AUTHORS' RESPONSE TO THE REVIEWER'S COMMENTS

Manuscript **hess-2016-93** entitled

"Repeated electromagnetic induction measurements for mapping soil moisture at the field scale: validation with data from a wireless soil moisture monitoring network"

by Edoardo Martini, Ulrike Werban, Steffen Zacharias, Marco Pohle, Peter Dietrich, and Ute Wollschläger

We would like to thank the anonymous referee #4 and #5 for the valuable comments. In the following, we addressed all the comments and indicated the specific changes (marked in red) to the revised manuscript.

ANONYMOUS REFEREE #4

Reviewer's comment

"This paper investigates whether electromagnetic induction (EMI) measurements of the soil electrical conductivity (ECb) can be used to estimate and monitor soil water content. This is not trivial since there is a range of factors that influence ECb. The results from a hillslope transect equipped with a wireless soil moisture network showed poor correlations between ECb and water content for a range of measurement days. It is concluded that there are too many confounding factors to determine soil water content using EMI at this site.

Overall, I am supportive of the general direction of the manuscript, and I think that it conveys an important message that is not well represented in recent literature on EMI measurements for soil moisture characterization. However, I do have three general comments and a wide range of specific comments that need to be addressed before this paper can be accepted for publication. Moderate to major revisions are still required to address these comments."

"GENERAL COMMENTS

1. As already indicated by other reviewers in round 1, the introduction is long and not really focused. At several places, I could not really follow the point that the authors were trying to make. I think this section still needs more focus. I have provided some specific comments below that could help. "

"2. I was not able to follow the presentation in the results and discussion at all times. The line of argumentation remained unclear in several places. Again, I hope that the specific comments below will show you where I got confused. The authors seem to have a lot of supporting data for the field site, but it is not used in this manuscript. For example, it is stated that soil texture is the dominant control (Page 14, Line 14) but this is not illustrated with supporting data. Now it is argued that soil water content is not a key factor, but no alternative data are presented to support the narrative explanation for this conclusion. It would great if this could be addressed."

"3. The balance between results and discussion seems inappropriate. There is a lot of discussion for a relatively small amount of results. I would prefer a more concise discussion that makes some key points. I felt that the current version was quite repetitive, which was partly also due to long replies to reviewer comments that were included in the manuscript. Also, section 4 comes after a long discussion in section 3. Shortening seems appropriate to me."

Authors' response

We acknowledge the contribution of the referee, who provided clear and consistent comments. We addressed all the specific comments and we feel that the revised manuscript was significantly improved. In particular, some parts were made more concise and some were restructured more clearly as recommended by the referee. For more details we refer to our responses to the specific comments below.

Reviewer's comment

"SPECIFIC COMMENTS

Page 1, Line 24-27. Although I agree with the general stance of this manuscript, I believe that these conclusions are too general. They should be formulated in a more site-specific manner. I am also not so happy with the formulation of point ii. Of course, this effect can be measured. However, changes in water content may co-vary with changes in pore water electrical conductivity and the relationship may be obscured. However, this is not valid in general. In short: reformulation is required here."

Authors' response

The main conclusions in the abstract were reformulated according to this comment.

> Page 1, Lines24-29:
> "Results suggest that i) depending upon site characteristics, stable soil properties ~~are~~ can be the major control of ECa measured with EMI, and ii) for soils with low clay content, the influence of θ on ECa may be confounded by changes of the electrical conductivity of the soil solution ~~θ itself has little influence on the measured ECa unless the electrical conductivity of the soil solution changes significantly~~. Further, ~~our~~ this study ~~provides the opportunity to~~ discusses the complex interplay between factors controlling ECa and θ, and the use of EMI-based ECa data with respect to hydrological applications."

Reviewer's comment

"Page 2, Line 4. Not sure whether they were developed for soil salinity. However, it was a first main area of application. Consider rewriting."

Authors' response

The sentence was changed.

> Page 2, Line 7:
> "Measurements of ECa using EMI are in use since the 1970's, initially having been ~~developed~~ used for applications related to soil salinity."

