Calvet el al. (2015), www.soil-discuss.net/2/737/2015/

Impact of gravels and organic matter on the thermal properties of grassland soils in southern France

Response to Reviewer #2

(T. Ren, tsren@cau.edu.cn**)**

The authors thank Dr. Tusheng Ren (China Agricultural University, Beijing) for his review of the manuscript and for the fruitful comments.

2.1 [**This paper investigates the influences of quartz fraction, soil organic matter (SOM) and gravel component on soil thermal conductivity. Field observations of soil temperature and water content from 21 weather stations in southern France, along with the information of soil texture and bulk density, were used to estimated soil thermal diffusivity and heat capacity, and then thermal conductivity. The quartz fraction was inversely estimated with an empirical thermal conductivity model. A pedotransfer function was further proposed for estimating quartz content from soil texture information. The effects of SOM and gravels on thermal conductivity values were also discussed. The information of quartz fraction in a soil is usually unavailable but has a major effect on the accuracy of many thermal conductivity models and their applications in other comprehensive model (e.g., the land-surface models). Therefore, the topic is interesting and has general applications in soil sciences and related areas. However, I have some concerns about the current approach for estimating soil thermal properties and quartz content, the presentation of the results, and the conclusions.**]

RESPONSE 2.1

Many thanks for these encouraging comments. We will do our best to account for your remarks in a revised version of the manuscript.

2.2 [**First, the method presented in the paper is based mainly on the 1D heat transfer equation and the de Vries (1963) mixed model for soil heat capacity. The authors estimated the apparent soil thermal diffusivity at 10-cm depth from temperature measurements at 5, 10, and 20 cm depths, and calculated soil heat capacity from the information of soil texture, bulk density, and water content at 10 cm. To apply the 1D Fourier heat transfer equation, they assumed that the soil physical properties were uniform and isothermal in the 5-20 cm layer, which was not the case. They stated that "soil properties are relatively homogeneous", but it is difficult to accept this because 1) at least 14 soils had a gravel fraction over 10% (as high as 70% in some soils); 2) there were strong soil moisture and temperature gradients in the 0-20 cm layer; and 3) the existence and spatial distribution of grass roots were ignored. The authors are required to convince the readers that the 0-20 cm soil layer was uniform, and soil temperature and water content measurements at each depth were representative values of the depth. Otherwise, the soil thermal diffusivity estimates are flawed, and further analysis is invalid.**]

RESPONSE 2.2

Yes, we agree. This is a very good point.

We acknowledge that the impact of vertical heterogeneities in λ values has to be properly accounted for in the λ retrieval technique we used. In order to address this issue, we revised our data analysis procedure in order to limit this effect as much as possible. In particular, we used only the soil temperature data presenting a relatively low vertical gradient close to the soil surface, where most differences with deeper layers are found. This refined data sorting increased the λ_{sat} retrieved value for all the stations. A very interesting side effect of the improved procedure was that LHS, SVN, and PRD now present non-zero values of q. On the other hand, the NBN observations are now filtered out as NBN presents very large differences in soil density from one soil depth to another. The new procedure is described below.

The 1D Fourier equation in heterogeneous soil conditions can be written as:

$$C_h \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) \qquad \text{(R1)}$$

and discretized as:

$$\frac{T_i^n - T_i^{n-1}}{\Delta t} = \frac{1}{C_{hi}}\left[\frac{1}{2}\left(\frac{\lambda_{i+1/2}\gamma_{i+1}^n - \lambda_{i-1/2}\gamma_i^n}{\Delta z_m}\right) + \frac{1}{2}\left(\frac{\lambda_{i+1/2}\gamma_{i+1}^{n-1} - \lambda_{i-1/2}\gamma_i^{n-1}}{\Delta z_m}\right)\right] \quad \text{(R2)}$$

