Dear Editor,

dear anonymous referees,

We would like to thank you very much for publishing our manuscript in NHESS Discussions and for your thorough review and detailed comments. All of these comments have been addressed in the final response and we found that they greatly helped in further improving our manuscript. Amongst others, a new table and figure have been added as well as several figures and sections of the text adapted. Please find our detailed responses (in italics) to all of your comments as well as the revised manuscript below.

Best regards,

Christian Schunk

and co-authors

Anonymous Referee #1

3737, 12. Please, specify what EMC are, how they can be useful and give references.

A short section to this effect has been added.

3739, 1. What I know are sensors to measure soil water content that are based on the apparent dielectric constant and the ionic conductivity of the soil (or, more in general, any porous media). Please, check what term is more correct/appropriate between 'permittivity' and 'conductivity'.

We have checked the respective terms and found 'relative permittivity' to be more suitable (the historical term used to be 'dielectric constant', but this is no longer supported by standards organizations). Water has a very high relative permittivity ε of about 80, whereas dry materials (litter, soil) exhibit values between 4 and 8. This is the reason for the good applicability of permittivity measurements for water content determination in materials and therefore, permittivity is the term used for the measurements with FD and TDR techniques. The terms dielectric and dielectric number have been removed and replaced by relative permittivity ε following a comment by Referee #2 and as they are out of date (cf. above). Conductivity is the appropriate term for electrical current measurements with unisolated electrodes (cf. electrical resistance sensing device).

3739, 1-8. Explain better how these sensors works. Explain what the permittivity (conductivity?) is and is used for.

The whole paragraph has been re-written and both the physical background as well as its consequences for the measuring technique are now better explained.

3739, 1-18. Recently, new moisture sensors based on the TDT (Time Domain Transmission) technology have been introduced in the market. I understand that these were not tested in the present study but at least they should be mentioned here since the technology is very similar to TRD and FDR and is considerably cheap. Reference on the technology: J.M. Blonquist Jr., S.B. Jones, D.A. Robinson, 2005. A time domain transmission sensor with TDR performance characteristics. Journal of Hydrology 314 (2005) 235–245

A short section on the existence of this novel technique has been added.

3741, 7-11. This paragraph should be remove from here since it’s not an objective but more a result. Moreover, I suggest to include a couple of specific objectives (that should be picked up the Results section) in order to make the aim of the paper immediately clear.

The paragraph mentioned has been replaced by more specific objectives in line with the findings in Results, Discussion and Conclusions.

3742, 10. Here the authors have to include a new Fig.1 showing the experimental site, the 30-m transect and the area where measurements were collected through each sensor.

Done.

3743, 1. The instrumental precision for each sensor tested is missing and should be reported. Moreover, a discussion, even if short, about how the instrumental precision affects/can affect the total measurement uncertainty-and so the reliability of the results should be added.

A short note regarding the instrumental precision has been added for each sensor, as well as an assessment of instrumental precision vs. other factors. It has to be pointed out, however, that instrumental precision is usually given only for soils and not for the instrument itself. In general, problems due to the installation and contact to the highly porous, low density and variable litter layer can be expected to have a much greater influence than any instrumental precision.

3743, 10. Again, check if 'permittivity sensing' is the correct definition.

'sensing' has been removed; otherwise, permittivity has been kept according to the comment above.

3744, 13. I suggest to include a new table (and a short description in the text) reporting basic statistics (total number of measurement, mean, SD) of all gravimetric measurements as well as measurements from each of the tested instruments for i) the total period; ii) for the dry period 1; iii) for the dry period 2; iii) and for the dry period 3. Please, state also in the header the DOYs of each period.

The new table has been added and the text changed to refer to it.

3745, 3-ff. I understand that rescaling allows raw data of the various sensors to be compared. However, this is an asset but it's probably not strictly necessary in order to compare the gravimetric and the sensor-based data. I think that the authors should be better explain the need for such an operation. Moreover, I wonder how and if the rescaling process affects the results, and I suggest the authors to provide some data on this.

The rescaling greatly helps to visualize and compare the data from the different sensors, as these may have been placed in areas with different litter properties (e.g. more or less bulk density) and therefore may have produced radically different raw signals. This has been explained in more detail in the manuscript and it has also been added that due to correlations and linear regressions being invariant to linear transformations, we can exclude any interference of this process with our results.

3746, 12. The title of section 3.2 is not convincing. I suggest to change it. A possible solutions are 'Litter water content variability' but similar ones are acceptable.

Changed to 'Sensor data and correlation to gravimetric fuel moisture'.

3747, 17-ff. I suggest not to talk about ‘calibration’ but simply about ‘relationship between gravimetric and automatic measurements’ or some similar definition. ‘Calibration’ is misleading for the reader because it implies that all relationship are robust and can actually be used to convert raw data into moisture content data. However, this is not perfectly the case.

‘Calibration’ has been changed to ‘relationship between gravimetric and automatic measurements’ or to ‘regression’ throughout the manuscript, wherever appropriate.

3748, 9-ff. The Discussion section should be expanded, especially around three main points: i) inclusion of a mention of instrumental precision on the fitness of the sensor estimates; ii) potential and limitations of these methods according to the obtained results; iii) short mention about how the dry period values compare with data found in the literature that were considered critical for wild fire starting. The last parts is important because it gives a closer connection with the main topics addressed in this journal.

The Discussion (and Conclusions) sections have been revised with these points in mind. The potentials and limitations, as well as the relevance of those limitations for forest fire applications are now clearer.

3748, 20. This sounds speculative. Please, make clearer hypotheses, explaining the reasons, on the observed variability of gravimetric measurements. Otherwise, say that reasons are unknown.

The statement was extended and clarified, as is comes from very clear observations during sampling.

3748, 20. ‘…suboptimal transformation’. Again, this is a bit speculative. Moreover, why the electric resistance technique should be affected by not optimal transformation of raw values and not the other sensors, that were subject to the same process?

It has been clarified that exclusively for the electric resistance sensors, inversion and log-transformation of the signal was necessary before rescaling and that there may be more advanced/appropriate conversions. This had already been mentioned in Sections 1.2.3 and 2.6.

3750, 9-ff. Why the increased bulk density should not have influenced the groups a, c, d as well? Please, explain.

It most certainly also had an effect on sensor groups a and d, as they use the same measuring principle. However, the data available from those sensor groups was too limited to analyze this (only one group a sensor and group d sensors being removed before the start of dry period 2). A note explaining this has been added. As the electrical resistance (group c) measurement is not directly related to bulk density (rather to resistance/contact of the electrode to the measured material), this is most probably not the case for group c. A statement regarding this has also been added.

Minor comments and technical corrections 3739, 2. Why 'dielectric' is in parenthesis? Moreover, I think that the correct definition is 'dielectric constant', and not 'dielectric number'. Please, correct. Also at lines 5, 12, and at 3740, 4.

Dielectric has been removed and 'dielectric number' changed to 'relative permittivity', as this is the new standard term for this measure (cf. comment by Referee #2). Other occurrences have also been changed.

3739, 2. The most used and accepted definition is 'FDR (Frequency Domain reflectometry)'. I suggest to change it this way here and anywhere in the manuscript.

It is our understanding that in the FD method, the sensor acts as a capacitor in an electrical oscillating circuit. The frequency of this oscillator is depending on the relative permittivity ε, which in turn is depending on the water content. Thus, the permittivity is measured directly without any reflection or travel-time analysis and we therefore do not believe that the term FDR / Frequency Domain reflectometry is adequate. Therefore, the terms FD-sensors, method, etc., have been kept as is. In *contrast, short electrical pulses are reflected at the tips of TDR sensor rods and a travel-time analysis of these reflections is carried out in the TDR method.*

3739, 24. Add that mw, md have the same meaning than in Eq. 1.

Done, also for u_G.

3740, 3. '…discussed later in this paper.' Give a reference to the appropriate paper Section.

Done.

3740, 3. Add 'to' before 'compare'.

Done.

3742, 4. I don't like the definition 'standard parameters' and suggest to change the sentence here (and in the rest of the manuscript) into 'meteorological data (so, skip also 'observations).

Done.

3742, 10. 'Well within' is rather vague. Please, give more precise information (and refer to the new Fig. 1)

This sentence has been changed to indicate that the transect was more than 25 m from the edge of the stand. Fig. 1 has also been referred to.

3742, 12. I suggest to replace 'coincidental' with 'concurrent' or 'at the same time'. I think that the author mean that, whereas 'coincidental' means something else. Please, also change it at 3748, 21

Changed to 'at the same time each day' and 'concurrent', respectively.

3743, 6. After '…similar conditions' add 'than the transect'.

Done.

3744, 22. Dead batteries? Are there no solar panels for most of the sensors? Please, specify which sensors are battery-operated and solar panel-operated.

In fact, all sensors/data loggers for this initial study were battery-powered, although there is of course solar power available for the more permanent installations. Remarks about battery operation were included for all sensor types.

3745, 1-2. 'daily sum of precipitation' should be changed into 'daily cumulative precipitation'. The same holds for 3746, 3.

Done for both occurrences.

3745, 21. 'weather' should be replace by 'meteo data'. Moreover, the sentence is not very clear: please, rephrase.

The beginning of the sentence has been rephrased and 'weather' changed to 'meteo data'.

3746, 17. 'Logistic relationship'. Yes, but it could be also defined a non-linear relation with a sort of threshold around 100% UG and saturation above 300 sensor value. I suggest to change the term 'logistic' into the more general 'non-linear'.

Non-linear has been used for the relationship, with 'almost logistic' remaining as one possible example. Also, a later occurrence of 'logistic' has been changed to 'non-linear'.

3748, 16. It's not the technique itself that produces variability (I suggest to use this term instead of 'variation') but it's the data themselves. I suggest to change into 'data are characterized by high variability…'.

The sentence has been rephrased accordingly.

3748, 16. Why 'relative'?

As the measuring unit of gravimetric fuel moisture is already %, relative was added to point out that the standard deviation reported here is not in an absolute (% fuel moisture) but rather a relative (% standard deviation of the mean fuel moisture on the day with the highest variability) value. We suggest to keep the term 'relative' to avoid confusion.

3748, 24. Add '(group c)' after 'electric resistance technique'.

Done.

3750, 16. 'relatively poor weather conditions'… this is a bit vague and controversial (it can be very good weather for hydrologists…). Please, specify.

Changed to 'Despite relatively wet weather conditions and generally low fire danger…'

3750, 20. Check my comment above about 'calibration'.

Changed to regression.