Reviewer's comment

"Page 2, Line 12. Awkward sentence. I do not understand your link between EMI theory and the work of Rhoades here. Please formulate more carefully."

> **Authors' response**
>
> We agree with this comment. The sentence was changed.

> Page 2, Line 16:
> "The theory and basic principle of EMI ~~refers to the mechanistic soil EC model proposed by Rhoades et al. (1989)~~ are based on the soil equivalent resistance model (Sauer et al., 1955). "

Reviewer's comment

"Page 2, Line 23-24. I agree that soils with high CEC usually show higher ECw. However, the causality provided here is too simplified. Please improve by reformulating together with the next sentence that already goes in the right direction."

> **Authors' response**
>
> The sentence was changed together with the next one.

> Page 2, Lines 27-31:
> "Moreover, of particular importance is ECw, which often increases with higher CEC~~,~~: as soil water interacts with the soil minerals (especially clay) and with soil organic matter (SOM), ions from the soil minerals can be released into the soil solution and, conversely, free ions can be adsorbed to equilibrate the mineral surface charges. In this respect, the initial EC of rain water~~,~~ and its residence time in the soil ~~and the mineralogical composition of the soil~~ may play a key role along with the mineralogical composition of the soil."

Reviewer's comment

"Page 2, Line 29. Looking at this sentence, you seem to make a difference between soil properties and states. Perhaps it is better to avoid this. It is my experience that most people do not really make this distinction (e.g. they consider water content to be a soil property too). Removing this distinction will require some rewriting."

> **Authors' response**
>
> We understand that the referee is concerned about a possible misunderstanding that the distinction between soil properties and states may cause to some readers. However, we do believe that such distinction is correct and important in the context of this paper. Therefore, we would like to keep this concept as is and we hope the referee will understand our point.

Reviewer's comment

"Page 3, Line 4-5. Perhaps emphasize here already that depth-weighting is complicated. Your formulation seems to imply homogeneous depth weighting."

Authors' response

The sentence was changed.

> Page 3, Lines 11-13:
>
> "The parameter measured by EMI sensors refers to a certain volume of soil material according to a complex depth-weighting, thus it is indicated as apparent electrical conductivity ECa. "

Reviewer's comment

"Page 3, Line 5-15. This is very detailed for an introduction. Perhaps this can be moved to a more appropriate position later in the paper?"

Authors' response

We moved the method description to section 2.3.

> Page 3, Lines 4-31:
>
> "In the last decades, a number of sensors were developed for field measurements of ECa, based on the electromagnetic induction theory (Keller and Frischknecht, 1966). Technically, a transmitter and a receiver coil are placed on (or near) the soil surface at a fixed distance from each other, and the transmitter coil is energized with an alternating current. This generates a time-varying magnetic field, which induces electric fields in the soil, which in turn induce a secondary magnetic field. Such phenomena are described by Ampere's and Maxwell's laws. Both the primary and the secondary magnetic fields are sensed by the receiver coil and, under certain geometric conditions indicated as "low induction number" (McNeill, 1980; Callegary et al., 2007; Callegary et al., 2012), the ratio between the primary and the secondary magnetic field can be used to estimate the ECa of the volume of soil under investigation. As the final reading The parameter measured by EMI sensors refers to a certain volume of soil material according to a complex depth-weighting, thus it is indicated as apparent electrical conductivity ECa. Several factors influence the physical process described above. As the intercoil spacing s increases, the EM field propagates through a larger volume of soil. As the operating frequency increases, the EM field is more attenuated and therefore penetrates less into the soil, reducing the volume of investigation. Transmitter and receiver coils are commonly adjusted in coplanar configuration. Vertical coplanar coils (VCP) generate a horizontal magnetic dipole orientation (HDP), whilst the horizontal coplanar coil configuration (HCP) generates a vertical magnetic dipole (VDP). The coil configuration has implications for the volume of investigation. McNeill (1980) provided the relative response versus depth for an EMI device in both HDP and VDP and the "cumulative response" for homogeneous and layered soils. According to that, the response of an EMI device in HDP has larger sensitivity close to the soil surface (or, more precisely,