In this study, we assume that the retrieved λ values, at a depth of –0.10m, are representative of a bulk soil layer including the three soil temperature probes used to retrieve the thermal diffusivity, and do not differ much from the interfacial λ values along the bottom and top edges of the considered soil layer ($\lambda_{i+1/2}$ and $\lambda_{i-1/2}$, respectively):

$$\lambda \approx \lambda_{i+1/2} \approx \lambda_{i-1/2} \quad \text{(R3)}$$

and, at a given time *n*,

$$\lambda\gamma_{i+1}^n - \lambda\gamma_i^n \approx \lambda_{i+1/2}\gamma_{i+1}^n - \lambda_{i-1/2}\gamma_i^n \quad \text{(R4).}$$

In reality, differences may occur:

$$\Delta\lambda = \lambda_{i+1/2} - \lambda_{i-1/2} \quad \text{(R5).}$$

Considering the temperature gradient ratio R_{TG} at a given time *n*:

$$R_{TG} = \frac{\gamma_i^n}{\gamma_i^n - \gamma_{i+1}^n} \quad \text{(R6)}$$

and combining Eqs. (R4), (R5) and (R6), the retrieved λ can be written as:

$$\lambda \approx \lambda_{i+1/2} - R_{TG}\ \Delta\lambda \quad \text{(R7).}$$

Since soil temperature gradients were more pronounced close to the soil surface and since soil density presented smaller values close to the soil surface, the $\Delta\lambda$, R_{TG}, and $R_{TG}\Delta\lambda$ values were ≥ 0. Since in the soils considered in this study, differences in soil density were much less pronounced at depth than between the –0.05m and –0.10m soil layers, we considered that $\lambda_{i+1/2}$ was closer to the final value to be retrieved, λ^*, than the initial λ retrieval:

$$\lambda^* \approx \lambda + R_{TG}\ \Delta\lambda \quad \text{(R8).}$$

Eq. (R8) shows that the target λ^* value is larger than the initial λ retrieval. The relative error on λ^* can be written as $R_{TG}\Delta\lambda/\lambda^*$ (dimensionless). We used $R_{TG}\Delta\lambda/\lambda^*$ as an indicator of the quality of the λ retrieval, with large values of $R_{TG}\Delta\lambda/\lambda^*$ corresponding to erroneous estimates. In the revised data analysis procedure, a subset of 20 λ retrievals per station was used, at most, corresponding to the lowest $R_{TG}\Delta\lambda/\lambda^*$ values, with the condition $R_{TG}\Delta\lambda/\lambda^* < 10\%$.

Since the NBN station presented $R_{TG}\Delta\lambda/\lambda^*$ values systematically higher than 10%, the NBN data were excluded from the analysis.

The impact of the refined data selection is illustrated in Fig. R2.1 for the MNT station. For the LHS soil, which presented the highest λ RMSD together with q=0, the new procedure permits obtaining a non-zero value of q (Fig. R2.2).

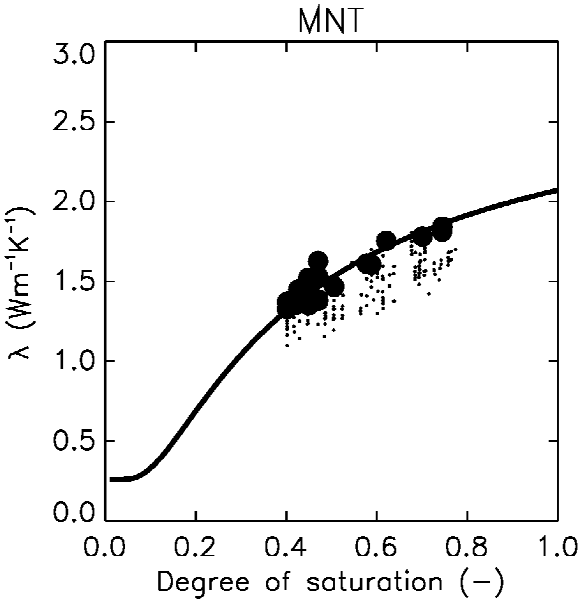

Figure R2.1 - Retrieved and modelled λ values (dots and solid line, respectively) vs. the observed degree of saturation of the soil, at a depth of 0.10 m for the MNT station. The 20 λ retrievals used to fit λ_{sat} are represented by large dots.