Tables and Figures

3755, Table 1, caption. Replace 'calibrations' with 'relationships'.

Done.

3756, Fig. 1. I'm not sure I understood how the daily moisture mean was calculated (I found no explanation neither in the text nor in the caption). Why don't the author simply connect the point with a line? Moreover, change 'parameters' into 'data' and perhaps 'test' into 'study'. In the legend of the bottom panel, change 'precipitation' into 'daily cumulative precipitation' or 'daily precipitation'. Most of all, add three new horizontal panels displaying the three relationships reported in Fig. 4 (see comment below).

'Precipitation' has been turned into 'daily cumulative precipitation' and 'daily precipitation' in the axis label and legend, respectively. The three new horizontal panels formerly in Fig. 4 have been added to this figure. As each of them is displaying the (mean) litter moisture, the former top panel showing this curve as well as the individual measurements has been left out. This also avoids the issue with the daily moisture mean, which is a simple mean that is calculated from the three concurrent samples taken every day (cf. Sect. 2.3). To point out the three dry periods (essentially defined by the standard deviation of the sensor groups) more clearly, shaded areas were added to all of the panels.

In the caption, 'parameters' has been changed to 'data' and 'test' to 'study'. Explanations for the three new panels were added as well.

3757, Figure 2. Add '-' between the parentheses '[]' to indicate the lack of measurement unit. Replace 'cor' with 'r' (rho), and of course mention this symbol for the Speaman rank correlation also in the text. Explain in the caption what the asterisks mean. Please, also consider to add a linear interpolation to panels a, b, d.

'-' have been added, 'ρ' used instead of 'cor' and the caption changed according to the reviewer's requests. As there is a rather obvious non-linear relationship in panel c and we therefore selected using Spearman's rank correlation coefficient, we have not added linear regression lines to this plot, however, as they are based on a different method altogether.

3758, Figure 3. Replace ‘by’ with ‘as a function of’. Less than three observations means necessarily two (one cannot compute a mean and SD of one value!). Please, explain better. I suggest to change ‘correlated linearly’ into ‘more correlated’.

‘By’ was replaced with ‘as a function of’. Furthermore, ‘less than three observations’ was changed to ‘two observations only’ and ‘correlated linearly’ was changed to ‘more correlated’. We hope the meaning of the caption is now clearer. ‘[-]’ has also been used as a symbol for lack of measurement unit (as in Fig. 2).

3759, Figure 4. I suggest to skip this Figure (the panels are too narrow and are difficult to read) and to incorporate it in Fig. 1 (that will become Fig. 2 after adding the new Fig. 1, with the study area).

The figure has been incorporated into the new Fig. 2 as suggested (cf. comment above).

3760, Figure 5. Use colours that differentiate more. Add ‘-‘ between the parentheses ‘[]’ to indicate the lack of measurement unit. Replace ‘calibrations’ with ‘relationships’.

Skipping the confidence interval would make the subplots clearer.

The colours have been changed, different symbols used for the three periods and ‘-’ added. However, we decided to keep the confidence intervals as they are helpful to assess whether there are significant differences between the regression lines and as this is mentioned in the text. In the caption, ‘calibrations’ has been replaced by ‘regressions’.

Anonymous Referee #2

Line 4 pag 3734 : The comprehensive review didn’t find a paper specifically designing a new TDR probe for forest litter moisture content. It is: Canone et al.(2009) A new coaxial Time Domain Reflectometry probe for water content measurement in forest floor litter. Vadose Zone Journal.

Unfortunately, we were not aware of both the sensor and publication at the time of the study. The reference has been included and a section on this sensor has been added to the Introduction.

Line 5 pag 3739 : “Dielectric number” is better replaced by permittivity.

Done for all occurrences (cf. comment of Referee #1).

Line 15 pag 3739 : The fact that “FD is more sensitive than TDR to small water content variations” has to be supported with references.

Unfortunately, we were not able to retrieve the reference supporting this statement anymore and thus have replaced it by ‘FD sensors employ a simpler and more direct measuring method’, which is supported by Lin (2003).

Line 13 pag 3740 : What shape and length had the TDR probe?

The model and manufacturer, as well as shape and dimensions of the TDR probe (CS-615 two-rod sensors with a length of 30 cm and a separation of 3.2 cm by Campbell Scientific, Inc.) were retrieved from the literature and added to the text.

Line 28 pag 3740 : Some description is necessary about the “duff moisture meter” (Robichaud and Bilskie, 2004).

A short description of the ‘duff moisture meter’ and its operation has been added; more details are available from the reference.

In fig.4 the timescale is too much compressed to be able to compare points and lines.

According to comments from Referee #1, this figure has been combined with the original Fig. 1 (now Fig. 2) and the layout of the individual panels has been changed from portrait to landscape. It is now much easier to read.

In the Conclusions it should be stressed the worst behavior of the resistance sensor, if compared to the three others (see figure 2).

Along with other changes suggested by Referee #1, the low performance of the resistance sensors has been stressed more clearly in the Discussion and in Conclusions.

Comparison of different methods for the in-situ measurement of forest litter moisture content

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Abstract

Dead fine fuel (e.g. litter) moisture content is an important parameter for both forest fire and ecological applications as it is related to ignitability, fire behavior as well as soil respiration. However, the comprehensive literature review in this paper shows that there is no easy-to-use method for automated measurements available. This study investigates the applicability of four different sensor types (permittivity and electrical resistance measuring principles) for this measurement. Comparisons were made to manual gravimetric reference measurements carried out almost daily for one fire season and overall agreement was good (highly significant correlations with 0.792<=r<=0.947). Standard deviations within sensor types were linearly correlated to daily sensor mean values; however, above a certain threshold they became irregular, which may be linked to exceedance of the working ranges. Thus, measurements with irregular standard deviations were considered unusable and ~~calibrations~~ relationships between gravimetric and automatic measurements of all individual sensors were compared

only for useable periods. A large drift in th~~e sensor raw value litter moisture~~ ese relationships became obvious from drought to drought period. This drift may be related to installation effects or settling and decomposition of the litter layer throughout the fire season. Because of the drift and the in-situ calibration necessary, it cannot be recommended to use the methods presented here for monitoring purposes. However, they may be interesting for scientific studies when some manual fuel moisture measurements are made anyway. Additionally, a number of potential methodological improvements are suggested.

1 Introduction

1.1 Background

Dead fine fuel moisture content has been a focus of forest fire research since its start, mainly because it is one of the critical determinants of ignitability and fire behavior (Pyne et al., 1996). A range of applications such as planning of prescribed fires, diurnal fire danger rating, and model validation require knowledge of the in-situ fine fuel moisture dynamics. However, fine fuel moisture dynamics are not easily measured since standard techniques, e.g., destructive sampling and oven-drying, on-site moisture analysis of destructive samples (e.g. Wiltronics ME2000, Campbell Scientific DMM600) or the weighing of fuel moisture sticks, are very cumbersome and labor-intensive. Results of these measurements often become available only after a remarkable delay (e.g. drying time) and are therefore not suitable for real-time decision making, especially as diurnal variations in fine fuel moisture can be of considerable importance.

Measuring fuel moisture content automatically is difficult because of a range of fuel properties: dead fine fuels such as litter layers are often highly heterogeneous and discontinuous with usually only a shallow depth as well as a low density and compactness (Chandler et al., 1983; Ferguson et al., 2002). Additionally, in temperate regions and deciduous stands, strong annual dynamics with a fresh supply of litter every fall followed by weathering and degradation throughout the rest of the year are present. Fuel moisture values can be expected to have a wide range from several 100% gravimetric fuel moisture content during or after rain to few % in dry periods. In this range, values less than 30% are of special importance for forest fire applications as they correspond to a high flammability (Wright, 1967).

1.2 Existing and potential measurement techniques

1.2.1 Gravimetry

Non-automated gravimetric measurement can be considered the standard technique for determining fuel moisture content. In many studies (e.g. Beck and Armitage, 2001; Wotton et al., 2005; Gonçalves et al., 2006; Lopes et al., 2006; Aguado et al., 2007), destructive manual sampling was used. The gravimetric moisture content u_G in % is determined from the sample wet (m_w) and dry (m_d) mass using:

$$u_G = \frac{m_w - m_d}{m_d} \times 100\,. \qquad (1)$$

Fuel drying is usually performed in drying ovens with temperatures ranging between 60 and 105°C and drying times of 24 to 48 h, depending on the study considered. In a recent laboratory study, Matthews (2010) found that drying temperature has a significant effect on the oven-dry mass, thus the fuel moisture content, and recommended 105°C for general use.

Time-series can be created by repeating the destructive sampling process; however, the material sampled will be different at each time point. In case of day-to-day time-series, sampling has to be carried out at the same time every day to correctly account for the diurnal variation. Transport to the laboratory and drying time determine the delay until the moisture values become available. However, since gravimetric measurements offer the most direct and exact inference of fuel moisture, they are regarded as a reference method.

To facilitate measurements based on the identical fine fuel material, some researchers (e.g. Wright, 1967) used trays with fine fuel material which were periodically re-weighed in the field. The dry mass of those samples was determined before or after the field campaign. However, the modification of contact to deeper layers (e.g., duff, soil) as well as loss, degradation or accumulation of material over time can cause errors in this method.

To create a truly automated measuring method, Wittich (2005) placed such a fine fuel tray on top of an automatically recording balance, thus constructing a “mini-lysimeter”. Excess rainwater was allowed to run off freely through a fine-mesh wire netting. In addition to the drawbacks mentioned earlier, the influence of the underlying soil in natural conditions is therefore neglected and wind effects may produce additional errors. The operation of a system with moving parts may also be problematic in the field.

In other studies, the original fuels were replaced by other reference material such as fuel moisture sticks (Gisborne, 1933), which were also weighed periodically. In this case, attention has to be paid to the type of material (e.g. wood species) used and to weathering in order to obtain consistent results (Haines and Frost, 1978; Hardy and Hardy, 2007). The "CS506 10-hour fuel moisture stick" by Campbell Scientific, Inc., which uses time-domain-reflectometry (TDR) to determine the moisture content of a 1.27 (diameter) by 50.8 cm (length) *Pinus ponderosa* (Dougl. ex Laws.) dowel provides an automated version of this method.