immediately below the coils), with monotonic decay with depth, whilst the VDP configuration provides maximum sensitivity to the depth of ca. 0.4·s (i.e., 40% of the intercoil spacing). Additionally, the effective depth of exploration, defined as the portion that contributes with 70% to the measured value of ECa, is 0.75·s for the HDP and 1.50·s for the VDP configuration. Callegary et al. (2007 and 2012) discussed these concepts this concept using a forward model of electromagnetic field propagation, and found that the sensitivity of any EMI sensor to soil ECa as well as the depth of investigation can differ significantly from those suggested by McNeil (1980). Nevertheless, it appears clear that the final ECa reading of any EMI device is a complex physicochemical measurement which results from the propagation of the EM field within the volume of investigation and its interaction with stable and transient soil properties/states, and that the effective measurement depth and volume of investigation of an EMI sensor may vary at different times and locations (Sudduth et al., 2001; Corwin and Lesch, 2005; Farahani et al., 2005; Callegary et al., 2007; Corwin et al., 2008; Werban et al., 2009; Zhu et al., 2010; Robinson et al., 2012; Callegary et al., 2012)."

Page 7, Line 25 to Page 8, Line 23:
"In the last decades, a number of sensors were developed for field measurements of ECa, based on the electromagnetic induction theory (Keller and Frischknecht, 1966). Technically, a transmitter and a receiver coil are placed on (or near) the soil surface at a fixed distance from each other, and the transmitter coil is energized with an alternating current. This generates a time-varying magnetic field, which induces electric fields in the soil, which in turn induce a secondary magnetic field. Such phenomena are described by Ampere's and Maxwell's laws. Both the primary and the secondary magnetic fields are sensed by the receiver coil and, under certain geometric conditions indicated as "low induction number" (McNeill, 1980; Callegary et al., 2007; Callegary et al., 2012), the ratio between the primary and the secondary magnetic field can be used to estimate the ECa of the volume of soil under investigation.
Generally, EMI systems consist of a transmitter and a receiver coil spaced s and operating at a certain frequency f. As s increases, the EM field propagates through a larger volume of soil. As f increases, the EM field is more attenuated and therefore penetrates less into the soil, reducing the volume of investigation. Transmitter and receiver coils are commonly adjusted in coplanar configuration. Vertical coplanar coils (VCP) generate a horizontal magnetic dipole orientation (HDP), whilst the horizontal coplanar coil configuration (HCP) generates a vertical magnetic dipole (VDP). The coil configuration has implications for the volume of investigation. McNeill (1980) provided the relative response versus depth for an EMI device in both HDP and VDP and the "cumulative response" for homogeneous and layered soils. According to that, the response of an EMI device in HDP has larger sensitivity close to the soil surface (or, more precisely, immediately below the coils), with monotonic decay with depth, whilst the VDP configuration provides maximum sensitivity to the depth of ca. 0.4·s (i.e., 40% of the intercoil spacing s). Additionally, the effective depth of exploration, defined as the

portion that contributes with 70% to the measured value of ECa, is 0.75·s for the HDP and 1.50·s for the VDP configuration.

For this study, s~~S~~oil ECa was measured using an EM38-DD device (*Geonics Ltd.*, Ontario, Canada), widely used for environmental studies hence severely tested under various conditions. The system is composed by two units mounted perpendicularly to each other, both consisting of a transmitter and a receiver coil ~~spaced~~ (s = 1 m~~.~~), which ~~This~~ allows simultaneous measurements of ECa over two depths for every measurement location. ~~The measured data for the two dipole configurations have a different sensitivity response. For the vertical dipole configuration (VDP), this results in a theoretical maximum sensitivity at the depth of ca. 0.40 m and a theoretical maximum investigation depth of ca. 1.50 m at the operating frequency (*f*) of 14.5 kHz. The sensitivity in the horizontal dipole configuration (HDP, *f* = 17 kHz) decreases with depth (i.e., maximum sensitivity to very shallow structures), with a theoretical maximum investigation depth of ca. 0.75 m (according to the cumulative sensitivity function by McNeill, 1980).~~ In VDP, given the operating frequency f = 14.5 kHz, the theoretical maximum sensitivity corresponds to the depth of ca. 0.40 m and the theoretical maximum investigation depth to ca. 1.50 m. In HDP (f = 17 kHz), the sensitivity of the device decreases with depth down to a theoretical maximum depth of investigation of ca. 0.75 m (McNeill, 1980)."

