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The Soil heat flow sensor functioning checks, imbalances' origins and forgotten energies.

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Abstract. Soil heat flux is an important component of the Surface Energy Balance (SEB) equation. Measuring it require an indirect measurement. Every used technique may present some possible errors tied with each specific technique, soil inhomogeneities or physicals phenomenon such as latent heat conversion beneath the plates especially in a desiccation cracking soil or vertisol. The installation place may also induce imbalances. Finally, some errors resulting from the physical sensor presence, vegetation presence or soil inhomogeneities may occur and are not avoidable. For all these reasons it is important to check the validity of the measurements. One quick and easy way is to integrate results during one year. The corresponding integration should be close to zero after a necessary geothermal heat efflux subtraction which should be included into the SEB equation for long term integrations. However, below plate evaporation and vegetation absorbed water or rainfall water the infiltration may also contribute to the observed short scale or/and long scale imbalance. Another energy source is usually not included in the SEB equation: the rainfall or irrigation. Yet its importance for a short- and long-term integration is notable. As an example, the most used sensors: Soil Heat Flux Plates (SHFP), is given.

1 Introduction

On the surface of the soil, a daytime solar radiation and nighttime soil infrared radiation generates an important heat flow called *G*. This flow is either positive, heat flow going down to the depths of the soil and mainly due to solar heating, or negative, the soil surface temperature drops and therefore a heat flow rises from the ground to the surface mainly lasting at night. This heat exchange is important as that energy stored into the soil may be used for the water evaporation (Penman, 1948, Monteith, 1965). Many process, especially biological process such as roots and microbial activities, are temperature dependent which is directly related to *G*. Also, the knowledge about *G* is necessary to check the well-known Surface Energy Balance or Budget (SEB) (Lettau and Davidson, 1957, Lemon, 1963) given by equation 1:

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$$R_n - G = H + L_e \tag{1}$$

With R_n being the net radiation, H being the sensible heat flow into the atmosphere and L_e being the latent heat flow (evaporation).

By the sake of SEB closing, this equation may be completed including the vegetation heat storage S_C and photosynthesis activity S_P (Meyers and Hollinger, 2004). SEB closure allows us to have a quick quality check on all the concerned measurements (Oncley et al., 2002 and Oncley et al., 2007).

Depending on the concerned surface and period, all over the different energy fluxes, G part is significant and may reach up to 50% of R_n (Monteith, 1958, Idso et al., 1975, Choudhury et al., 1987). The soil heat flow is not a direct measurement and not evident as it cannot be done on the surface but, more or less, deeply buried into the soil. Different techniques are employed: flux plates (heat flux sensing thermopiles), calorimetric (temperature temporal variation), temperature gradient or combination (simultaneous calorimetric and gradient measurement or flux plate and above storage measurement), see Sauer and Horton (2005), for recent review see Gao et al. (2017). All the used techniques are sensing only conduction heat transfer. Radiation or convection are not sensed. The radiation concerns a soil surface and is sensed by radiometer and included in R_n and the convection concern fluids (liquids or gases) and may potentially bias the measurements but are not sensed and usually are not included into SEB or G corrections.

One of the most used technique is the SHFP buried in the soil. As every sensor, these plates are subject to biases and errors. Some of these errors are specific to the heat flux plate technology, others are rather specific to the surface exchanges and soil inhomogeneities. Whatever is the sensor used for G determination, it is important to check if the acquired measurements were representative of the surface energy exchanges or possibly biased by inhomogeneities. Further considerations threating the flux plates sensors example.

SHFP sensing temperature difference across their thickness. This temperature difference is proportional to the heat flux going through the plate and inversely proportional to the plate thermal conductance. Nevertheless, because the soil thermal conductivity is not the same as SHFP thermal conductivity (and then its thermal conductance) the heat flux density is deformed and the measurement is biased (Philip, 1961; Sauer et al., 2003). As the soil thermal conductivity change greatly with soil water content and density (Sepaskhah and Boersma, 1979), flux plates have to be periodically calibrated. Nowadays, the commercial self-calibrating SHFP are available and are calibrated by heating their upper side by a deposited thin resistor then checking the proportion of the sensed heat versus proportion of the produced heat forming a real-time calibration factor. Liebethal (2006) checks the correct functioning of this calibration. However, SHFP are invasives and are subject to bias measurements (Sauer and Horton, 2005). As every sensor, there should be enough installed plates in order to ensure a spatially representative measurement. The measurement of SHFP buried at some depth need to be completed by adding the upper soil layer heat storage in order to obtain surface soil heat flux (Ochsner et al., 2007). And finally, as the soil heat plates are sensing only sensible heat fluxes by conduction, any evaporation taking place under the plate is not sensed causing an imbalance of up to 100W/m² (Buchan, 1989, Mayocchi and Bristow, 1995).

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Nevertheless, the flux plates placement remains controversial. On the one hand, in order to avoid sensible heat to latent heat conversion (evaporation) beneath the plates biasing measurement, numerus authors and adopted ICOS protocol (de Beeck et Al., 2018) are suggesting 5 cm depth burring. On the other hand, Gentine et al. (2012) is indicating a systemic error due to high frequency solar radiations variation not sensed by a deeply buried SHFP or temperature profile sensors and suggest then 2mm depth.

This short note deals with how to assess the correctness of SHFP functioning and highlighted possible imbalance. It does not deal with the soil layer heat storage above the plate which should be measured and added. Other energies than solar radiation energy should be added to the surface energy balance equations if applicable.

2 Materials and Methods

Soil heat plates used for these studies were HFP01SC self-calibrating flux plates from Hukseflux Thermal Sensors B.V., Delftechpark 31, 2628 XJ Delft, The Netherlands. The used datalogger was a CR1000 from Campbell Scientific, Logan, Utah, USA. Autocalibration is triggered every seven hours: during four minutes heating with 1.4 W power.
For comparison of different operational modes, including or not including the data acquired during and immediately after all calibration periods, data are collected by the logger either every one minute and stocked with a flag corresponding to the calibration initialized every seven hours or averaged every 30 minutes including the calibration periods. This allows checking the influence of the calibration heater inclusion in the collected data. Plates are used on a ICOS cropland site FR-Lam (43°29'47.21"N, 1°14'16.36"E, silty-clay: 50.3% clay, mainly Kaolinite, 35.8% silt, 11.2% sand, 2.8% organic matter). Results reported in this paper concern year 2020 with winter wheat (Triticum aestivum) culture.

3 Results and discussion

3.1 SHFP a posteriori checks.

Using the SHFP is probably the easiest way for monitoring *G* and this point may explain the relative popularity of this technique. In this paper only the soil flux plate functioning is described and no consideration is given to above soil heat storage measurement which is another challenge.
In the ideal conditions, the soil temperature changes seasonally but after one year it recovers its initial temperature whatever is the sensed soil temperature depth. Off course it is an approximation because there are no two identical years and the soil temperature may vary slightly from one year to another. By simplification, if we are assuming the solar radiation heat stored in the soil did not change after one year, then the total sensed surface heat flux exchange should be negative.