1.2.2 Near-fuel relative humidity

Another technique for measuring fuel moisture content is to determine the relative humidity close to or inside (in case of porous fuel beds) fuels and to use specific field calibrations or equilibrium moisture content (EMC) curves determined in the laboratory for conversion. EMC is the moisture of a fuel in steady-state conditions, i.e. when it is subjected to constant climate conditions for an infinite time and there is no net moisture exchange (Pyne et al., 1996). Assuming instant fuel drying, EMC curves may be used for the conversion from near-fuel temperature and relative humidity for very light fuels. ~~For example, t~~The duff hygrometer (Beall, 1928) for example used a rattan strip to measure relative humidity by its elongation; the instrument had a dial that could be calibrated to display fuel moisture content directly. In the building physics context, a similar application was the determination of moisture dynamics in a loose-fill wall insulation layer in Germany (Vogel et al., 2002), where the insulating material consisted of compacted wood chips. Since these particles have a similar moisture behavior as dead fine fuels in the forest, there is some comparability. In this case, the actual measurements were performed by a standard electronic relative humidity sensor buried in the center of the insulation layer. However, moisture contents exceeding fiber saturation (when external water is present) cannot be accounted for with this method. In forest fuels, this limit is at about 50% moisture content (Wright, 1967). Consistent sensor placement (cf. the general fuel properties mentioned above) and calibration are further challenges and led to the dismissal of the historical duff hygrometer (Hardy and Hardy, 2007). Conedera et al. (2012) used a temperature/relative humidity sensor in the "litter sentry" of their "FireLess2" system, which is inferring litter moisture from those parameters. However, the coefficients of determination for this measurement and manually determined volumetric litter moisture samples are very low (0.13-0.25) and high uncertainties in the critical low moisture range have been determined (Conedera et al., 2012).

1.2.3 Electrical resistance

The electrical resistance method is based on increased electrical resistance (R) as a hygroscopic material becomes dryer. It is used mostly for determining construction timber moisture and works in the range of approximately 15-80% moisture content, depending on the instrument used and material measured. Calibration equations exist, but are mostly kept confidential by device manufacturers. One such equation can be found in Keylwerth and Noack (1956):

$$\log_{10}[\log_{10}(R)] = u_R \times a + b. \tag{2}$$

With u_R the moisture content as measured by the resistance method, a and b constants characterizing the calibration equation and $\log_{10}$ the logarithm to base 10. Early fire researchers tried to measure the moisture content and drying behavior of large logs with this technique (Hardy and Hardy, 2007). Schröder (1968) tested rating of fire danger based on the electrical resistance of manually removed bulk litter samples and the Wiltronics T-H fine fuel moisture meter (Chatto and Tolhurst, 1997) is a commercial product for measuring such samples. Borken et al. (2003) used the method to examine litter moisture automatically, measuring the electrical resistance of a 1.59 mm thick 9 cm^2 basswood (*Tilia americana* L.) veneer which was placed within the litter. Apart from the limited measuring range both for very wet and very dry conditions, selection and ageing of the material measured as well as placement in the fuel bed (when trying to obtain in-situ measurements) can be an issue. Because of the measuring principle, errors due to electrical interference or short circuit (at locally high moisture contents) can not be excluded. Reference materials different from the material under analysis (e.g. wood used in Borken et al., 2003) may show a distinctly different moisture behavior than the original fuels.

1.2.4 Permittivity

A variety of non-conductive materials in an electric field, e.g. between electrically charged, isolated sensor electrodes, reduce said field and thus allow further electrical charge to flow onto the electrodes. The quantity of this effect, which especially occurs for water and humid materials, is scaled by the relative permittivity ε, ranging from 3-8 for dry soil (Thomas, 1966) to 80 for water. In the field, the sensor acts as a capacitor in an electrical oscillating circuit. With increasing water content, the permittivity is increased and thus the frequency of the oscillator reduced, providing an excellent measure of the material permittivity and thus the volumetric water content (θ, [cm^3 cm^{-3}]). Due to this way of measurement, the sensors are termed frequency domain (FD) sensors (Robinson and Dean, 1993; Nadler and Lapid, 1996). In contrast to that, short electrical pulses are reflected at the tips of the sensor rods in so-called time-domain-reflectometry (TDR) sensors (Topp et al., 1982; Campbell, 1990). (Dielectric) permittivity sensors for water content determination take advantage of the large difference between the dielectric number of water (80) and that of the corresponding dry material. This method has been widely applied in soil water content determination. In this case, the measured dielectric number starts with that of dry soil (3-8) (Thomas, 1966) and increases non-linearly with water content. It can be transformed into the volumetric soil water content (θ, [cm^3 cm^{-3}]) by utilizing appropriate calibration. There are two main measuring principles, the TDR-method (time-domain-reflectometry) and the FD-method (frequency domain). While in TDR probes the transmission time of electrical pulses along sensor rods is measured (Topp et al., 1982; Campbell, 1990), FD sensors operate as capacitors in an electrical circuit; its frequency scales the dielectric number around the sensor and thus the soil water content (Robinson and Dean, 1993; Nadler and Lapid, 1996). TDR is the standard method; however, FD sensors employ a simpler and more direct measuring method (Lin, 2003), are less expensive and thus, more flexible in application, and more sensitive to small water content variations. For a wide range of applications, TDR and FD results can be considered similar (v.Wilpert et al., 1998; Lin, 2003; Seyfried and Murdock, 2004). The calibration function depends on the measuring principle, sensor design, and soil specifications. More recently, novel time domain tramsmission (TDT) sensors have become available that are said to provide a performace similar to the TDR method at a reduced cost (Blonquist et al., 2005).

These measurement methods can also be used for materials other than soil, as long as the relative permittivity of the dry material is significantly different from that of water. In most materials the permittivity is dependent on the bulk density. However, changes in bulk density and the influence of temperature have been neglected in most cases.

The volumetric water content (θ) of a given material is calculated using:

$$\theta = \frac{m_w - m_d}{m_d} \times \frac{\rho_m}{\rho_w} = u_G \times \frac{\rho_m}{\rho_w}. \qquad (3)$$

Where ρ_m and ρ_w are the bulk density of the measured material and the density of water, respectively, and m_w, m_d as well as u_G correspond to the same parameters as in Eq. (1). With the knowledge of the mean bulk density, reference measurements can also be carried out on a gravimetric basis, facilitating much easier sampling and analysis. However, in practice the bulk density of soil or litter are frequently not constant (cf. soil settlement, annual changes in deciduous litter as described above), which causes problems that will be discussed ~~later~~ in Sect. 4 of ~~in~~ this paper.

Since the ~~dielectric number~~relative permittivity of forest litter (cf. the ~~dielectric number~~relative permittivity for oven-dry solid wood, which is 2 to 5 at room temperature (Forest Products Laboratory, 1999)) is much lower than that of water, permittivity methods can also be used to measure directly the fine fuel moisture content. Additional difficulties of measuring dead fine fuels with this method are related to the fine fuel layer properties themselves. Especially their common shallowness, low-density and high porosity lead to problems in sensor installation and contact between the sensor and the measured material (Ferguson et al., 2002). Nevertheless, in an experimental burn study, Ruthford and Ferguson (2001) and Ferguson et al. (2002) tried this approach using ~~is~~in-situ field calibration. Over a whole season, 8 TDR sensors (CS-615 two-rod sensors with a length of 30 cm and a separation of 3.2 cm by Campbell Scientific, Inc.) were installed in the litter and duff layers as well as in the underlying sand of a longleaf pine (*Pinus palustris* Mill.) forest in Florida. Individual reference measurements were made by (almost) weekly volumetric sampling for litter and duff, however, the in-situ calibration turned out to be difficult and lead to R^2 values only in the range of 0.13 to 0.56. Nonetheless, Ferguson et al. (2002) found that there were consistent magnitudes and trends between calibrated sensor outputs and qualitative observations of moisture conditions and that the real-time sensor outputs were a great help for scheduling the experimental burns. A coaxial TDR sensor has been developed specifically for the measurement of forest floor litter by Canone et al. (2009). This 'OZ'-probe is a mixture of the coaxial (cylinder with a fully confined electrical field) and three-rod sensor designs and has been shown to measure volumetric water content in forest litter with an error range of 0.02 m^3m^{-3}. Conedera et al. (2012) used soil moisture sensors of unknown type for duff and coniferous litter moisture measurements ("humus sentry", R^2 to manual volumetric samples 0.5 to 0.88 and 0.79, respectively). Recently, Sheridan et al. (2014) used a high number of replications of low-cost soil moisture sensors installed in artificially constructed "litter packs" to investigate the spatial and temporal variability of fuel moisture in complex terrain in Victoria, Australia.

A commercial device for measuring fuel moisture by permittivity sensing is available in the "duff moisture meter" (Robichaud and Bilskie, 2004). To use this device, samples have to be obtained manually, passed through a sieve into a sample chamber, compressed using a torque-limiting knob and are then measured using FD technique. While this procedure ensures more uniform packing and density of the fuels, manual sampling and device operation are required~~, however, requires manual sampling and device operation~~.

1.2.5 Objectives

This study aims to compare and evaluate four different sensor types, three based on permittivity and one on the method of electrical resistance sensing, in comparison to a large amount of gravimetrically determined moisture content data as reference. These electronic methods were chosen because they measure the fuel moisture content at the original fuel particles in the field without any destruction and because they can operate autonomously for a prolonged period. Type, strength and stability over time of the correlation between sensor and gravimetric moisture data are analyzed and compared to other studies in order to identify if and which of the sensors is suitable for routine monitoring.~~This type of analysis, which is based on the availability of near-daily values throughout a whole season including several drying periods, provides new insights into factors influencing automated dead fine fuel moisture measurements and is therefore vital for a potential use of these techniques.~~

2 Methods

2.1 Research site

The study site is located in the Kranzberg Forest (48°24' N, 11°39' E) close to Freising, Germany. It is part of a network of forest climate stations run by the Bavarian Forest Institute (Bayerische Landesanstalt für Wald und Forstwirtschaft - LWF). The 7.1 ha site consists of a 160 year-old single-storied mature mixed forest stand made up of European beech (*Fagus sylvatica* L., 218 trees/ha) and pedunculate oak (*Quercus robur* L., 36 trees/ha). The shrub and especially the moss layers are very scarce and patchy, thus the mull type humus layer is mostly found revealed. Its litter (O_L) layer had an average height of 1.6 cm with a fuel load (oven-dry) of 7.7 t/ha and a bulk density of 48 kg/m³ on September 1st, 2010. Where ground vegetation is present, major species are small balsam (*Impatiens parviflora* DC.), touch-menot balsam (*Impatiens noli-tangere* L.), European woodland sedge (*Carex sylvatica* Huds.) and European beech regeneration. The climate is subatlantic to subcontinental with an average annual temperature of 7.5°C and an average annual precipitation sum of 803 mm, most of which occurs in summer (LWF, 1996).