Reviewer's comment

"Page 3, Line 17. You write "…the sensitivity of any EMI sensor to soil ECa…". This is physically incorrect. ECa is a property of the device, not of the soil. There are multiple occasions of this error within the manuscript. I think you need to additionally use the bulk electrical conductivity at specific points in the manuscript."

Authors' response

We agree and thank the referee for pointing this out. The mistake was corrected throughout the manuscript, referring to "*measured ECa*" or to "*bulk soil electrical conductivity*" when appropriate.

Page 3, Line 25:
"… found that the sensitivity of any EMI sensor ~~to soil ECa~~ as well as the depth of investigation can differ significantly from those suggested by McNeil (1980)."

Furthermore, in Page 2, Line 10:
"… the dependence of the measured ECa on a number of parameters …"
Page 4, Line6:
"ECa measurements ~~is~~ are widely used in the context of precision agriculture …"
Page 6, Line 19:
"… might alter EC_w and effect the measured ECa."
Page 14, Line 29:

> "… EC$_w$ that is presumed to have contributed significantly to the ~~soil ECa~~ bulk soil electrical conductivity for the entire study area …"
>
> Page 17, Line 6:
>
> "… most of the soil properties that influence ~~ECa~~ bulk soil electrical conductivity exhibit co-dependency… "
>
> Page 17, Line 33:
>
> "… may be significant for ~~sites with~~ ~~higher ECa~~ more conductive soils …"
>
> Page 20, Lines 5-6:
>
> "… soil moisture is not the major control on ~~ECa~~ the bulk soil electrical conductivity measured with EMI …"
>
> Page 20, Lines 24-25:
>
> "… all properties and states which influence soil ~~ECa~~ bulk electrical conductivity …"

Reviewer's comment

"Page 3, Line 19. I am not sure that this is a "physico-chemical" measurement. Consider rewriting."

Authors' response

We believe that the statement *"… the final ECa reading of any EMI device is a complex physicochemical measurement …"* is correct as ECa responds to physicochemical properties in a nonlinear manner. However, it is probably incorrect to state that ECa is a physicochemical property; as we did later in the text (Page 18, Lines 16-18 of the discussion paper). We corrected that sentence.

> Page 19, Lines 25-27:
>
> "Our results apply to the Schäfertal site and to landscapes with similar soil characteristics (low conductive silty loam soils evolved on loess deposits are widespread over large areas of Central and Northern Europe) and call~~s~~ for proper interpretation of ECa, which ~~is a~~ respond to complex physicochemical ~~property~~ properties~~, due to the complex nature~~ of soil."

Reviewer's comment

"Page 3, Line 15-20. I am not so convinced that the discussion of Callegary et al. is really necessary here. Do you expect significant first-order effects here because of violation of the low-induction number approximation? Here I see some potential to shorten the introduction, which is not really focused and perhaps picks up too many threads at the same time."

Authors' response

We do not expect violation of the low-induction number approximation. However, we believe that the works of Callegary et al. (2007 and 2012) are important to illustrate a severe limitation of EMI measurements for direct estimation of any single property or state. We would like to keep this paragraph in its current form, as it anticipates an important concept that is picked up later in the discussion section. We shortened the introduction elsewhere.

Reviewer's comment

"Page 5, Line 13. You state "…specific attention to the physical principles controlling the EMI measurements…". However, it is not clear from the introduction what you mean with this. I would have expected that you wanted to focus on physical principles affecting soil bulk electrical conductivity after reading the introduction. Needs clarification."

    Authors' response

    We agree with the referee that this statement may be misleading and we changed it in order to clarify our intention.

> Page 5, Lines 20-22:
>
> "Findings of the studies summarized above show clearly the need for a more in-depth examination of the ECa-θ relationship for soils under field conditions, with specific attention to the ~~physical principles~~ suite of physicochemical properties and states controlling the EMI measurements."