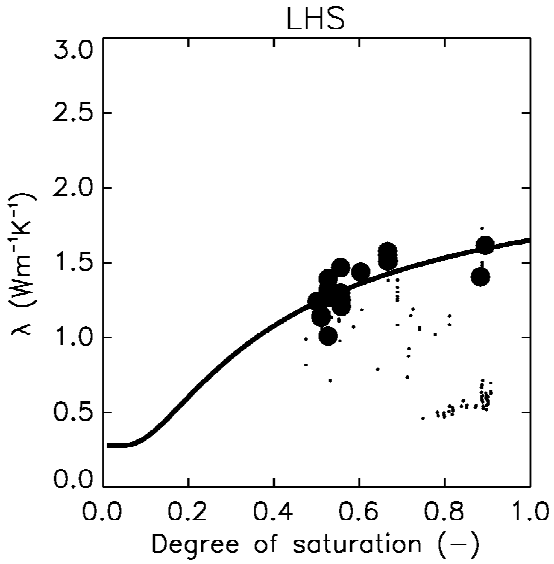

Figure R2.2 - As in Fig. R2.1, except for LHS station.

In practise, the $\Delta\lambda$ term was estimated using top-soil and deep dry density observations (at –0.05m and –0.10m, respectively) and the sensitivity of λ to changes in dry density, $\Delta\lambda/\Delta\rho_d$. The latter was derived numerically using the Eqs. (10)-(13) model, in soil wetness conditions ranging from S_d = 0.4 to S_d = 1. Since the derivation of $\Delta\lambda/\Delta\rho_d$ depends on the obtained q pedotransfer function (Eq. (12)), $\Delta\lambda/\Delta\rho_d$ values were recalculated with the new pedotransfer function, and a few iterations permitted refining these estimates.

At saturation (S_d = 1) $\Delta\lambda/\Delta\rho_d$ ranged between 0.64×10^{-3} $Wm^2K^{-1}kg^{-1}$ for PRD to 1.24×10^{-3} $Wm^2K^{-1}kg^{-1}$ for SBR. At S_d = 0.4, $\Delta\lambda/\Delta\rho_d$ ranged between 0.46×10^{-3} $Wm^2K^{-1}kg^{-1}$ for PRD to 0.81×10^{-3} $Wm^2K^{-1}kg^{-1}$ for SBR.

The $\Delta\rho_d$ term ranged from 10 kg m^{-3} for CBR to 284 kg m^{-3} for NBN. R_{TG} ranged between 0.5 and 2.4, with a median value of 1.3.

2.3 [**Second, the de Vries (1963) mixing model was applied to estimate soil volumetric heat capacity. To do so, a fixed value of 2.0 MJ m-3 K-1 was used for soil solids. The authors should give justification to use a constant value for the 21 soils with different textures. Tarara and Ham (1997) used a value of 1.92 MJ m-3 K-1. A soil-specific value may be better for estimating the volumetric heat capacity of soil solids.**]

RESPONSE 2.3

Yes, soil-specific values for the volumetric heat capacity of soil minerals (C_{hmin}) may be more appropriate than using a constant standard value. However, we were not able to find such values in the literature and we did not measure this quantity.

We investigated the sensitivity of our results to these uncertainties, considering the following minimum and maximum C_{hmin} values: C_{hmin} = 1.8 J m^{-3} K^{-1} and C_{hmin} = 2.2 J m^{-3} K^{-1}. The impact of C_{hmin} on the retrieved values of λ_{sat} and q is presented in Figs. R2.3 and R2.4, respectively. The impact of C_{hmin} on the q pedotransfer function will be published in the final version of this work.