2.2 Meteorological measurements

~~Observations of m~~Meteorological ~~standard parameters~~data (2 m temperature, precipitation, 10 m wind speed and direction, radiation) w~~ere made~~as recorded throughout the study period at the open-air site of the forest climate station, which is approx. 400 m air-line distance from the study site (cf. Fig. 1). All parameters were gathered on a 15 min basis (mean, maximum or sum, where appropriate) and aggregated to the daily values presented here.

2.3 Reference method

~~Well within the~~More than 25 m from the edges of the forest stand, a 30 m-long transect was established along which the sampling took place (cf. Fig. 1). This transect had the same sparse ground vegetation as the location of the sensors. Three samples were collected almost ~~coincidental~~ at the same time~~at~~ each ~~date~~ day near the start, midpoint and end of the transect, between 11:00 and 13:00 h local standard time. The exact sampling locations were chosen randomly every day; care was taken not to sample any litter that had been excessively trampled. Each sample was gathered by carefully removing the litter (O_L) layer by hand and placing the material (e.g. dead leaves, small branches with a diameter <4 mm, dead parts of inflorescence or fruits) in a 500 ml polypropylene bottle until the bottle was loosely filled. Typical dry mass per sample was 13 g. All bottles were closed air-tightly immediately after sampling to be weighed wet in the laboratory. Afterwards, they were opened, oven-dried at 105°C for 24 h and weighed again after a cool-down period of 30 min in desiccators. Along with the bottle tare weight determined previously, the gravimetric fuel moisture content of the individual samples (Eq. (1)) and the daily mean of the three samples could be calculated. A precision balance (readability 0.01 g) was used for the analyses.

2.4 In-situ measurements

All in-situ devices were placed inside the litter layer within the fenced-off area of the onsite forest climate station, about 25 m from the closer and about 50 m from the farther end of the manual sampling transect (cf. Fig. 1). The sensors were spread out in a randomised, rectangular grid over an area of approximately 2.0×1.5 m² and thus subjected to similar conditions than the transect. All sensors were placed in the middle of the height of the litter layer with a horizontal orientation and were not fixed in their positions. However, all cable ends were fixed to the nearby fence to avoid unintentional extraction of the sensors while reading out the data loggers and sensors from outside the fence.

2.4.1 Permittivity sensing devices

Three different types of permittivity sensors were used. The first sensor (sensor 1, group a) was a special FD-sensor with a flat sensitive volume (approx. (height × breadth × length) 1×7.5×14 cm³, Ruth and Munch, 2005). Further eight non-commercial 2-rod FD sensors (sensors 2-9, group b) with a sensitive volume of approximately 2×3×10.5 cm³ shared the same capacitance (C, [pF]) calculation shown in Eq. (4). The input frequency values (f, [kHz]) were recorded manually from a battery-powered, handheld display unit as data logging was not considered necessary for this initial study.

$$C = \frac{584}{f - 52.9} + 8.45 . \quad (4)$$

Instrumental precision for this type of sensor is usually reported for calibrated soil moistures only (in this case: mean relative accuracy 0.14, according to Ruth and Munch, 2005). However, intrinsic instrument precision depends solely on the accuracy of frequency measurements, which is very high ($\sim 10^{-4}$). Considering the material to be measured is highly porous and low-density forest litter, other measuring errors such as installation and contact to the litter itself can be expected to have a much higher influence on the overall error.

Furthermore, 12 commercial two-rod FD sensors (sensors 13-24, group d, ECH$_2$O EC-5 by Decagon Devices) were used for a limited time period. They consisted of two rods cut-out of each sensor's printed circuit board. Length and separation distance of the rods were 55 mm and 10 mm, respectively. The sensor measurements were recorded automatically every 10 min with a battery-powered data logger and the values closest to each manual sampling time were chosen for analysis. All measurements were automatically converted into volumetric soil moisture θ using a standard (linear) calibration equation in the data logger (Campbell, 2004). The accuracy of this measurement was reported to be ±3% in mineral soil; once more this error can be expected to increase markedly in forest litter.

2.4.2 Electrical resistance sensing devices

A low-cost wood-moisture meter and data logger, featuring three separate channels (sensors 10-12, group c, Scanntronic Materialfox mini, 20kΩ-500MΩ, battery-powered, accuracy not given) was used for electrical resistance measurements. Individual leaves were used as the sensitive objects in this measuring method and connected by two alligator clips with a separation of approximately 1 cm each. Sampling interval and choice of values for analysis was identical to the commercial FD sensors. For this type of measurement it has to be considered that in addition to instrumental precision and installation, the available measuring range (corresponding roughly to 15-80% gravimetric moisture content in wood) may well be exceeded in forest fuels.

2.5 Data availability

Reference sampling was started on March 22nd, the 81st day of the year (DOY), and completed on October 31st, 2010 (DOY 304). During this time, gravimetric fuel moisture measurements were obtained for 215 days (96%) as a reference.

The in-situ sensors were operational for different time periods, depending on the sensor type. Details about this, as well as some basic statistics, can be found in Table 1. It should be noted, however, that the number of sensor per group that were operational may have changed from day to day, e.g. due to short-term equipment malfunction (dead batteries and wiring problems) and the long-term erratic behavior of electrical resistance (group b) sensor no. 12 from DOY 114 onwards. ~~The flat FD sensor (group a), 2-rod sensors (group b) and R-sensors (group c) were installed from DOY 88 to DOY 304. During this period, 186 daily flat FD-sensor values, between 182 and 186 2-rod sensors values, and 205 R-sensor values were recorded. However, one R-sensor (no. 12) showed erratic behavior from DOY 114 onwards due to a cable break and all subsequent data had to be removed from the analysis. ECHO sensors (group d) were operational from DOY 89 to DOY 138, producing 47 daily measurements. Days without measurements of single sensors were caused by rare equipment malfunction, e.g. due to wiring problems or dead batteries.~~

2.6 Data analysis

For an overall assessment of meteorological and fuel moisture conditions during the sampling period, manually determined fuel moisture is plotted along with standard meteorological parameters (daily maximum and mean temperature, daily ~~sum of~~cumulative precipitation).

In order to investigate the relationship of the individual sensor signals with manually determined litter moisture, each sensor's signal was rescaled linearly to the minimum and maximum of the manual measurements. For the flat-FD (group a), two-rod (group b) and ECHO (group d) sensors, this was done directly using the R package "scale"'s function "rescale", as a linear correlation with manual measurements can be assumed irrespective of the physical value of the measurements. The resistance signal from sensor group c was inverted and log-transformed before rescaling to achieve a near-linear relationship with manual gravimetric measurements. It should be noted that rescaling was not only necessary to make the values from different sensor groups (i.e. different physical values) comparable, but that there was also a large sensor-to-sensor variation within each group due to the high variability of the litter layer (e.g. one sensor may have been installed in a rather shallow, low-density part of the litter layer, whereas another of the same type might have been located in a high density area; this produces highly different sensor outputs especially for the bulk-density dependent FD-sensors). As the rescaled values were only analysed in reference to the litter moisture content and not to themselves (e.g. no correlation of one rescaled sensor to another rescaled sensor), we can exclude any interference of the rescaling process on our results, because correlations and linear regressions are invariant to linear transformations such as the rescaling used here. A similar approach was used by Conedera et al. (2012) for their soil moisture sensor-based "humus sentry", which is also highly affected by the bulk density in the immediate sensor vicinity.

For all sensor groups, Spearman correlations with the manually determined litter moisture were examined. In groups featuring more than one sensor (b-d), the standard deviations of the daily values of all sensors of one group were investigated in relation to the respective daily sensor mean value, and sensor values with erratic standard deviations were identified. Sensor values as well as litter moisture and meteo data for ~~Time, weather and litter moisture~~ periods corresponding to erratic and non-erratic sensor standard deviations are shown and the coherence of the sensor-gravimetric moisture relationship investigated using linear regression and associated confidence intervals. Finally, the influence of the observations and analyses on the applicability of the different sensor types is discussed. All data analyses and plotting were performed in the statistical package R, version 3.1.1 (R Core Team, 2014) and its packages RODBC, doBy, scales and Metrics.

3 Results

3.1 Gravimetrically determined fuel moisture and weather conditions

Results of the gravimetric reference measurements, daily ~~sum of~~cumulative precipitation as well as mean and maximum temperatures are summarized in ~~Fig. 1~~Fig. 2. During most of the study period, unusually frequent and heavy precipitation events kept fuel moisture high and fire danger low. However, two major dry periods occurred in April (DOY 90 onwards) and July (DOY 165 onwards) 2010. Minimum, median and maximum daily fuel moisture throughout the study period was 13%, 175% and 395%, respectively. The relative standard deviation within the daily gravimetric measurements of 1.1 to 66.9% was rather high (data not shown here). However, it tended to decrease with decreasing fuel moisture.

3.2 ~~In-situ data and standard deviations~~Sensor data and correlation to gravimetric fuel moisture

~~Figure 2~~Figure 3 shows scatterplots as well as Spearman's rank correlation coefficients for the mean rescaled sensor value, manually determined litter moisture and the different sensor groups, respectively. While the permittivity-based sensor groups a, b and d show relatively obvious linear correlations, the resistance sensors (group c) exhibit a non-linear and almost logistic relationship with many high and low values and a sharp transition in between. As there was only one sensor in group a (flat permittivity sensor), all of its values are marked as $n<3$ (grey). The same is true for all resistance (group c) readings taken after DOY 114 when one of three sensors developed a fatal error.

Spearman's rank correlation coefficients showed highly significant ($p<0.001$) correlations for all four sensor groups with higher correlations for permittivity (group a, 0.837; group b, 0.891; group d, 0.947) than for electrical resistance (group c, 0.792) sensors. The highest rank correlation coefficient was observed for group d (ECH2O commercial two-rod sensors, 0.947), which were only used for a very limited time period, however.

Considering the dependence of standard deviation on sensor mean values shown in ~~Fig. 3~~Fig. 4, all sensors of groups b-d exhibited an increase that is nearly linear to the sensor mean value at first, while showing some irregular patterns and scatter at higher sensor mean values. For the resistance sensors (group c), a marked decrease of standard deviation could be observed at very high mean values (>300).

Those ranges of sensor mean values, where sensor standard deviation was behaving irregularly and showing a high scatter, have to be considered as potentially unsuitable for reliable measurements. Therefore, a threshold sensor value of 100 for the permittivity sensors (groups b and d) and 50 for group c (electrical resistance sensors) was defined visually and shown in ~~Fig. 3~~Fig. 4 as vertical dashed lines.