Reviewer's comment

"Page 5, Line 30. You write "… with a sub-continental superimposed.". It is not clear to me what you mean with this. Please clarify."

    Authors' response

    Here, "*sub-continental superimposed*" refers to a specific meteorological phenomena that occurs in the Harz region. Such information is not necessary in the context of this paper, hence can be deleted.

> Page 6, Lines 8-9:
>
> "The catchment receives an average precipitation of 630 mm per year (of which a large fraction may be falling as snow, according to the annual winter conditions) and has an average annual air temperature of 6.9°C ~~with a subcontinental superimposed~~."

Reviewer's comment

"Page 6, line 25. Consider using two significant digits for the porosity values. I think this better reflects the measurement accuracy for this soil property."

    Authors' response

    We agree with the referee. We added the second significant digit.

> Page 7, Line 4:
>
> "Porosity was estimated using volumetric soil samples and ranged between 0.45 and 0.80."

Reviewer's comment

"Page 8, line 13. More quantitative information needs to be provided about this drift correction. Is the correction a function of time? How appropriate is the linear drift assumption? How strong is the correction as compared to the measured values?"

Authors' response

The drift was evaluated by plotting the ECa as a function of time and was as low as 1.14 mSm^{-1}, on average, among the 21 data sets. Linear functions were well able to correct for the small drift that we observed occasionally in the ECa data measured in the VDP configuration. More complicated models would have been necessary for correcting the less stable ECa data measured in the HDP configuration, thus we decided to exclude those data from our analysis. We improved the description of the processing in the revised manuscript.

> Page 9, Lines 13-18:
>
> "The measured crossing lines were used to identify and correct the drift: with the help of the interfaces of normal profiles and crossing-lines, a linear drift function was derived for ~~each~~ the data set~~s~~ which required this~~,~~ and used for drift correction. On average, the observed drift was as low as 1.14 mSm^{-1}. In this step, we assumed that ECa along the reference profile remains constant during the time of survey, i.e., ca. 45 min for the south-facing slope (STU 1 and STU 2 in Figure 1), ca. 15 min for the valley bottom (STU 3) and ca. 30 min for north-facing slope (STU 4), hence that the reference profile measured at the beginning and at the end of each of the surveys must show similar values of ECa."

Reviewer's comment

"Page 8, Line 24. Perhaps also state here that you will be using rank correlations later."

Authors' response

The sentence was changed.

> Page 9, Lines 22-23:
>
> "… on the analysis of differences in spatial patterns of θ and ECa identified using the Spearman rank correlation coefficient"

Reviewer's comment

"Page 8, Line 26. Also the corrections based on the reference transect should be discussed in more quantitative terms. How much shift was applied, and how does this relate to the mean measured ECa?"

Authors' response

The correction based on the reference profile measured at the beginning and at the end of each of the surveys was as low as 0.86 mSm^{-1}, on average, among the seven measurement dates. We added this information to the description of the processing. This step of the processing affected the mean measured ECa by 0.47 mSm^{-1} over a measurement range of 24 mSm^{-1}.

> Page 9, Lines 26-28:

> "ECa data measured along the reference profile ~~within~~ for the same day were plotted against time and, if necessary, field-data were corrected by applying a shift (on average as low as 0.86 mSm⁻¹) based on the mean ECa of the reference profiles. We tested that this did not produce artefacts in the spatial pattern of ECa."

Reviewer's comment

"Page 9, Line 8. Not sure that spatialization is the correct choice of word here. Why not interpolation or regionalization?"

    Authors' response

    The use of "spatialization" was changed to "interpolation".

> Page 10, Lines 6-9:
>
> "The fitting parameters were used to ~~spatialize~~ interpolate the data using block kriging with a cell size of 1 m. The choice of using linear variogram models was supported by the fact that, despite not all experimental variograms showed a linear behaviour at larger lag distances, linear behaviour is always given for the 1-m distance used later on for ~~spatialization~~ interpolation (data not shown)."