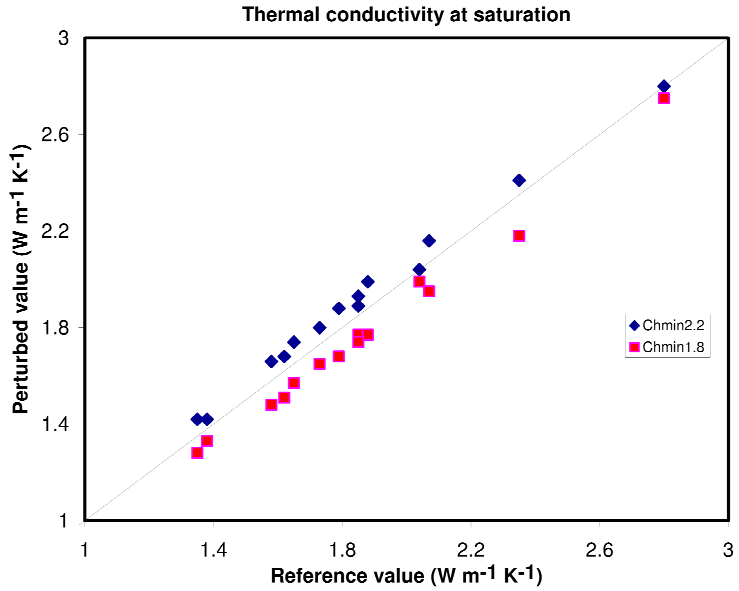

Figure R2.3 - Impact on the retrieved λ_{sat} of using values of C_{hmin} = 1.8 J m^{-3} K^{-1} and C_{hmin} = 2.2 J m^{-3} K^{-1} instead of C_{hmin} = 2.0 J m^{-3} K^{-1}.

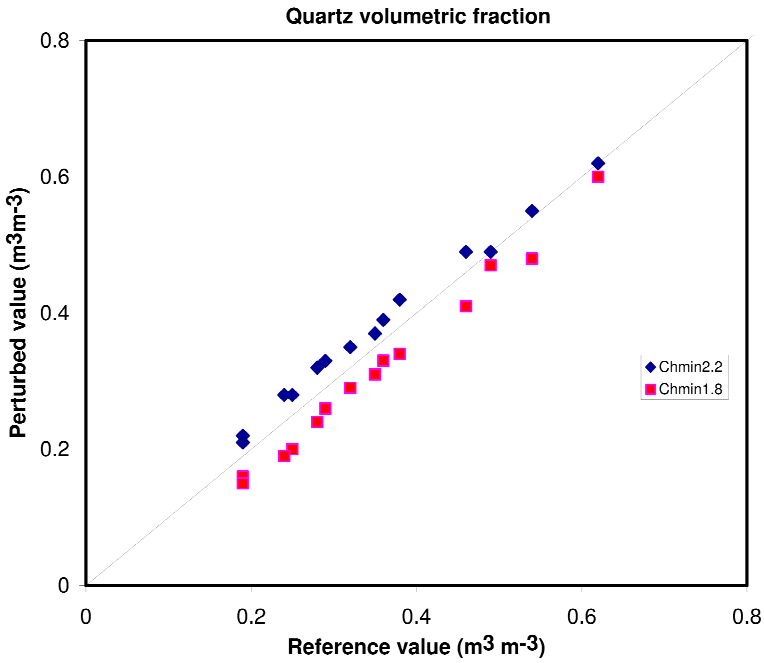

Figure R2.4 - As in Fig. R2.3, except for volumetric fraction of quartz.

2.4 [**In addition, what were the volumetric fractions of grass roots in the 0-20 cm soil layer? Does the heat capacity of grass roots have a significant influence on the bulk soil heat capacity?**]

RESPONSE 2.4

The grasslands considered in this study are not intensively managed. They consist of set-aside fields cut once or twice a year. Calvet et al. (1999) gave an estimate of 0.160 kg m^{-2} for the root dry matter content of such soils for a site in southwestern France, with most roots contained in the 0.25m top soil layer. This represents a gravimetric fraction of organic matter ≤ 0.0005 kg kg^{-1}, i.e. less than 4% of the lowest m_{SOM} values observed in this study (0.013 kg kg^{-1}) or less than 5% of f_{SOM} values. We checked that increasing f_{SOM} values by 5% has negligible impact on heat capacity and on the λ retrievals.

2.5 [**Third, no independent data or measurements were used to evaluate the estimates of soil thermal conductivity and quartz fraction. In Table 2, for example, the estimated thermal conductivity values for saturated soils ranged from 0.52 to 2.79 W m-1 K-1 for 15 soils, all were much lower than the published results of Lu et al. (2007) and Tarnawski et al. (2011). The authors may need to verify the results by compare the model estimates against thermal conductivity measurements with the line-source probe or the heat pulse technique**.]