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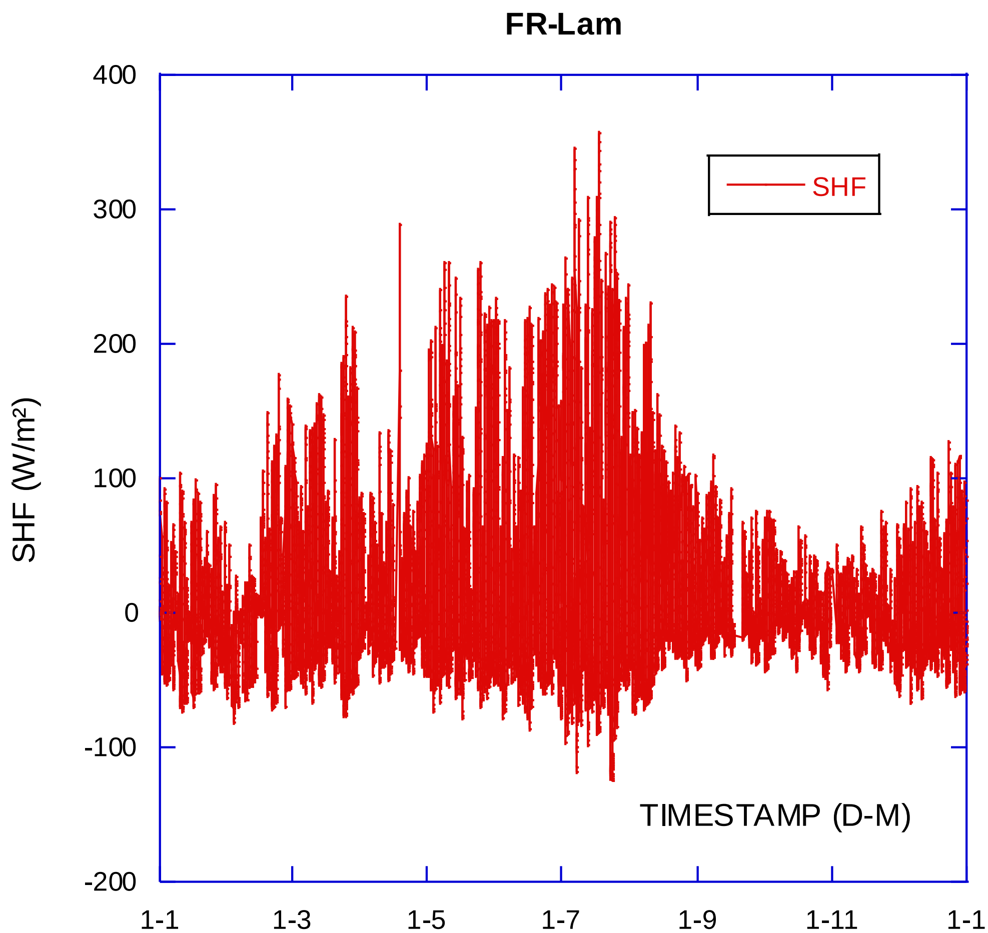

Figure 01) Soil Heat flux measured by a self-calibrated heat flux plate during a year.

95 **3.2 Heat flux origins and imbalances.**

Indeed, it is not nil since it includes the geothermal heat flux G_{TH}^{L} emitted by the Earth (Elder, 1965). On average, the soil emits 82 mW/m² that is -25 MJ/m² a year depending of the glocalization. Figure 01 depicts the soil heat flux recorded by one of our SHFP installed at the border of an enclosure and considered as "reference" for data gap filling when others plates have to be temporarily removed (soil operation on a cropland). It is difficult or even impossible to know if the measurements are valid

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based only on that figure. Using an integration of the concerned measures, after G_{TH}^{L} subtraction and during one year, starting from zero, we should also end the year at zero (Fig. 02). As mentioned previously, we have to subtract the geothermal heat flux to the sensed heat flux if expecting to reach a zero level by heat flux integration over a year. The geothermal heat flux varies a lot on the Earth surface being localization specific. In our case it is about 75 mW/m² (W = -24 MJ/m² a year). As we can see on the Fig. 02, SHFP measurements integration is not nil and the geothermal energy correction make the imbalance even worse. Far to be negligible, the observed imbalance represents about 10% of the integrated absolute sensed soil heat flux. The same plate emplacement gives an imbalance more or less important during different years but still always largely positive and represent always about 10% of the integrated absolute flux. The observed largely positive imbalance may be tied with the heat flux plate technique and the installation emplacement. Indeed, Ochsner et al. (2006) compared different methods and reporting mains errors sources for SHFP; thermal conductivity causing a possible heat flow distortion, a thermal contact between the plate and the soil, latent heat loses and water (liquid or vapor) flow disruption. Both, the different from surrounding soil plate thermal conductivity and the poor thermal contact can be overcome by self-calibrating plates. For the rest of this paper, by convention, for the long-term important heat flows correction a superscript "L" is added and for short-term important heat flow corrections a superscript "S" is added. When a correction is important for both, short- and long-term measurements, no superscript annotation is added.

3.2.1 Beneath SHFP evaporation.

The heat conversion from sensible to latent heat is arising below the plate bias balance as the corresponding upcoming energy (latent heat) is not sensed anymore by the plate, however is still sensed by air phase L_e sensors such as eddy covariance setup. The subsurface evaporated water is then added to the surface evaporated water when the corresponding energy was already accounted by the soil heat flux plate measurement as sensible heat before the conversion. It is a *double counting* as highlighted by Ochsner et al. (2006). Nota bene, the reality is even more complicated as the water vapor created under the plate may needs some time to emerge from the soil. The sensed water vapor in the air is then not only with multiple origins but also with multiple conversion time complicating SEB closure.

In our case, the positive imbalance may be, in part, due to the below plate evaporation. As the plate is buried in a high clay content soil, the desiccation cracking may allow deep soil evaporation (Selim and Kirkham, 1970).