Reviewer's comment

"Page 9, Eq. 1. I am not convinced that this is the correct way to obtain the profile water content. I think the weights should add up to one, so a normalization is missing in the equation. Also, it may be a good idea to consider the measurement depths that the sensors represent. You mention that you associate layers to each sensor. Would it not be better to use layer depth instead of sensor depth here, and the associated cumulative sensitivity?"

    Authors' response

    We thank the referee for pointing out this mistake that we did not spot before. A normalization was included in the calculation, indeed, but not displayed by the formula. In the revised manuscript we wrote the correct formula and simplified its explanation. We did use the depth of soil moisture measurements instead of the soil layers depth because at the site the latter is not constant within the area covered by ECa interpolation, hence we tried to avoid this additional source of uncertainty.

> Page 10, Lines 20-26:
>
> ~~$$\theta_{d,CS} = \theta_1 \left[4\left(\frac{z_1}{5}\right) + 1\right]^{-1/2} + \theta_2 \left[4\left(\frac{z_2}{5}\right) + 1\right]^{-1/2} + \theta_3 \left[4\left(\frac{z_3}{5}\right) + 1\right]^{-1/2}$$~~
>
> $$\theta_{d,CS} = \sum_{i=1}^{n} \frac{\theta_n [CS(z_{i-1}) - CS(z_i)]}{\sum_{i=1}^{n} CS(z_i)}$$
>
> ~~where θ_1 and z_1 are the soil water content and measurement depth (i.e., 0.05 m) for the topsoil; θ_2 and z_2 are the soil water content and measurement depth (i.e., 0.25 m) for the intermediate soil horizon; θ_3 and z_3 are the soil water content and measurement~~

depth (i.e., 0.50 m) for the deep soil horizon; ~~s is the coil separation of the EMI device (i.e., 1.0 m).~~ where θ_n are the soil moisture measurements at the three depths of monitoring and $CS(z_i)$ refers to the cumulative sensitivity function of the EMI (McNeill, 1980).

Reviewer's comment

"Page 12, Line 5-7. I do not really agree with this statement here. What other factors do you want to blame? This should be immediately discussed when this statement is made. I guess the main point is that the soil water content and the pore water electrical conductivity co-vary in different manners for different landscape positions, but this point could be made in a clearer manner."

Authors' response

We agree with the referee. As we discussed the factors responsible for the ECa_e-θ_d relationship in the next paragraph, we can make this statement less vague and more concise.

> Page13, Lines 10-12:
>
> "Nevertheless, no unique correlation between ECa_e and θ_d could be identified for the complete time series which clearly shows that ~~observed stronger relationships on some measurement dates must be attributed to factors other than soil moisture and that~~ ECa_e cannot be used as a proxy for quantitative spatial soil moisture distribution at the investigated site."

Reviewer's comment

"Page 12. Line 8 onwards. I found the discussion presented here difficult to follow. What are you trying to say? It seems that you are building up towards an explanation of the different patterns derived from the rank stability, but you need to help the reader better here."

Authors' response

We thank the referee for this hint. Here we introduce the reader to the explanation of Figure 4 that we interpret in the next paragraphs based on the hydrological knowledge gained at the site. We clarified this in the revised manuscript.

> Page 13, Lines 13-21:
>
> "~~For most of the cases, measurement points within the same STU clustered within a limited region of the scatter plot to form point clouds, as highlighted by the different colours in Figure 4. This observation supports the concept of STUs, which may facilitate the interpretation of soil moisture and ECa dynamics along the field site. Therefore, useful~~ Deeper insights into the factors controlling the temporal dynamics of the ECa_e-θ_d relationship ~~are provided~~ can be gained by considering the relative position of the point clouds of the four STUs (represented with different colours in Figure 4)~~, which can be interpreted based on the knowledge of the factors controlling the soil moisture dynamics (gained with the hydrological monitoring as described in Martini et al., 2015) and ECa (from the basic principles already discussed)~~. The fact that measurement points

> within the same STU clustered within a limited region of the scatter plot illustrates the rather low within-STU variability of the soil bulk electrical conductivity at the site."