RESPONSE 2.5

It must be noted that in many studies (e.g. Lu et al., 2007) λ_{sat} estimates are derived from reassembled sieved soil samples excluding the gravels, while our data concern undisturbed soils.

In our revised analysis, we found λ_{sat} values ranging between 1.26 $Wm^{-1}K^{-1}$ and 2.75 $Wm^{-1}K^{-1}$. These values are consistent with λ_{sat} values reported by other authors. Tarnawski et al. (2011) gave λ_{sat} values ranging between 2.5 $Wm^{-1}K^{-1}$ and 3.5 $Wm^{-1}K^{-1}$ for standard sands. Lu et al. (2007) gave λ_{sat} values ranging between 1.33 $Wm^{-1}K^{-1}$ and 2.2 $Wm^{-1}K^{-1}$.

2.6 [**Finally, I do not think the empirical equations (13) and (14), and related results and discussion, are related to and helpful for the purpose of this paper**.]

RESPONSE 2.6

The empirical Eq. (13) for θ_{sat} is used for the end-to-end simulation for the sensitivity study of Table 3, as such an equation has to be used in land surface models. Eq. (14) is equivalent to Eq. (1). The impact of using Eq. (13) in the sensitivity study (current Sect. 4.1) will be shown

and discussed. Note that we found and corrected a bug in the program we developed to perform this sensitivity analysis. In the revised manuscript, the sensitivity study will be performed with and without using this equation, and for several plausible pedotransfer functions.

2.7 [**The current title does not fully represent the content of this paper. The title talks about the effects of gravels and organic matter on soil thermal conductivity values. In the text, on the other hand, the authors spent a lot effort on discussing the influences of quartz content on soil thermal conductivity. The title also addresses the grassland soils, but the detailed information about grass cover and roots was missing.**]

RESPONSE 2.7

Yes, in the revised version of the manuscript, the effects of gravels and organic matter on soil thermal conductivity values will be included in the result section. More information of vegetation characteristics will be given.

2.8 [**Page 739 Line 7-8: The authors stated that soil thermal conductivity was hard to obtain directly and in situ. This is not true today. Recent advances in line-source probe and heat pulse method have made it easy to monitor soil thermal conductivity in the field (e.g., Bristow, K.L., G.J. Kluitenberg, and R. Horton. 1994. Measurement of soil thermal properties with a dual-probe heat-pulse method. Soil Sci. Soc. Am. J. 58:1288–129; Zhang, X., J. Heitman, R. Horton and T. Ren. 2014. Measuring near-surface soil thermal properties with the heat-pulse method: correction of ambient temperature and soil–air interface effects. Soil Sci. Soc. Am. J. 78:1575–1583. The authors may also include the reference of Bristow (1998) who investigated the influences of quartz fraction on soil thermal conductivity.]**

RESPONSE 2.8

Yes, this sentence will be rephrased. Note however that such measurements are currently not made in operational meteorological networks. Using standard soil moisture and soil temperature observations is a way to investigate soil thermal properties over a large variety of soils, as the access to such data is facilitated by online databases (e.g. https://ismn.geo.tuwien.ac.at/).

2.9 [**Page 740 Line 21: Fig. 2 should be cited as Fig. 3 here. Page 741 Line 17: 'Figure 3' should be 'Figure 2'.**]

RESPONSE 2.9

Yes. This typo will be corrected.

2.10 [**Page 740 Line 23-26: How were gravel and SOM contents determined? Grass roots may also influence soil thermal conductivity and heat capacity in the shallow soil layers, but were ignored in the paper. Please give supporting evidence about this. In addition, what depth was bulk density measured? Did soil bulk density differ with depth?**]

RESPONSE 2.10

Soil texture, gravel and SOM fractions were measured by an independent laboratory we contracted (INRA-Arras) from samples we collected in situ.