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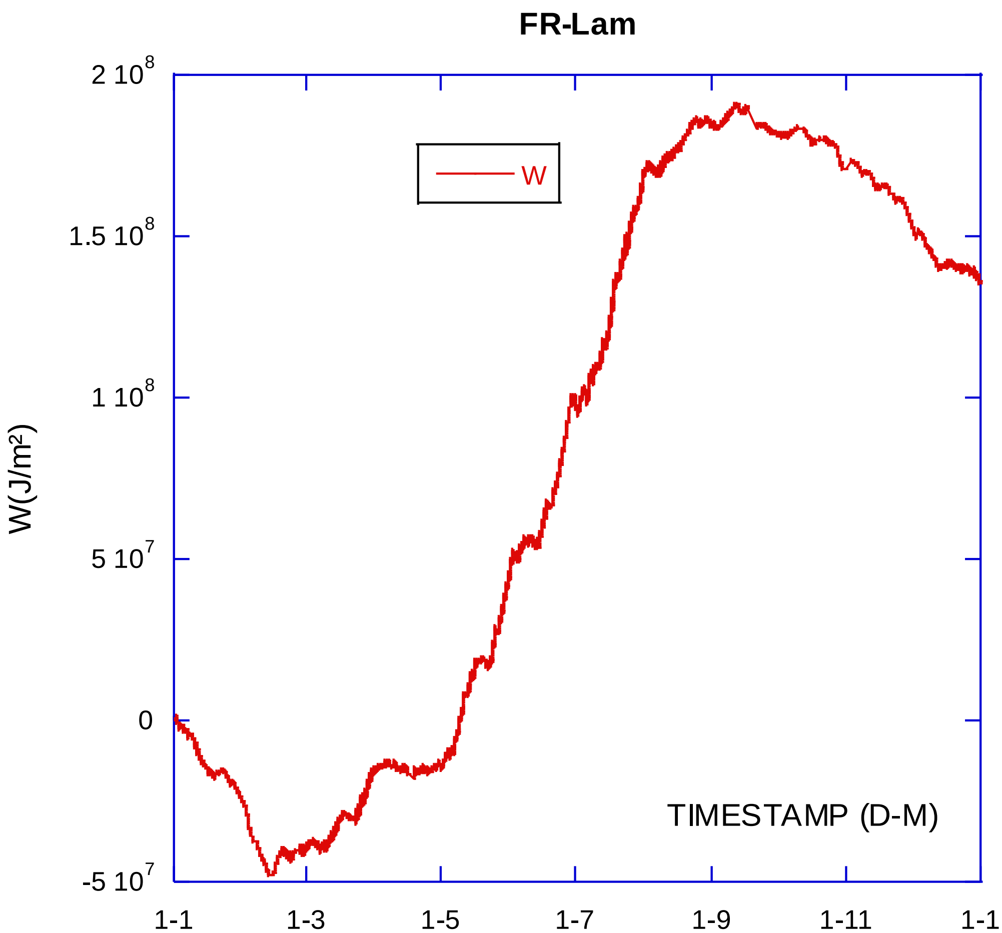

Figure 02) Soil heat flux Integrated during a year.

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3.2.2 Sunshine or soil inhomogeneities.

Another cause may be the enclosure proximity with a higher soil density comparing to the surrounding tiled soil, the explanation given further in the text. Yet another possible bias, either positive or negative imbalance, is the soil surface inequal sunshine resulting in a non-uniform, direction dependent, heat flow density. Making abstraction of a heat storage above the flux plates and a possible non-uniform soil heat capacity below the plates, we can consider a simple limited shadowed surface case.

Figure 3 depicts a partially shadowed soil surface with three SHFP. Plate A is installed on a sunny surface far from any shadowed surface. Plate B is installed under a sunny surface but close to a shadowed surface and plate C is installed under a shadowed surface. During a day (Fig 03.a) plate A and plate B will sense the same amount of heat resulting from the solar heating. Plate C being installed under a shadowed surface, only a little heating is sensed by this plate. Bellow the plate A, the soil is constituting a heat storage S_A with all the heat penetrating the soil. Below the plate B, one parts of the penetrating heat is going under the near, shadowed surface as the soil is over there colder and only a part of the total heat sensed by plate B is stored as S_B. Below the plate C, only a weak heat is penetrating the surface and the storage S_C is constituted from this heat raised by the heat coming from the near sunny surface. We have then a relation:

$$S_A > S_B > S_C \quad (2)$$

In, the case of a relatively small shadowed surface we can even assume $S_B = S_C$. The night (Fig. 03.b), the soil below the plate A is giving back the heat drawing from the storage S_A. The same for the soil below plate S_B and S_C. However, the heat flowing up will be proportional to the corresponding heat storage and the equation 2 is also valid for nocturnal heat effluxes. Then, the daily balance of the plate A will be close to zero, B plate balance will be positive and C plate balance negative. We can observe then imbalances with perfectly working flux plates without latent heat problems. Of course, if the plate B is placed at "symmetrical" emplacement of the plate C, the positive daily imbalance of plate B is then opposite of C plate imbalance, averaging these two plates will recover the accurate measurements. This is one of the reasons to have numerus plates installed. However, a common behavior would push us to do not install plates under a shadowed surface. Furthermore, this case is valid for a coldest soil location due to a higher soil water content (Cabidoche and Voltz, 2005), especially in a clayey soil. Indeed, if the soil surface is not perfectly flat or cracked, after a consequent rainfall and possible runoff (Novák et al., 2000) the rainfall water will naturally concentrate in all surface hollows and cracks.

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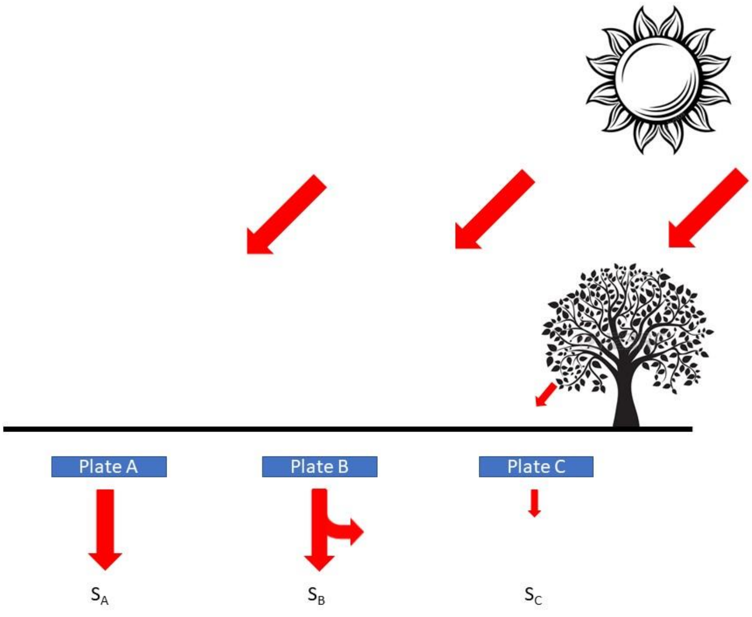
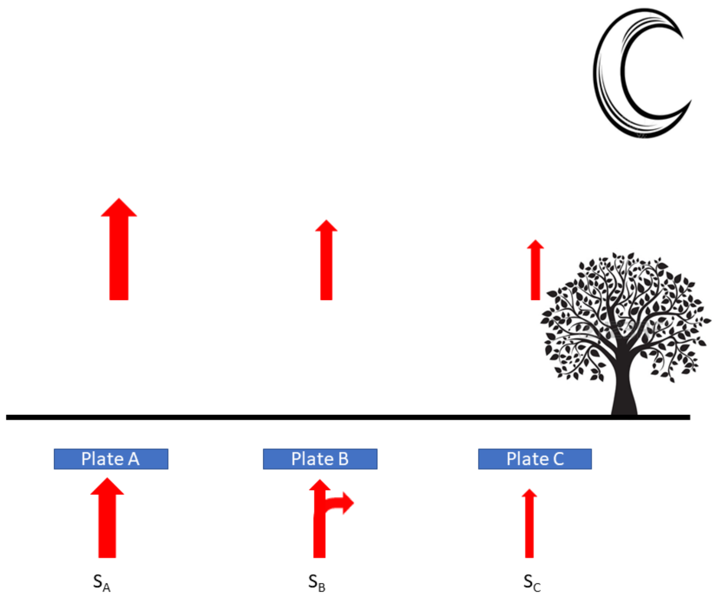


b)



c)

Figure 03) a) Daylight resulting heat flow on a sunny surface A with resulting Heat storage S_A, sunny surface B (Storage S_B) with close shadowed surface C (Storage S_C). b) Nighttime heat flow resulting from heat storages emptying.