Reviewer's comment

"Page 14, Line 10. Soil texture is not a factor that affects bulk soil electrical conductivity directly. What physical process are you thinking of here? If it is porosity, can the results be improved when the soil saturation instead of the water content is used in Figure 4?"

> **Authors' response**
>
> We agree with the referee that soil texture does not affect directly ECa. Here we mean that the spatial pattern of ECa mirrors primarily the spatial heterogeneity of soil textural properties (i.e., more generally, to the soil spatial variability).

> Page 15, Lines 18-19:
> "The spatial pattern of ECa$_e$ (Table 2) appears to ~~represent~~ mirror primarily the spatial ~~variability~~ heterogeneity of soil ~~texture~~ textural properties, i.e. higher ECa for the valley bottom (STU 3) than for the slopes (STUs 1, 2 and 4)."

Reviewer's comment

"Page 14, Line 14. Here you state that spatio-temporal variations in ECw are of secondary importance. However, this seems to be in contrast with the previous text where different hydrological regimes are discussed. If ECa is primarily affected by static soil properties as suggested here, you should be able to find correlations that are persistent."

> **Authors' response**
>
> Following the response to the previous comment, in this sentence we conclude that temporal changes of ECw add to the signal from static soil properties (which remain the major control as stated at the beginning of the paragraph). We clarified this in the text.

> Page 15, Lines 22-24:
> "In summary, our observations suggest that static soil properties (such as texture, porosity and organic matter content) and~~, of secondary importance,~~ superimposed temporal variations of ECw, control the spatial pattern of ECa measured with EMI at our site."

Reviewer's comment

"Page 16, Line 15-25. A lot of words to say that it is likely not important for this site. I think that this can be shortened."

> **Authors' response**
>
> We thank the referee for this hint. We revised the paragraph to make it more concise.

> Page 17, Lines 20-34:

"In addition to that, important aspects to be considered in the interpretation of EMI-based ECa data~~,~~ are the volume of investigation of the EMI instrument and its spatial sensitivity. Callegary et al. (2007) found that the instrument vertical sensitivity varied significantly ~~with changes in ECa~~ both for homogeneous and heterogeneous soils~~,~~ although the general shape of all cumulative sensitivity distributions was similar to those predicted by McNeill (1980)~~. According to their results, the depth of investigation indicated by McNeill (1980)~~ , which holds true only for non-conductive soils~~,~~ and decreases with increasing ECa. ~~In particular, they reported deviations of 10% or more already at ECa of 3 mSm^{-1}, with depth of investigation reduced to 0.51·s and 0.80·s for the HDP and the VDP configurations, respectively, for the case of the most conductive soil they simulated.~~ In a more recent study (Callegary et al., 2012), the same authors simulated the distribution of the EM field in a 3D space, and found that the sensitivity pattern has a highly complex shape, including areas of negative contribution (i.e., conductive anomalies may contribute negatively to the instrument ECa reading)~~, and that the HDP- and VDP-volumes of investigation are not as different as assumed from previous studies, although depth-sensitivity functions are different~~. This implies that caution is required when the ECa data are to be used quantitatively, as the volume of soil sensed by the EMI device may change spatially and temporally. Such an effect may not be a severe limitation for the Schäfertal site, where ~~ECa~~ bulk soil electrical conductivity is low, but may be significant for ~~sites with~~ ~~higher ECa~~ more conductive soils or with more contrasting soil textures."

ANONYMOUS REFEREE #5

Reviewer's comment

(Page 2, Line 8) *"Explicitly addressing the parameters affecting ECa would help in understanding your difficulties in correlating soil moisture and ECa. In addition it would better introduce the explanations in lines 18-30 and give an overview of the parameters."*

> **Authors' response**
>
> We thank the referee for this recommendation. As in the next line we already start introducing the problem, we would prefer to keep this part of the text.

Reviewer's comment

(Page 2, Lines 21-22) *"You repeat this in the next line. As this sentence is already complex, you could cut "which in turn has the potential to increase the ECw"*

> **Authors' response**
>
> We thank the referee for this hint. The sentence was improved accordingly.