We checked that grass roots should not significantly influence our results (see RESPONSE 2.4). One cannot exclude large root density values very close to the soil surface during the plant growth period, but the new data sorting procedure we implemented limits these soil heterogoneity effects (see RESPONSE 2.2).

Bulk density was measured at all depths (–0.05 m, –0.10 m, –0.20 m) using unperturbed oven-dried soil samples collected using metal cylinders of known volume. Most differences were observed from –0.05 m to –0.10 m, as soil density is lower close to the surface. The largest difference was observed for NBN (–284 kg m^{-3} at –0.05 m with respect to –0.10 m, or –18%). For the 14 stations now presenting successful q retrieval, –0.05 m density relative differences with respect to density at –0.10 m range from –3% or less (MNT, SFL, LGC, CBR, LHS, SVN, PRD) to about –13% (SBR, BRN, PRG), and from –7% to –9% for CDM, LZN, MTM, and URG.

2.11 [**Sect. 2.5: The estimated thermal conductivity values were used to retrieve quartz content data using the empirical thermal conductivity models. Leong et al. (2009) tried to use the Lu et al. (2007) model to inversely estimate quartz content in soil samples. In this work, the authors used the Yang et al. (2005) model. Please explain why the Yang et al. (2005) model was used, and how the quartz content estimates from the two models may differ.**]

RESPONSE 2.11

Yes, in the first version of this work, we used the Kersten number calculation used by Yang et al. (2005). Figure R2.5 shows the resulting K_e value, together the K_e value obtained using the Lu et al. (2007) model for fine and coarse soils. It can be seen that most differences between these models occur for S_d values < 0.4. Since we only use λ retrievals for S_d values > 0.4, the impact of the uncertainties in the determination of K_e is limited. However, using Lu et al. (2007) instead of Yang et al. (2005) tends to produce smaller values of λ_{sat} and q retrievals, as shown by Figs. R2.6 and R2.7. The impact of the Kersten number calculation will be discussed in the final version of this work.

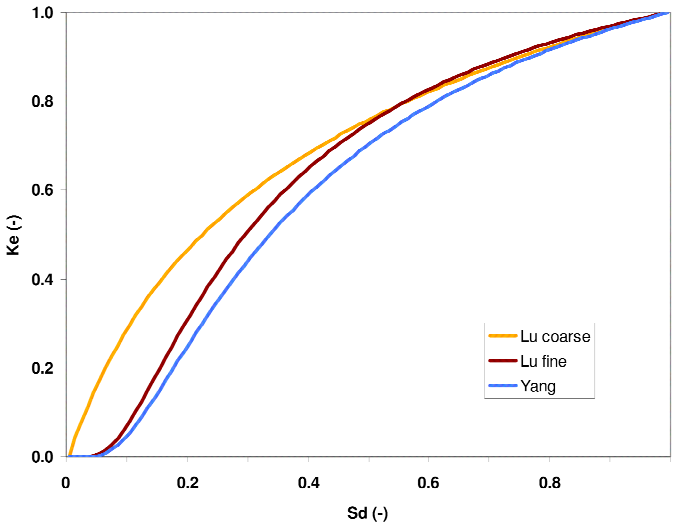

Figure R2.5 - Kersten number vs. degree of saturation as modelled by Lu et al. (2007) for coarse and fine soils, and as modelled by Yang et al. (2005).

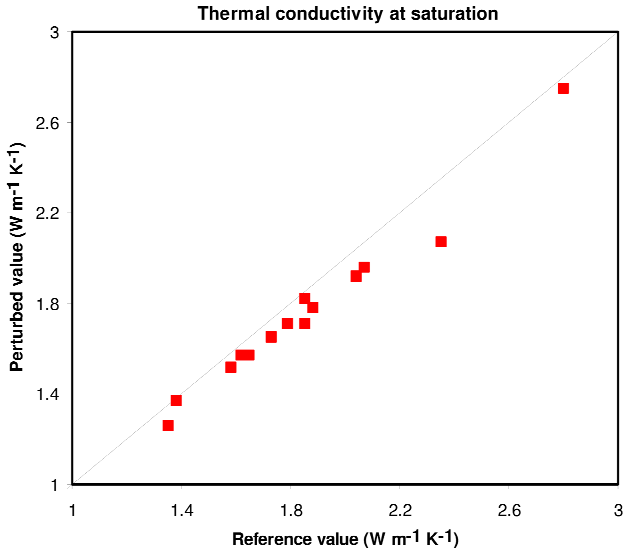

Figure R2.6 - λ_{sat} retrievals using the Kersten number as modelled by Lu et al. (2007) vs. those using the Kersten number as modelled by Yang et al. (2005).