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These hollows or cracks will become colder than the rest of the soil and a natural underground heat transfer will attempt to equalize soil temperatures creating corresponding SHFP measurements imbalances. A non-uniform evaporation (different texture or cracks) creates also non-uniform soil temperatures. A non-uniform soil heat capacity (non-uniform density) is causing also in-depth heat exchanges. During the day, soil heat fluxes tend to rise (vertical fluxes) and to equalizes soil temperatures (non-vertical fluxes) when during the night, the soil cooling is mainly resulting from a radiative exchange following Stefan-Boltzmann law:

$$M = \sigma \in T^4 \tag{3}$$

With M being radiant emittance (emitted energy per unit time per unit area), σ being a constant, $\in$ being the soil emissivity and T being the soil temperature.

Contrarily to the heat exchanges due to temperature differences this law is highly non-linear, then nighttime exchanges will not recreate day time soil temperature inhomogeneities and resulting non-vertical soil heat fluxes do not compensate the day time non-vertical soil heat fluxes. For this reason, for better representativity, SHFP shouldn't be placed in a vicinity of a pit dug for soil water content probes or any other recent pit with an altered soil density neither in a vicinity of an abnormally compacted soil (enclosures). In general, any soil temperature difference will give rise to below surface non-vertical heat exchanges creating surface heat fluxes imbalances. On can expect to overcome imbalances due to surface soil inhomogeneities using numerus flux plates judiciously placed. If we are assuming that the observed unbalance is mainly due to a beneath flux plate evaporation, a minimization of the corresponding systemic error (double counting) may be attempted by the yearly based soil heat balance closure with a deduced statistical correction.

Considering only a field deployed SHFP first we can integrate their measurements over a year in order to decide which plate is representative and which plate is not (Fig. 04). Discard data from obviously biased plates (G42 and G51 in this example) and form the average measurement with remaining data. Correcting with an adequate G_{TH}^{L}, by integration, we can estimate the soil surface heat exchange imbalance. We have to note that this year the soil December temperatures were slightly cooler than the soil January temperatures. Difference ranging from 2.5 degree to 1 degree depending of the depth (2.5 degree cooler at the surface and 1 degree cooler at 100 cm depth). The calculated heat flux imbalance does not correspond then to the soil temperature variation and would be even bigger if the soil temperatures were the same at the beginning and at the end of that year. The fact that there is a large soil heat imbalance in all the measured locations, is suggesting that this imbalance is not resulting from soil inhomogeneities.

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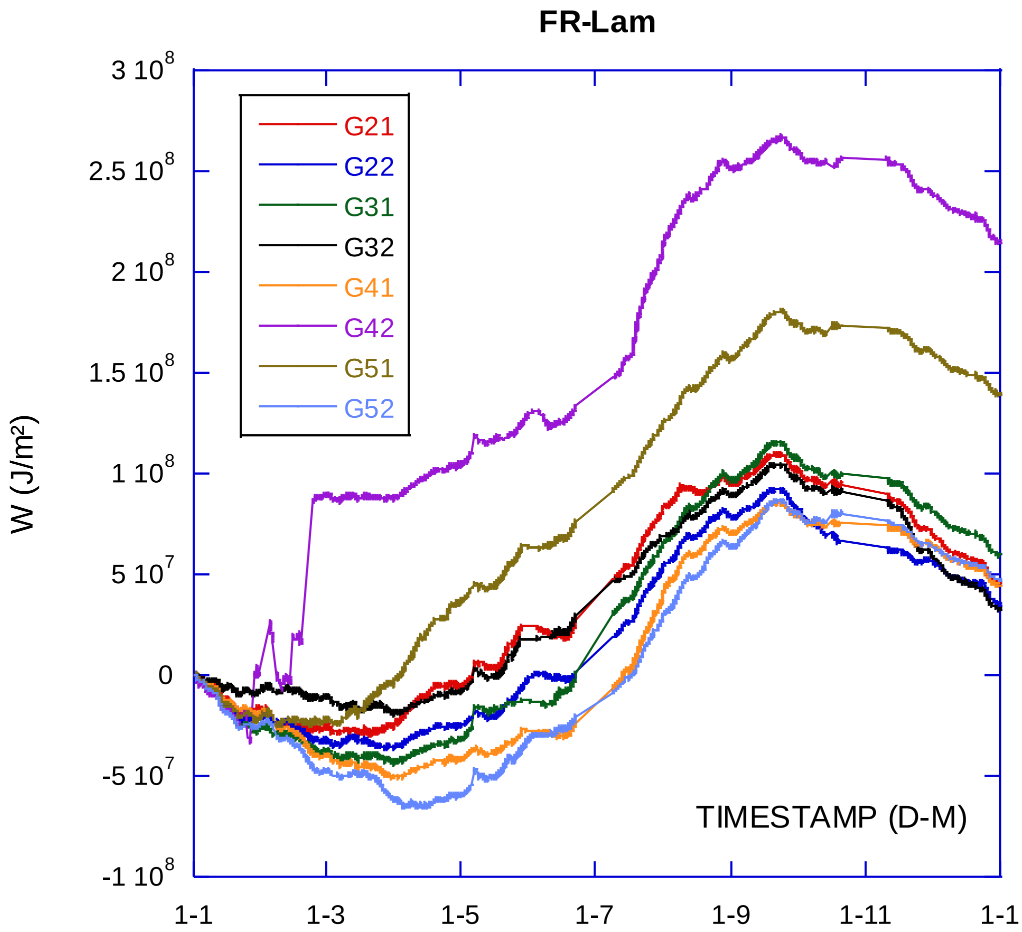

195 **Figure 04) Integrated raw measurements of eight heat flux plates installed on FR-Lam on an agricultural plot (cropland).**

3.2.3 Evapotranspiration, positive imbalances sources.

A question remains open: except a latent heat conversion below the SHFP is there another possibility to cause the soil heat flux imbalances? For example, the water absorbed by the roots is routed to the leaves and evaporated chiefly during a daytime. This water migration, is similar to a convection and is not sensed by any heat flux sensor. Moreover, the deep roots absorbed
200 water has lower temperature than the soil surface temperature. In order to equalize its temperature with the surrounding soil a

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heat transfer take place lowering the soil temperature then lowering soil the heat storage and accentuating the heat transfer from the soil surface. Figure 05 depicts the water absorbed by the wheat roots, flowing through the vegetable body and evaporating by the leaves.