~~Figure 4~~Figure 2 (lower three panels) shows the evolution of litter moisture content and the rescaled sensor mean values with the colors indicating values above and below the respective thresholds. Naturally, the values below the thresholds are almost exclusively limited to the dry periods mentioned above, with the exception of a very short dry period in the end of June. Based on the sensor data and standard deviation classification, these periods were defined and labelled as periods 1, 2 and 3 (indicated by green and black and yellow dots in Fig. ~~4~~2, respectively). For data concerning the exact start and end dates of these periods, as well as some basic statistics, consult Table 1.~~The only exception was the very short dry period 2 in the end of June (~DOY 160, June 9, marked by yellow dots).~~

For the two longer-lasting dry periods (periods 1 and 3), linear ~~calibrations~~ regressions and associated confidence intervals were calculated for each individual sensor of group b and c, and shown in Fig. 5 along with the data points of the short dry interval in June (period 2). The associated regression parameters can be obtained from ~~Table 1~~Table 2.

It can be observed that for most combinations, linear regression was well-suited to describe the relationship of the rescaled sensor values and the gravimetrically measured litter moisture content. However, there were large differences of those relationships determined in periods 1 and 3, with values from period 2 generally falling in between and/or slightly closer to those of period 3. The confidence intervals (dashed lines) of the respective ~~calibrations~~ regressions only overlapped at the extreme dry range of litter moisture and sensor values, thus indicating that the ~~calibrations~~ underlying relationships were actually significantly different. Additionally, only few measurements of one period could be found within the confidence intervals of the ~~calibration~~ regression based on the other period. For the 2-rod sensors (group b, 2-9), the calibration regression slope tended to decrease and the intercept tended to increase from period 1 to period 3. Even the few values of period 2 fell in between the two calibrations regressions and thus support this shift in the calibration regression line. Additionally, coefficients of determination tended to increase and confidence intervals to narrow from period 1 to period 3. The electrical resistance sensors (10-12, group c) showed an even more extreme behavior: while there were very poor fitting ($R^2<0.05$, $p>0.1$), negative regression lines in period 1, calibration regression in period 3 worked better ($R^2>0.32$, $p<0.05$), producing a positive slope.

4 Discussion

Due to the unusually frequent and intense precipitation (for the study area) during the test period in 2010, (cf. Fig. 1Fig. 2), conditions were generally not favorable to forest fire occurrence and greatly complicated a test of litter moisture measuring techniques. Only a very limited number of dry periods occurred during which (gravimetric) litter moisture dropped to levels low enough to be meaningful for fire danger and behavior applications (i.e. in the range of 30% and lower (Wright, 1967)). Interestingly, it can be observed that even data from the gravimetric reference technique are characterized by produces elevated high variation variability (relative standard deviation up to 66.9%) at high litter moisture (data not shown). A similar pattern was observed by Ferguson et al. (2002). Part of the variation in the gravimetric measurements may becertainly was due to spatial variation of fuel moisture on the ground (i.e. some sampling locations being more sheltered by the canopy whereas others are more open) and sampling inconsistencies (e.g. sampling depth linked to areas with a deeper or shallower litter layer and a steep vertical gradient of moisture within the litter when wetting or drying occurred).

When the sensor raw values were rescaled and the averages of each sensor group compared to coincidental concurrent gravimetric litter moisture measurements (cf. Fig. 2Fig. 3), linear relationships could be visually identified for all permittivity sensors (groups a, b and d). The very poor, seemingly logisticnon-linear relationships for the electric resistance technique (group c) could be due to an exceedance of the sensor range both in the maximum and minimum, or to a suboptimal transformation of the raw values. The latter may especially be due to the fact that it was necessary to invert and log-transform the resistance signal before rescaling in order to achieve a near-linear relationship (cf. Sect. 2.6) and that other, more complicated and partially confidential transformations are used by the wood moisture sensor industry (cf. Sect. 1.2.3 and Eq. (2)). As the device used was a wood moisture analyzer normally working in a range of 15 to 80% gravimetric moisture content, it was fairly clear that despite the different measuring setup, at least the upper end of the range was exceeded.

Overall, the correlation of automatic vs. manual gravimetric measurements seemed somewhat more robust than in Ferguson et al. (2002) (Spearman's rank correlation 0.792 to 0.947 compared to second-degree polynomial calibration R^2 of 0.129 to 0.558) and was very similar to the mean results of 3 "humus sentries" placed in conifer needles by Conedera et al. (2012), R^2 0.79. Borken et al. (2003) gave a calibration R^2 of 0.72 and 0.68 for the mean of their 12 Oi and 24 Oe/Oa horizon electrical resistance sensors, respectively. As they used the half-bridge voltage as the independent variable, no log-transformation of their resistance measurements was necessary and linear regressions could be carried out directly. The different strengths of correlation/regression may be due to a number of factors, including the sensor type and placement, litter type, fuel moisture range during the study period, number of reference measurements made, averaging effects for Borken et al. (2003) and Conedera et al. (2012), and the use of volumetric (Conedera et al., 2012) and log-scaled volumetric reference measurements in Ferguson et al. (2002).

The standard deviations across the range of sensor mean values for sensor types b, c and d (~~Fig. 3~~Fig. 4) suggest that there is a transition from an almost linear increase of standard deviation to an irregular pattern above a sensor value of 100 (sensor type b and d) and 50 (sensor type c), respectively. This transition may be due to proximity to the end of the measuring range, high spatial variability of litter moisture at high moisture contents (as suggested by increased gravimetric standard deviations), or even a redistribution of litter elements within the sensitive volumes due to heavy precipitation. For the electric resistance sensors (group c) it can be observed that as the measuring range is exceeded (mean sensor value >280), standard deviations are decreasing again. Fortunately, this irregular pattern of standard deviation as compared to sensor mean value occurs at the high end of the measuring scale, where fire danger is practically non-existent in any case (gravimetric litter moisture usually beyond 100%). Therefore, periods where the sensors had to be considered unreliable can be labelled as not representing fire danger. When trying to compare the standard deviations encountered to the instrumental precision reported in Sect. 2.4, it turns out that this is not readily possible, as different scales and measures are being used. It should be noted, however, that the absolute and relative standard deviations (e.g. reported in Table 1) are quite high. They may be one or several orders of magnitude higher than what has been reported for the instruments themselves, which is probably due to the placement of relatively precise sensors in a very heterogeneous and variable litter bed.

Introduction of thresholds for maximum reasonable sensor values lead to a limitation to few dry periods, as visible in ~~Fig. 4~~Fig. 2. When linear ~~calibrations~~ regressions were carried out and compared in those periods (Fig. 5, Tab. ~~1~~2), significant differences between periods 1 and 3 could be found, whereas the values of the very short period 2 lay in-between. For group b (2-rod permittivity sensors), slopes of regression tended to decrease from period 1 to period 3. Considering Eq. (3), an increasing sensor raw value (over time) for similar litter moisture content, and thus lower slopes of regression, suggest that an increase of the litter bulk density (ρ_m) had occurred in the meantime. Due to settling, decomposition of the litter layer as well as installation of the sensors only few days before the start of period 1, this was a process that certainly occurred in the litter layer while the measurements were carried out. Further corroboration for this was observed when the sensors were uninstalled and found in a dense mat of semi-decomposed litter. Higher bulk density around the sensors would also explain part of the increased sensor performance in period 3 (generally higher coefficients of determination and thus higher sensitivity). A similar behavior can also be expected for groups a and d (flat volume and commercial FD-sensors, respectively), however this could not be shown as there was only one group a sensor available (thus the standard deviation threshold analysis could not be carried out) and as the group d sensors were only in use for a limited time period not containing dry periods 2 and 3. The changes over time in litter properties and thus in the calibration equations necessary to convert the sensor raw values into measures of litter moisture present a severe limitation in the use of these sensors in the field, as frequent recalibrations would have to be carried out. Very poor regressions for the electrical resistance sensors (group c) during period 1, as opposed to period 3, suggest that the sensors were still showing influences of the recent installation and that the values gathered during period 1 are not reliable. As the measurement is not directly influenced by bulk density, however, this is probably not related to the same processes identified for sensor group b. The overall bad performance of the electrical resistance technique indicates that extensive additional fine-tuning and testing is required if this technique is to be used for litter moisture monitoring.

5 Conclusions

Despite relatively ~~poor~~ wet weather conditions and generally low fire danger, different sensors for the determination of litter moisture ~~(e.g. for forest fire applications)~~ could be tested and valuable insights gained. All sensors showed erratic behavior at very high litter moisture contents, which however are not relevant for forest fire applications as these conditions are not linked to fire danger and may not even occur in more fire-prone regions. While significant correlations and regressions between the rescaled sensor raw values and gravimetrically determined litter moisture could be obtained for all sensors tested, significant differences between the ~~calibrations~~ regressions for periods 1 and 3 (in March/April and June/July, respectively) suggest that changes over time within the litter layer affect the sensor raw value-litter moisture relationship. Thus, sensors should not be calibrated only once in-situ directly after installation. In contrast, relatively frequent recalibration (e.g. at least every two or three months) is necessary. Additionally, more work on the precise fine-tuning of the very poor performing resistance sensors would have to be done if this measuring technique were to be used. However, their~~and~~ generally limited measuring range ~~of electrical resistance sensors~~ should be considered.

Consequently, all of the tested methods may seem to be too complex for routine monitoring applications, whereas they may still be interesting for scientific studies, especially when manual gravimetric fuel moisture determination is to be carried out anyway. Placing the sensors described here in an artificially constructed fuel bed that is kept together e.g. by a wire frame (cf. “litter packs” in Sheridan et al. (2014)) or the use of other reference materials may reduce some of the difficulties found in this study.

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Table 1. Data availability and basic statistics for the entire study period and the three periods defined in Sect. 3.2. Note that on a given day, not all sensors of each group may have been operational due to equipment malfunctions.