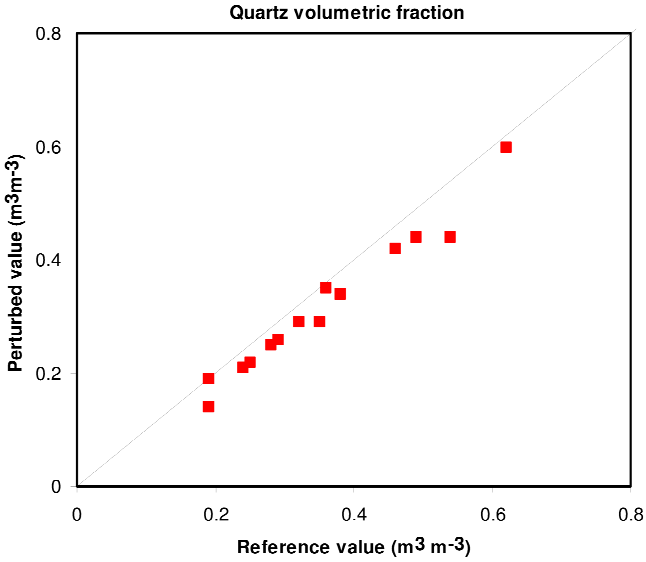

Figure R2.7 - As in Fig. R2.6, except for *q* retrievals.

2.12 [**Sect. 2.6: More in-depth explanations are required to explain the calculation of quartz content.**]

RESPONSE 2.12

Yes, we will publish a Supplement to the final version of the paper explaining the various calculation steps.

2.13 [**Sect. 3.2: I am not sure how useful to develop the pedotransfer functions for estimating quartz content. It is apparent that all errors in the measurement (e.g., temperature, water content, bulk density, and gravel fraction) and calculations (thermal diffusivity and heat capacity) have been included in the results of quartz content. In addition, I had a hard time to figure out how quartz content was related to the fraction of soil organic matter (Eq. [12]).**]

RESPONSE 2.13

In the revised version of the manuscript, we will improve the description and the assessment of the uncertainties affecting the obtained pedotransfer function(s).

2.14 [**Sect. 4.2: The authors suggested that the very low values of quartz content might be caused by (1) the natural heterogeneity of soil properties, (2) the living root biomass, and (3) stones that were not accounted for in the gravel fraction. All these factors lead to inaccurate estimates of soil thermal diffusivity and heat capacity. Therefore, I wonder if it is correct to include all the 21 stations in this work. On those soils with high fractions of gravel (and stones) and grass roots, it is impossible to obtain representative temperature and water content data at each depth, and it is inappropriate to apply the 1D heat transfer equation to estimate soil thermal diffusivity.**]

RESPONSE 2.14

The difficulties we had can be explained by heterogeneities in soil properties, soil density in particular. An enhanced procedure was implemented in order to mitigate this effect (see RESPONSE 2.2). LHS, SVN, and PRD now present non-zero values of q and the NBN observations are filtered out. We had no difficulty in measuring soil temperature and soil moisture, including at the BRN soil presenting the largest fraction of gravel (see Fig. R2.8).

Note that the sensors we use are designed to work in such difficult conditions. The ThetaProbe and PT100 sensors have very strong rods, 0.06 m and 0.10 m long, respectively.