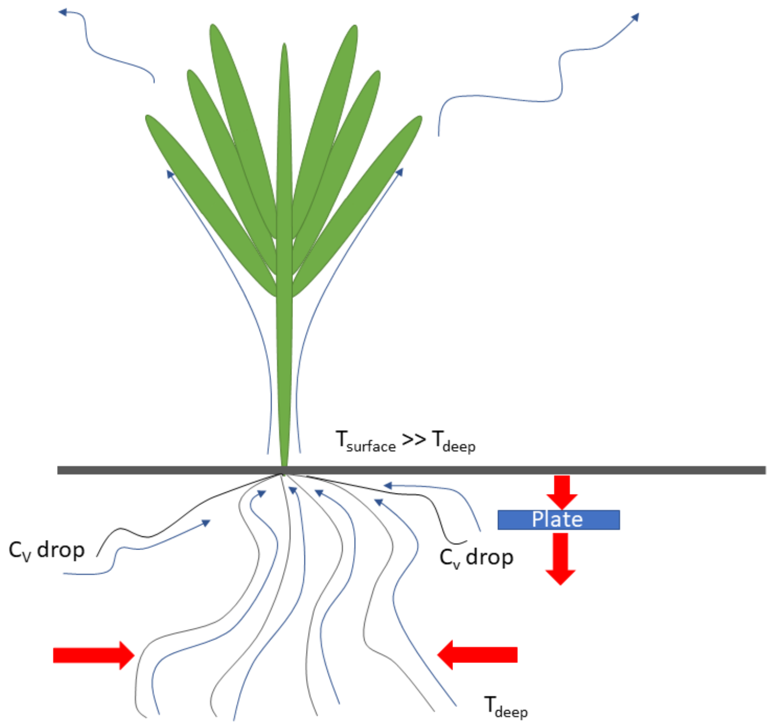

Figure 05) Root absorbed water is flowing up from the deep soil at low temperature to the hot sun heated soil surface provoking a heat transfer between the soil and the roots. Shallow roots absorbing water drying soil lowering its heat capacity *C_V*. Water is storing then energy evacuated from the soil.

Even if the root absorbed water coming from the shallow soil layer, as water is an important part of the soil heat storage due to its high heat capacity, the daytime dried soil's heat capacity drops and, by nighttime, the soil is not able to counterbalance the daytime heat flux as the storage is not only a question of temperature but also a question of heat capacity. The water absorbed by the root, with corresponding stored energy, is not sensed by SHFP and there will be a resulting positive unbalance as the water stored energy is no more disponible for nighttime opposite transfer. In general, any mass flow from beneath the SHFP, gaseous, liquid or solid, will give rise to an energy evacuation and then heat flux imbalance. Considering the winter wheat daily water usage, the soil water table (assumed as only one source of the root absorbed water as winter wheat roots may reach over two meters depth (Thorup-Kristensen et al., 2009)) and the temperature difference with SHFP level soil temperature, a very rough estimation of the energy withdrawn from the soil bellow SHFP, gives an imbalance of about 20 MJ/m² a year for winter wheat (the culture of the considered year). The assessed imbalance source is then comparable to the

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geothermal correction (see Sect. 2.2.5) with an opposite sign, and cannot explain alone the observed imbalance on Fig. 04 (50 MJ/m²). However, this estimation is certainly underestimated as the transpiration take place mainly during daytime when the temperature gradient between the soil surface and the deep soil is much more important than during the night. Then, the daytime deep soil water evacuation withdrawn more energy than during the night and the daily average of the transpiration is underestimating that energy. Also, during the bare soil period the surface evaporation is forcing the soil water to migrate from the deep layers to the dried shallow layers. This migration is not sensed either by SHFP and adds a positive imbalance again rather for a long-term imbalance. The corresponding correction is noted G_{ET}^{L}. Note that only the beneath SHFP cause *double counting* problem.

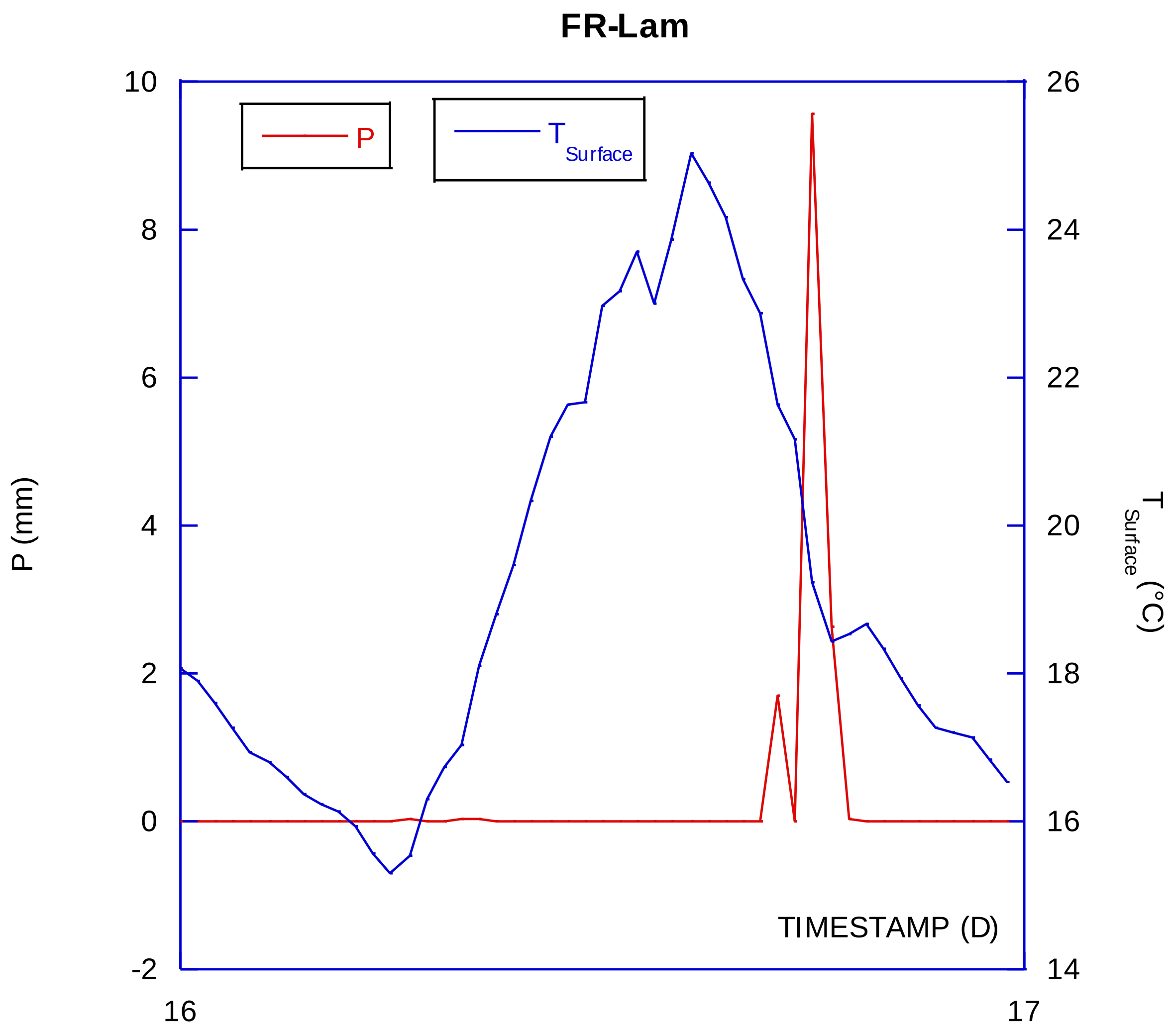

Figure 06) Rainfall soil surface temperature cooling.