		Entire study period	Period 1	Period 2	Period 3
Period	Start date	22.03.2010	29.03.2010	11.06.2010	28.06.2010
	Start DOY	81	88	162	179
	End date	31.10.2010	30.04.2010	13.06.2010	22.07.2010
	End DOY	304	120	165	204
	Length	224	33	3	25
Litter moisture	Days	215	30	3	25
	Mean	168.6	60.7	67.3	58.3
	SD	19.2	10.4	19.1	8.0
	Relative SD	11.4	17.2	28.4	13.7
Sensor group a	Days	186	30	3	23
	Avg. N per day	1	1	1	1
	Mean	151.2	27.0	49.7	61.1
	SD	-	-	-	-
	Relative SD	-	-	-	-
Sensor group b	Days	184	30	3	23
	Avg. N per day	7.9	8.0	8.0	8.0

	Mean	164.7	42.0	84.5	86.7
	SD	33.2	12.6	26.2	23.8
	Relative SD	20.2	30.1	31.1	27.5
Sensor group c	Days	205	29	3	25
	Avg. N per day	2.5	3.0	3.0	3.0
	Mean	259.8	55.8	139.6	111.6
	SD	19.3	18.3	18.0	15.6
	Relative SD	7.4	32.8	12.9	14.0
Sensor group d	Days	47	29	0	0
	Avg. N per day	12	12	0	0
	Mean	139.0	53.5	-	-
	SD	25.7	20.4	-	-
	Relative SD	18.5	38.3	-	-

Table 12. Regression parameters for the linear calibrations relationships shown in Fig. 5.

Group	Sensor	Period	R^2	p-value	N	Intercept	Slope
b	2	1	0.64	<0.0001	30	-44.49	1.73
b	2	3	0.07	<0.5	17	26.01	0.29
b	3	1	0.45	<0.0001	30	2.43	1.62
b	3	3	0.68	<0.0001	17	-18.63	0.69
b	4	1	0.50	<0.0001	30	-9.29	1.61
b	4	3	0.68	<0.0001	17	-18.88	0.64
b	5	1	0.67	<0.0001	30	-19.55	1.62
b	5	3	0.76	<0.0001	17	-10.17	0.57
b	6	1	0.45	<0.0001	30	-5.31	2.22
b	6	3	0.62	<0.0005	17	-39.81	1.04
b	7	1	0.49	<0.0001	30	-6.95	1.58
b	7	3	0.52	<0.005	17	-32.71	0.81
b	8	1	0.56	<0.0001	30	-35.55	2.73
b	8	3	0.27	<0.05	17	10.63	0.32
b	9	1	0.27	<0.005	30	21.65	1.03
b	9	3	0.26	<0.05	17	-2.05	0.40
c	10	1	0.04	<0.5	22	70.45	-1.98
c	10	3	0.32	<0.05	15	-7.26	1.35
c	11	1	0.05	<0.5	22	72.03	-2.10
c	11	3	0.38	<0.05	15	10.95	0.55
c	12	1	0.02	>0.5	22	58.42	-1.26

c	12	3	0.46	<0.01	15	-4.09	1.24
d	13	1	0.72	<0.0001	25	0.81	1.25
d	13	3	-	-	-	-	-
d	14	1	0.59	<0.0001	25	-10.75	0.91
d	14	3	-	-	-	-	-
d	15	1	0.34	<0.005	25	18.66	0.58
d	15	3	-	-	-	-	-
d	16	1	0.74	<0.0001	25	13.12	0.57
d	16	3	-	-	-	-	-
d	17	1	0.10	<0.5	25	29.15	0.62
d	17	3	-	-	-	-	-
d	18	1	0.65	<0.0001	25	-4.19	1.61
d	18	3	-	-	-	-	-
d	19	1	0.51	<0.0001	25	11.54	0.64
d	19	3	-	-	-	-	-
d	20	1	0.05	<0.5	25	33.46	0.37
d	20	3	-	-	-	-	-
d	21	1	0.65	<0.0001	25	1.58	1.59
d	21	3	-	-	-	-	-
d	22	1	0.75	<0.0001	25	6.41	0.94
d	22	3	-	-	-	-	-
d	23	1	0.35	<0.005	25	15.97	0.69
d	23	3	-	-	-	-	-
d	24	1	0.65	<0.0001	25	3.88	0.78
d	24	3	-	-	-	-	-

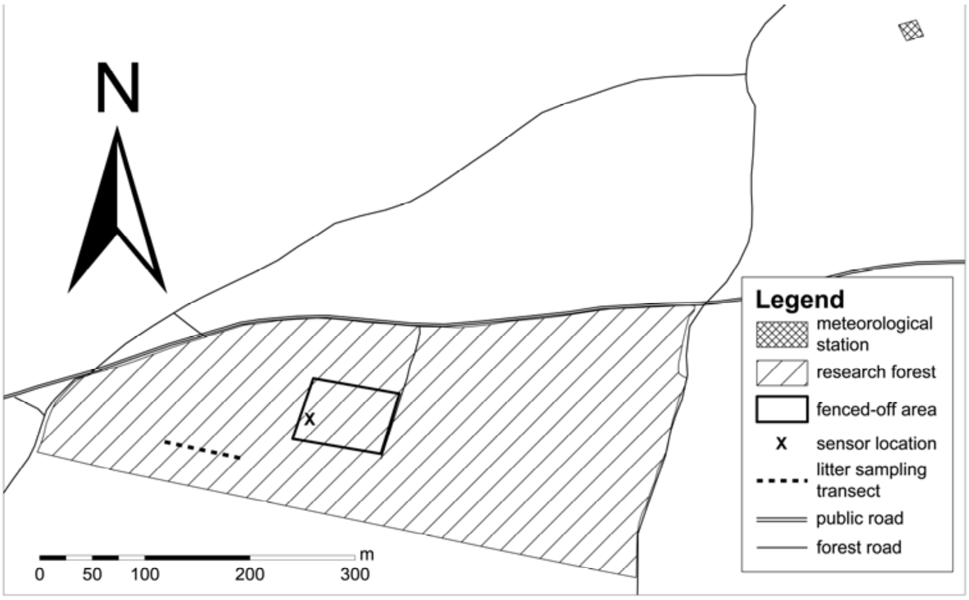
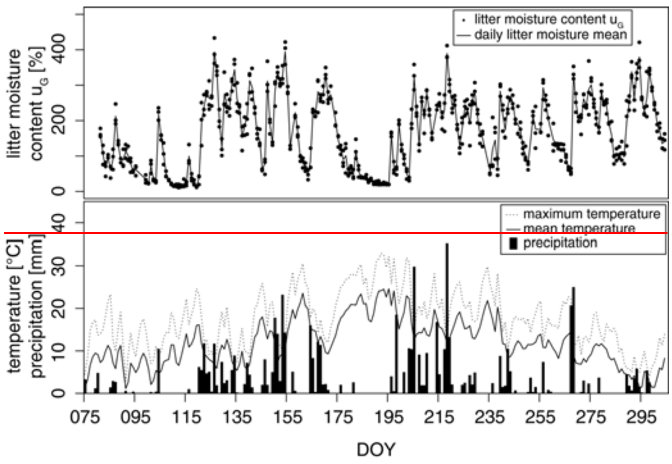
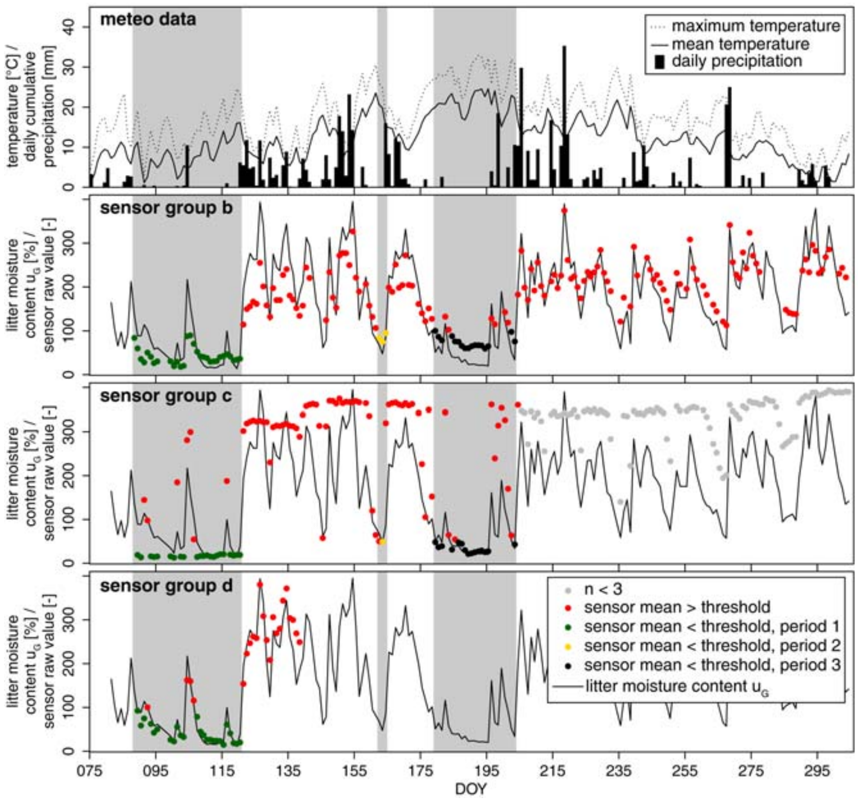
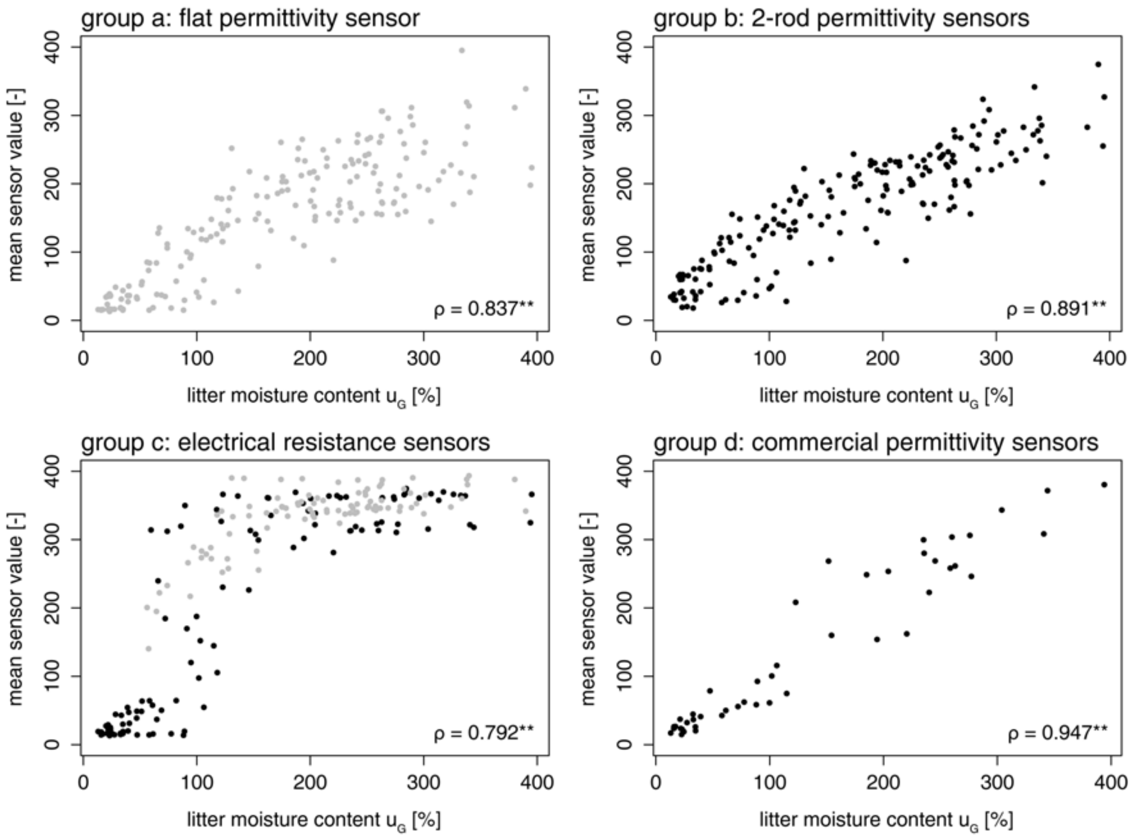