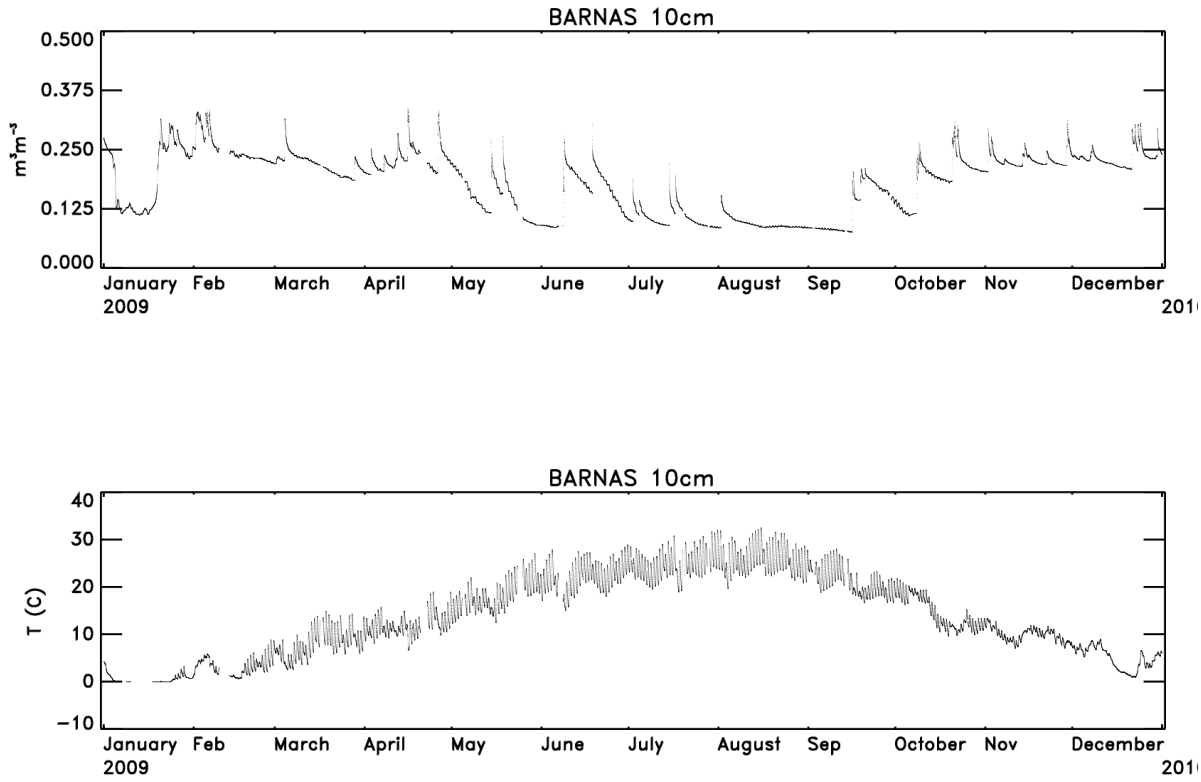

Figure R2.8 - Soil temperature and soil moisture measured in 2009 at the BRN station at a depth of –0.10m

2.15 [**Most symbols in this paper are not properly defined.**]

RESPONSE 2.15

We tried to use symbols used in other works. It will be made clear that in this study, q (f_{SOM}) represents the volumetric fraction of quartz (SOM) within the whole soil volume, while in many studies, it represents the volumetric fraction of quartz (SOM) within the volume of soil solids.

2.16 [**Table 1: The soil texture should be mentioned together with the particle size distribution.**]

RESPONSE 2.16

A new table will be added, listing the particle size distribution observations.

2.17 [**Figure 2 and 3 do not match with their captions**.]

RESPONSE 2.17

Yes. This typo will be corrected.

2.18 [**Figure 4: How were the solid lines obtained? For the SBR site, why a large variation in thermal conductivity was observed in a narrow range of degree of saturation? How come a gravel soil (the PRD site) had very low thermal conductivity in the degree of saturation range of 0.4-0.5 range?**]

RESPONSE 2.18

For several soils (SBR, SVN, LZC, PRD, LGC, BRN, and CBR), no λ retrieval or very few λ retrievals were obtained for S_d > 0.6. Since we did not use the data for Sd < 0.4, a narrow range of S_d is used for these soils. In the revised analysis (see RESPONSE 2.2), the lowest λ retrieval values are not considered as they result from heterogeneities in soil density.

==========END ==========