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230 **3.2.4 Rainfall or irrigation a negative and positive imbalance source.**

The rainfall or irrigation P (in mm of water) is causing the soil surface cooling and provokes a negative soil heat flux (Fig. 06). This does not affect the SHFP balance (not at this stage, see further text) but the corresponding energy H_p needs to be included in the SEB equation (see equation 6) as it is an external frigories apport proportional to rainfall intensity $P_I = \frac{\delta P}{\delta t}$, to the water heat capacity C_w and to the difference between falling water temperature T_w with the soil surface temperature T_s:

235 $H_p = P_I * C_w * (T_w - T_s)$ (4)

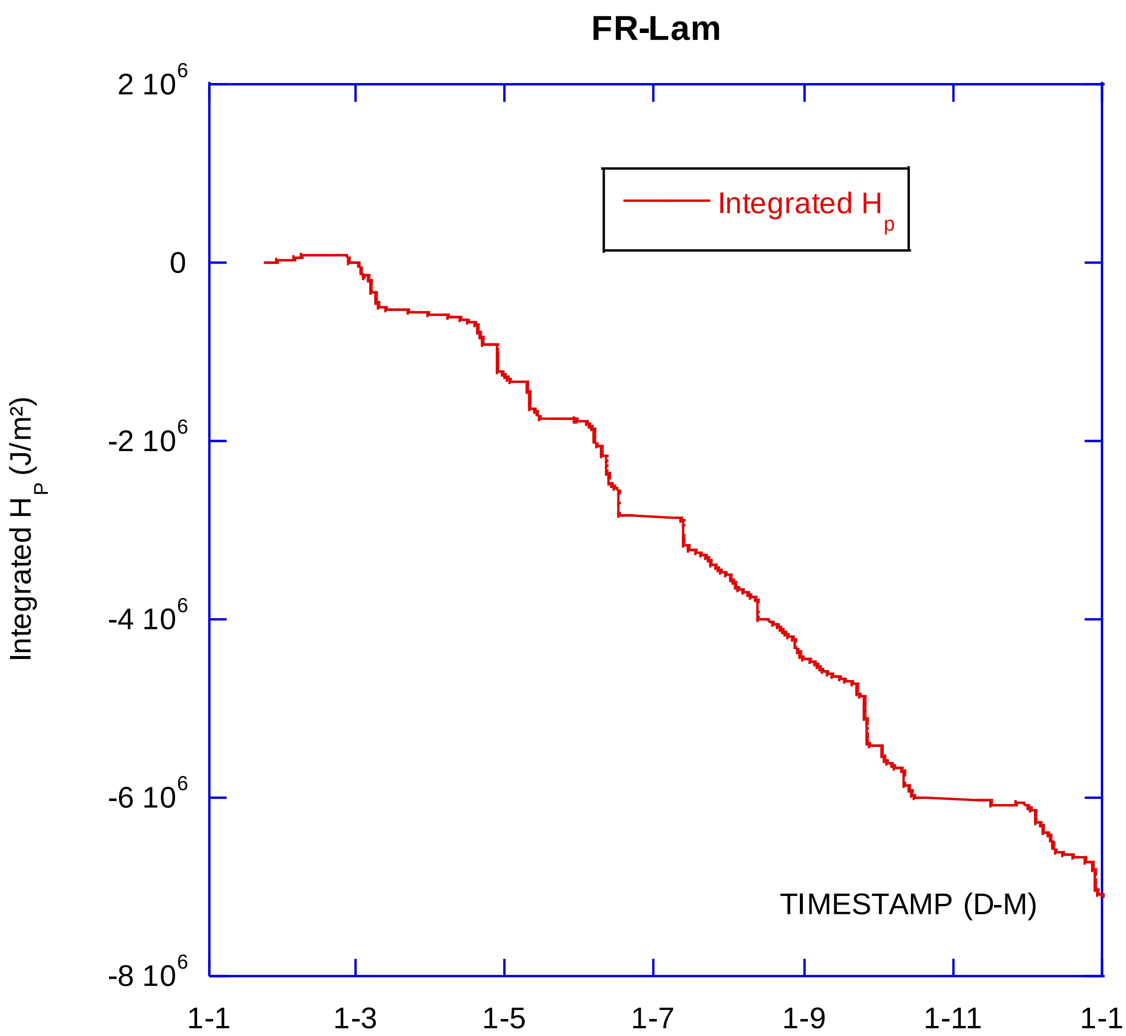

Figure 07) Integrated rainfall cooling H_P.

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Unfortunately, we do not have any instrument installed on FR-Lam that can provide us with a rain water temperature. As a rough approximation the air temperature is used assuming that the falling water has the same temperature as the ambient air (this assumption is absolutely not valid for irrigations and overestimate water temperature for natural precipitations). After one year precipitation we obtain -7 MJ/m² (Fig. 07) which is not negligeable on the annual scale. On the short scale, the rainfall soil cooling is very important and the corresponding SEB is greatly affected (considering data shown in the Fig. 06, cumulated rain cooling energy is $E_P =$ -289 kJ/m² and SHFP measurements shows that when it would be about -10 W/m² of heat flux without the rain, it was -70 W/m² with the rain).
When the rainfall water is on the soil surface the SHFP measurements are not yet not imbalanced. Afterwards the rainfall water is penetrating the soil and, similarly to the evapotranspiration, SHFP is not sensing this migration but an important heat transfer by convection may take place (Kollet et al., 2009). This time the imbalance would be negative if the infiltrating water was hotter than the deep soil bringing some calories. This happens when the soil surface temperature is higher than the SHFP level soil temperature (5cm on FR-Lam). This is not always the case especially by nighttime and event by daytime during colds seasons.

The resulting heat flow G_P^S would be similar to H_p but with the difference of the soil surface temperature T_S and the SHFP level soil temperature T_5.

$$G_P^S = P_I * C_w * (T_S - T_5) \tag{5}$$

Figure 08 depicts the cumulated G_P^S . We can note that after one year the results are almost nil, under 0.022 MJ/m². Then, we cannot assume the rainfall water convection counterbalancing the evapotranspiration water convection for SHFP measurements on a long-term scale. With nighttime irrigation, results would be positive and with daytime irrigation, results would be negative but if the irrigation is limited then the overall additive would be limited too however, à short-term correction may be necessary.
All these considerations may deserve more investigation work.