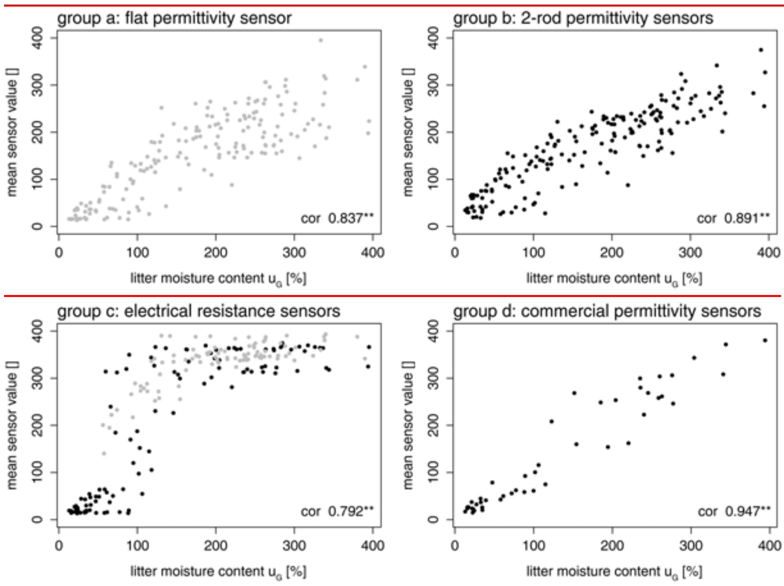
Figure 1. Map of the experimental site, including open-air meteorological station, research forest with fenced-off area, sensor location and litter sampling transect. Not to scale.



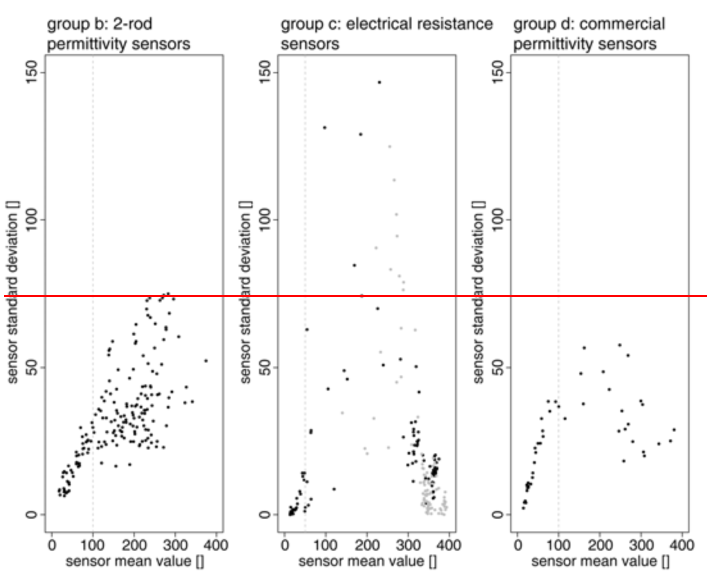


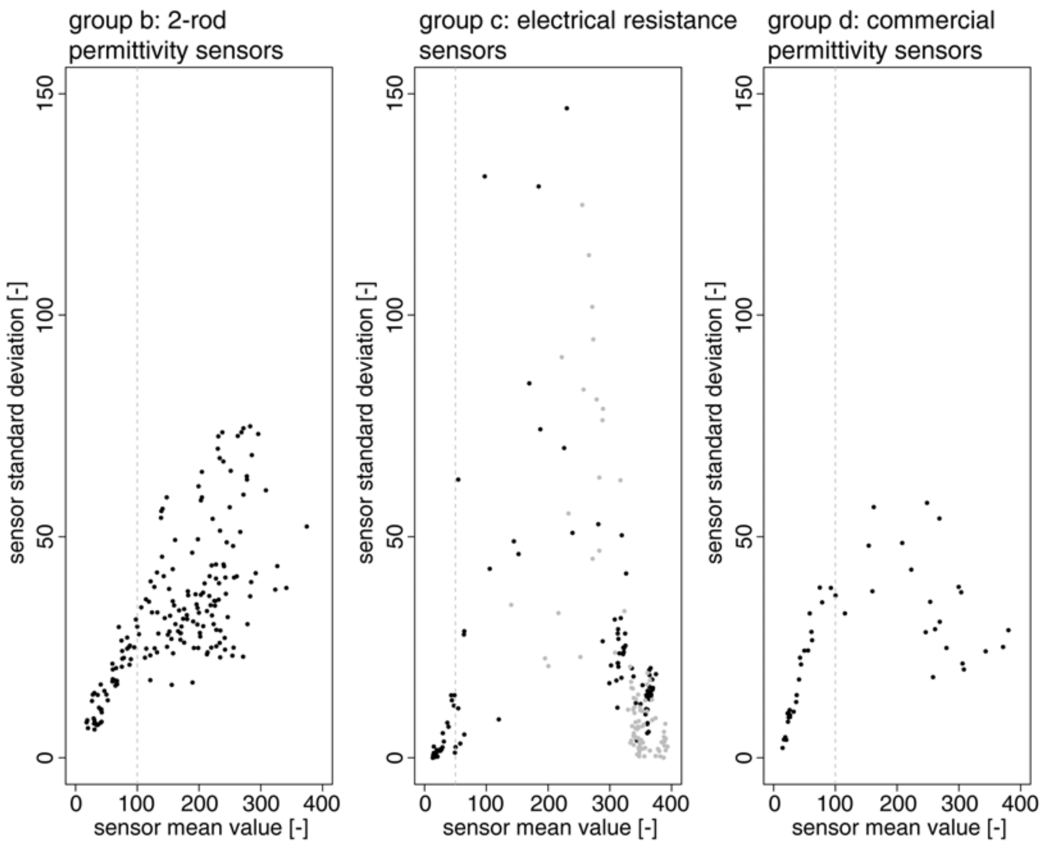
~~Figure 1~~Figure 2. ~~Litter moisture content u_G and m~~Meteorological ~~parameters~~ data and litter moisture content (u_G), as well as rescaled sensor mean values during the ~~test~~ study period. Colored dots indicate sensor mean values: calculated from less than three sensors (grey), beyond the threshold set in Fig. 4 (red), below the threshold and part of period 1 (green), below the threshold and part of period 2 (yellow), below the threshold and part of period 3 (black). The grey areas correspond to periods 1-3 defined in Sect. 3.2.



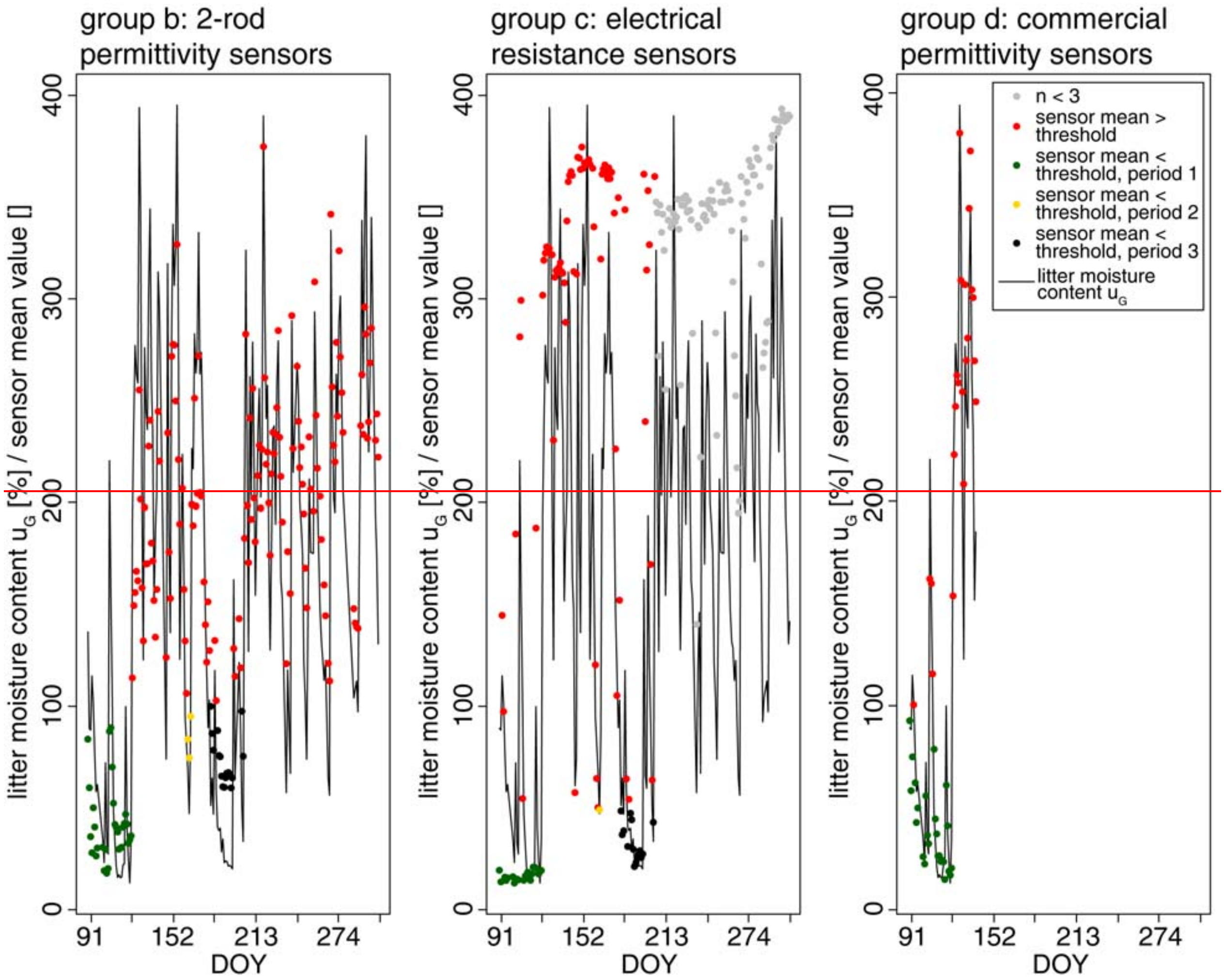


~~Figure 2~~Figure 3. Mean rescaled sensor values versus manually determined litter moisture content u_G for all data available. Grey dots indicate means that were calculated from less than three observations; Spearman's correlation coefficients (ρ) are based on all available data (black and grey dots) and the double asterisks indicate highly significant ($p < 0.001$) correlations.

