited. (Robichaud will make presentation)

Massman, WJ. 2015. A non-equilibrium model for soil heating and moisture transport during extreme surface heating: the soil (heat-moisture-vapor) HMV-Model Version 1. Geosci. Model Dev. 8: 3659-3680. Doi: 10.5194/gmd-8-3659-2015

Robichaud PR, Massman WJ, Bova A, Girona García A. 2019. Modeling soil heating and moisture flux during prescribed fires and wildfires. International Journal of Wildland Fire. In preparation.

Robichaud PR, Massman WJ, Lesiecki ML. 2018. High soil temperature data archive from prescribed fires and wildfires database. Ft. Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available at https://www.fs.fed.us/rmrs/projects/high-soil-temperature-data-archive.

Massman WJ, Robichaud PR 2018. Massman Soil Heating Model within First Order Fire Effects Model (FOFEM 6.0 or greater). Available from https://www.firelab.org/project/fofem.

Appendix C. Metadata

All soil temperature data are available on our web site.

Robichaud PR, Massman WJ, Lesiecki ML. 2018. High soil temperature data archive from prescribed fires and wildfires database. Ft. Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available at https://www.fs.fed.us/rmrs/projects/high-soil-temperature-data-archive.