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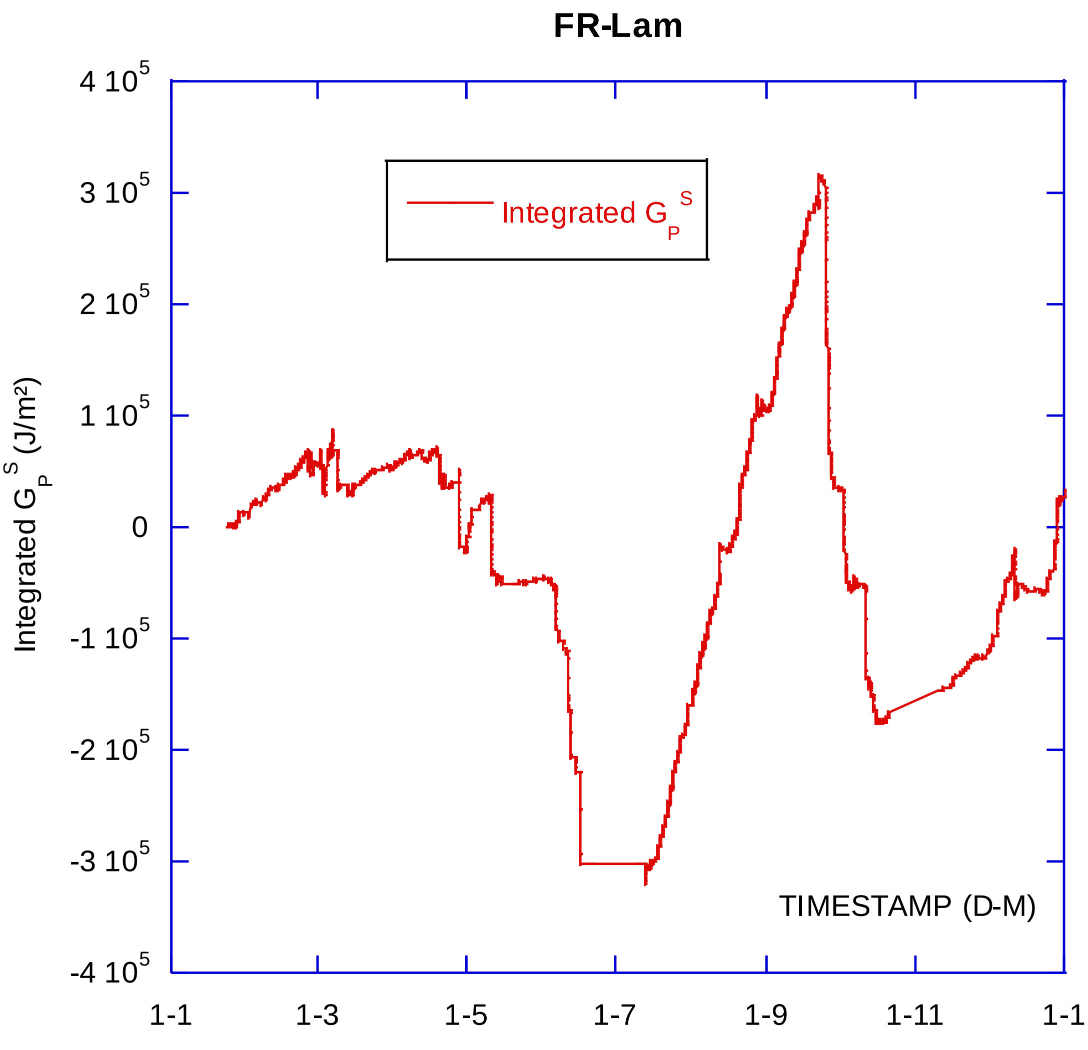

Figure 08) Integrated factor of precipitation with soil surface temperature difference with soil 5cm depth temperature.

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270 **2.2.5 Geothermal heat flux.**

Concerning the geothermal heat flux, even if G_{TH}^{L} is relatively small in respect of the solar maximum radiation and the nocturnal soil maximal heat efflux, this heat flux is always upgoing. Consequently, when totalizing energy fluxes, as a solar radiation heating is counterbalanced by a nocturnal soil radiation, the diurnal and especially the annual imbalance due to the geothermal heating flux may be important (Fig. 09). Consequently, a geothermal correction is rather for a long-term integration.

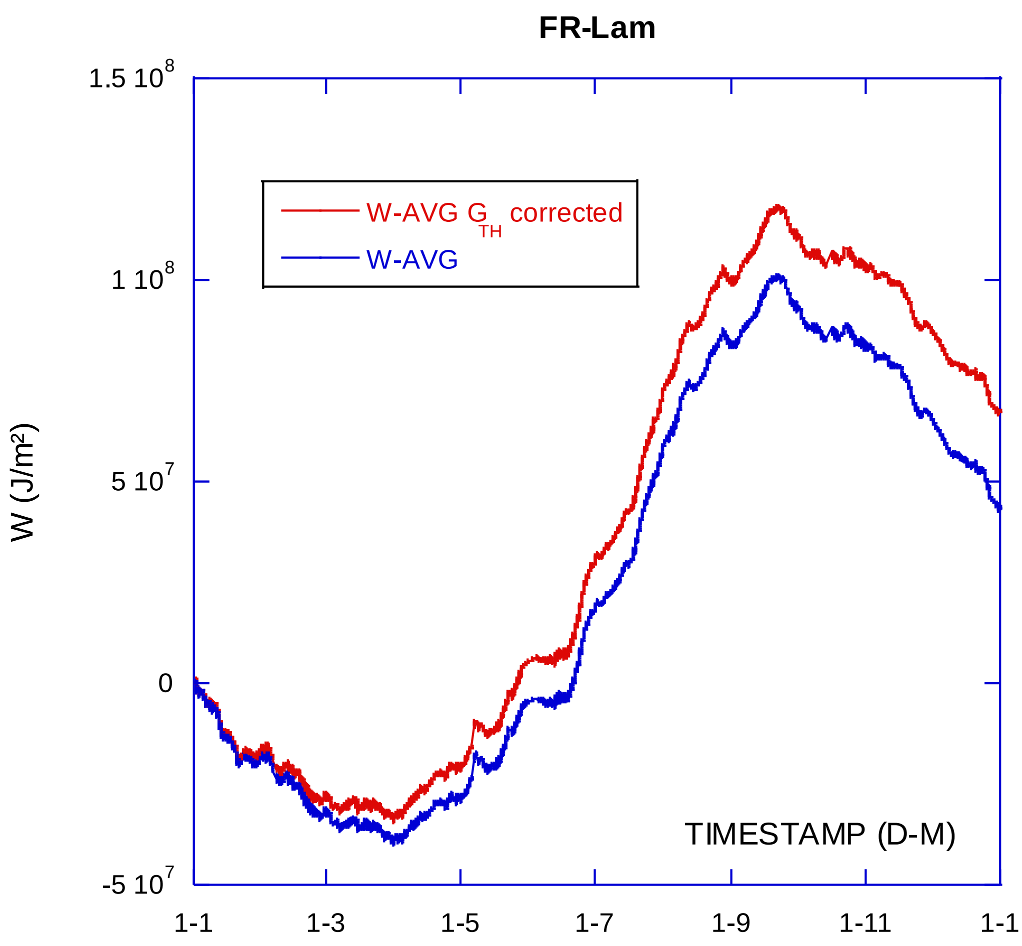

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Figure 09) Integrated averaged, among the plates, measured soil heat flux: W-AVG and the same integrated flux with geothermal efflux subtracted: W-AVG G_{TH} Corrected.