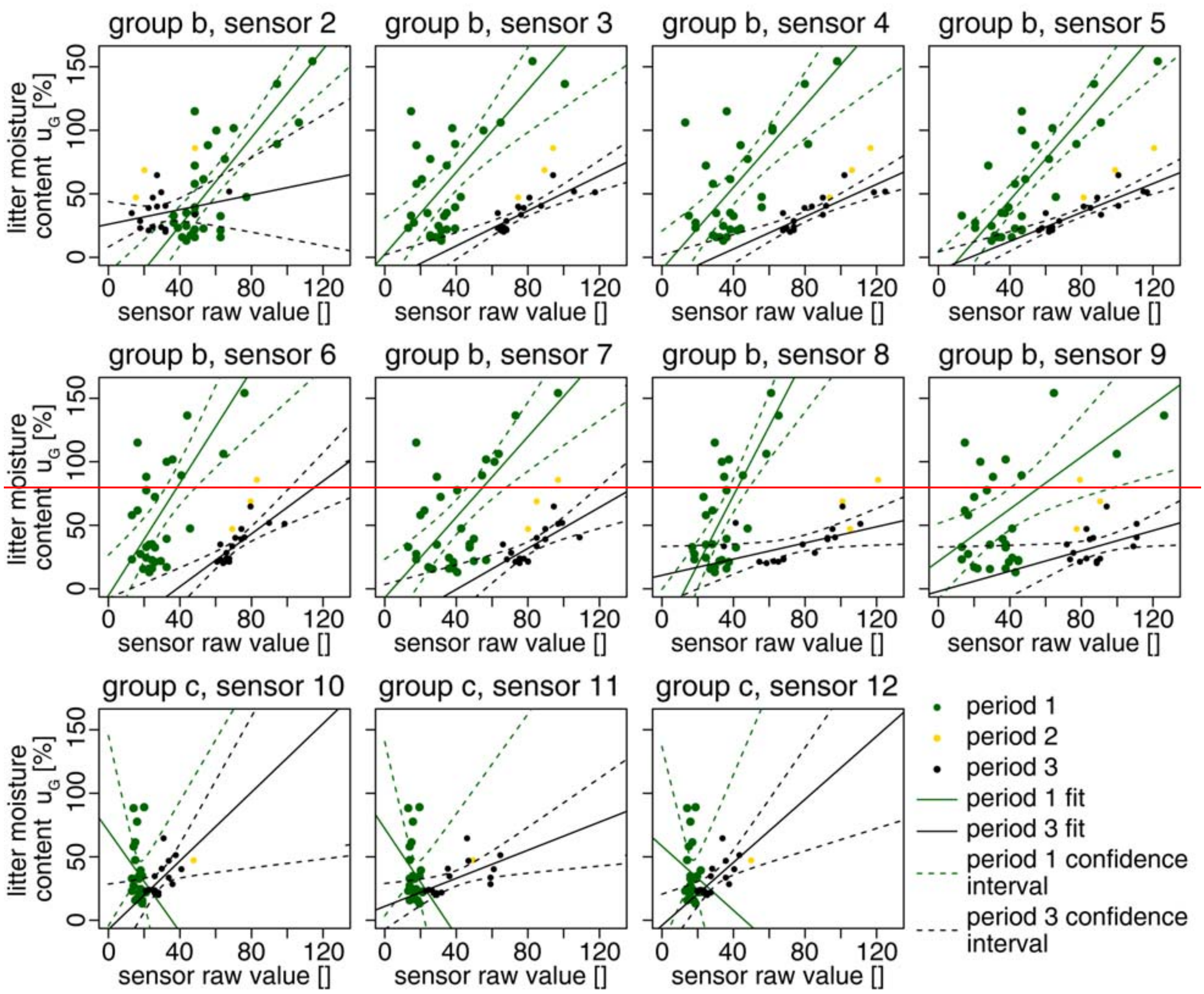




~~Figure 3~~Figure 4. Standard deviation of the different sensor groups ~~by~~ as a function of sensor mean value. Grey dots indicate standard deviations and means that were calculated from ~~less than three~~two observations only. The dashed grey line represents the threshold sensor mean value that was determined visually to limit the values to a range where sensor mean value and sensor standard deviation were more correlated ~~linearly~~. Group a was left out as it consists of one sensor only.



~~Figure 4. Variations of gravimetric litter moisture and the rescaled sensor mean values during the measuring period. Black line: mean gravimetric fuel moisture content; colored dots indicate sensor mean values: calculated from less than three sensors (grey), beyond the threshold set in Fig. 3 (red), below the threshold and part of period 1 (green), below the threshold and part of period 2 (yellow), beyond the threshold and part of period 3 (black).~~


group b, sensor 2
group b, sensor 3
group b, sensor 4
group b, sensor 5
group b, sensor 6
group b, sensor 7
group b, sensor 8
group b, sensor 9
group c, sensor 10
group c, sensor 11
group c, sensor 12
litter moisture content u_G [%]
sensor raw value []
period 1
period 2
period 3
period 1 fit
period 3 fit
period 1 confidence interval
period 3 confidence interval

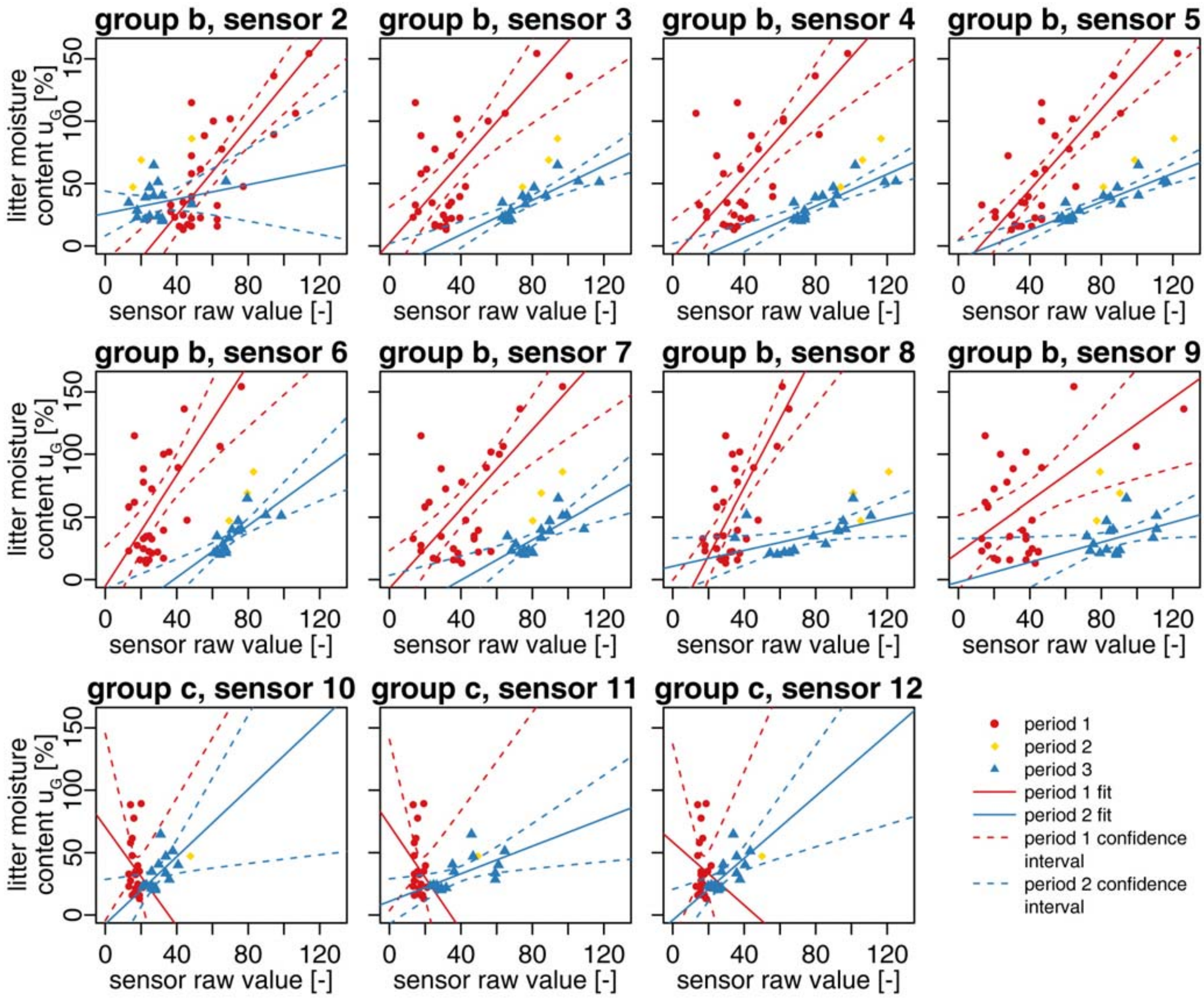


Figure 5. Linear ~~calibrations~~ regressions and associated confidence intervals calculated for periods 1 and 3 for each individual sensor of groups b and c, respectively. Yellow ~~dots~~diamonds: sensor and litter moisture values during period 2. Group b: 2-rod permittivity sensors, sensors 2-9; group c: sensors 10-12, electrical resistance. For basic statistics regarding the periods and regression parameters, cf. Tables 1 and 2, respectively.