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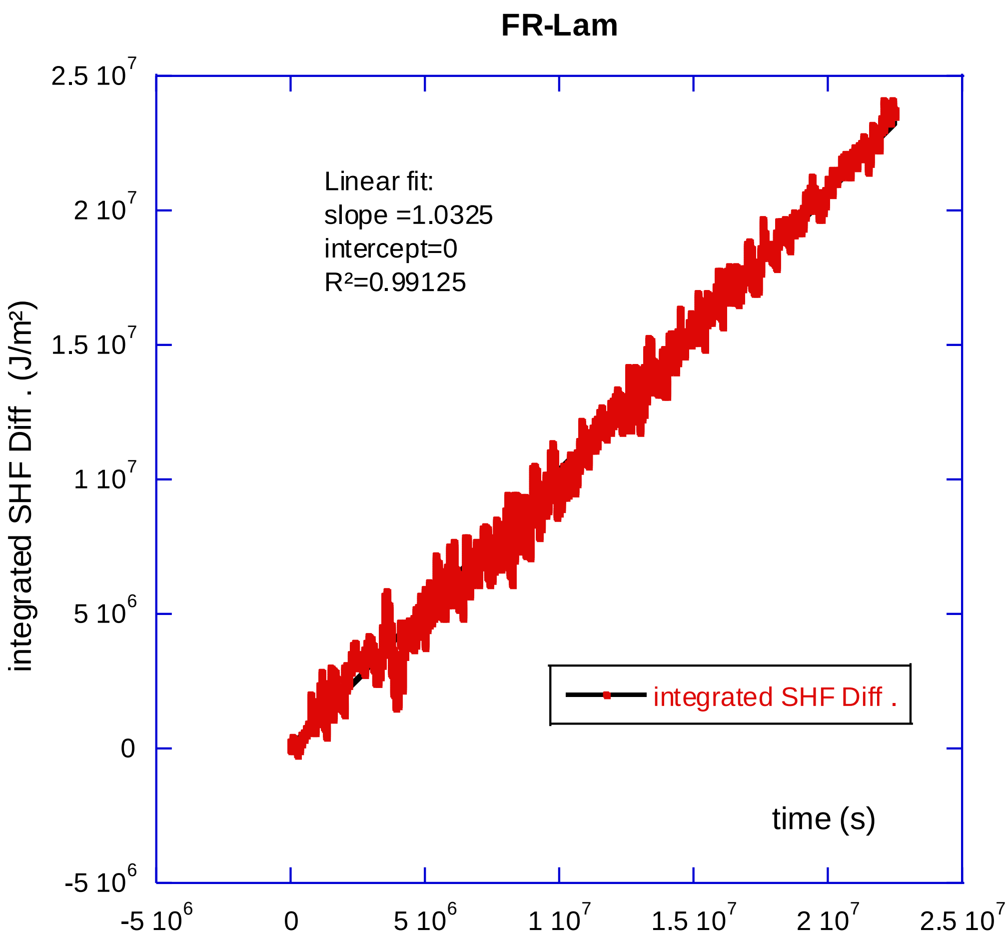
2.2.6 Soil gas exchanges.

280 The soil is exchanging also the gazes, mainly CO_2 coming from the soil and absorbing O_2. Due to their characteristic heat capacity difference, we may expect an energy exchange. This is the case but the total amount remains negligible (yearly about 100 J/m² for winter wheat culture).



285 **Figure 10) Integrated SHF Diff. along with a linear regression.**

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2.2.7 Calibration data.

There is also a well-known, but deserving to be signaled again, the precaution that should be taken when working with the self-calibrated flux plates. Because during the calibrations an artificial heat flow is generated, during and one hour, or even more, after the calibration the initialization data have to be discarded. Not only the generated heat is sensed but also the surrounding soil is heated and needs time to cool down. If corresponding data are not discarded an overestimation of the heat flux is observed. It is less known that for the committed error, when not discarding calibration period data, a rough correction remains possible. Figure 6 shows the integrated difference (SHF Diff.) between measurements with all data including calibration periods and measurements where, during and one hour after calibration, the data are discarded.

SHF Diff = (Half hurly averaged measurements with all data available) – (half hurly averaged measurements with discarded data during and one hour after calibration).

(5)

As we can see, this difference integrated over a time is following a straight line which means the average heat fluxes measurements, with calibration data, can be corrected with a simple additive: -1.0325 W/m² in our case, with a rather good accuracy ($R^2 > 0.99$). It is consistent with the calibration process as the total applied heating is 1.4 W during 4 minutes every 7 Hours then averaging this heating power along with SHFP diameter (80 mm) gives an average of 2.65 W/m².

Conclusion. Self-calibrated SHFP are probably the most used sensors for *G* measurements. This technique is reliable however, important errors which are not always taken into account may bias the results. Some of the errors are avoidable, others result from physical phenomenon and may still be present even if all the precautions are undertaken. It is important to carefully chose the installation place and check the possible imbalance by a yearly integration. The annual integration allows to check quickly each SHFP, individually, and to select representative plates. This way, is very easy to compute and allows an immediate sight check contrarily to the non-integrated soil heat fluxes results. In case of a systematic relative imbalance, a statistical correction may be attempted. However, beneath SHFP water evaporation and others phenomenon such as the evapotranspiration or the rainfall may contribute to the sensed heat imbalance.

Concerning the SEB equation (Eq. 1), since SHFP are sensing only the conduction heat flow, *G* term should also include corrections for a short- or long-term measurements such as G_{ET}^{L} or G_{P}^{S} and the geotherm heat flux G_{TH}^{L} or rainfall cooling term H_P which should be added as these energy fluxes are not negligible when totalizing energy variations and do not originate from a solar radiation but may be sensed by flux plates or others heat flux sensors. Assuming the beneath plate evaporation negligible, SEB equation become:

$$R_n - (G + G_{TH}^{L} - G_{ET}^{L} - G_{P}^{S} + S_C + S_P) - H_P = H + L_e \tag{6}$$

Here, as mentioned previously, by simplification, G contain the below SHFP heat storage. Note that all the corrections on G are not solving SEB closure problems when using eddy covariance technique for $H + L_e$ measurement as these corrections rather lowering sensed G or $H + L_e$ are usually already too small for SEB closure (over 30% disclosure on FR-Lam (Dare-Idowu et Al., 2021)) suggesting that the eddy covariance technique sensibly underestimate H and L_e measurements. The H_P term is not helping either for SEB closure as it represents a soil surface cooling then a negative term. The vegetation heat storage and photosynthetic activity may be added to complete this equation.
For a better energy transfer monitoring, I'll suggest to measure not only the water table depth but also the soil water table temperature and the rainfall water temperature for further calculation.

Competing interests. The author declares that he has no conflict of interest.

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