> Page 2, Lines 25-26:
>
> "A higher clay content and/or higher organic matter content usually correspond to a higher content of adsorbed water (i.e., higher θ), higher EC_s, and higher cation exchange capacity (CEC~~, which in turn has the potential to increase the EC$_w$~~), thus potentially leads to higher EC (e.g., Hudson, 1994; Dingman, 2002; Lal and Shukla, 2004; Roth, 2012)."

Reviewer's comment

(Page 6, Lines 29-31) *"You state 4 STUs but write only 1 in this sentence: either list all 4 types in this period and explain the positioning in the next one or merge this and the next sentence."*

> **Authors' response**
>
> We improved the text according to this comment.

> Page 7, Lines 7-11:
>
> "Four soil topographic units (STUs) were identified: silty loam Cambisols were found on the slopes (namely STU 1, STU 2 and STU 4), with little textural and morphological differences according to the topographic positions~~.; C~~characteristic hydromorphic features were identified in the valley bottom as indicators of distinct wet state of the loam and silty loam stagnic Gleysols (STU 3)~~. Here, in winter and spring seasons~~, where soils are frequently water saturated in winter and spring seasons."

Reviewer's comment

(Page 14, Line 31) *"Reading the relation STU-ECa in Figure 4 is not really immediate: a figure plotting the timeseries (different colors for different days) for every STU may be more helpful."*

Authors' response

We thank the referee for this comment. As discussed in the text, intrinsic limitations exist in the EMI measurement technique which may limit the comparability of absolute ECa values collected at different dates. Thus we did not attempt to interpret the temporal changes of ECa_e from one measurement date to the other, but rather we focus on the ECa_e-θ_d relationship for every single measurement date and depth of monitoring. For the same reason, we believe that plotting data collected on different dates in the same scatter plot may confuse the reader.

Reviewer's comment

(Page 17, Lines 23-24) *"correct this sentence."*

> **Authors' response**
>
> We corrected this typo.

> Page 18, Lines 31-32:
>
> "Soil spatial heterogeneity was found to be responsible for the nonstationariety of the relationship between electrical resistivity (ER) and θ in a heterogeneous ~~a~~ soil system."

Reviewer's comment

(Page 17, Lines 27-30) *"What about reformulating with: "A proper calibration of ECa for soil moisture monitoring would only be possible if the temporal variations of all other state variables that induce co-dependencies on ECa (such as temperature and ECw) could be determined and if the influence of the water content on ECa would be strong enough to make it measurable with EMI"*

> **Authors' response**
>
> We improved the sentence according to this useful suggestion.

> Page 19, Lines 2-6:
>
> "A proper calibration of ECa~~, suitable~~ for soil moisture monitoring would only be possible if the temporal variations of all other state variables that induce co-dependencies on ECa (such as temperature and EC_w) ~~would not change over time or their temporal changes~~ could be ~~measured~~ determined and if the influence of the water content on ECa would be strong enough to ~~significantly change ECa in a way that it is make it~~ measurable with EMI."

Reviewer's comment

(Page 19, Line 5) *"The effect is not simply additive, I would use "changes" instead of add."*

> **Authors' response**
>
> Correct. We improved this sentence.

> Page 20, Lines 13-14:

"… water infiltration and transport through the soil and dynamics of the groundwater from the catchment, modify EC_w and, in turn, ~~add to~~ change the signal from the stable pattern of soil properties …"

Repeated electromagnetic induction measurements for mapping soil moisture at the field scale: validation with data from a wireless soil moisture monitoring network

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Abstract

Electromagnetic induction (EMI) measurements are widely used for soil mapping, as they allow fast and relatively low-cost surveys of soil apparent electrical conductivity (ECa). Although the use of non-invasive EMI for imaging spatial soil properties is very attractive, the dependence of ECa on several factors challenges any interpretation with respect to individual soil properties or states such as soil moisture (θ). The major aim of this study was to further investigate the potential of repeated EMI measurements to map θ, with particular focus on the temporal variability of the spatial patterns of ECa and θ. To this end, we compared repeated EMI measurements with high-resolution θ data from a wireless soil moisture and soil temperature monitoring network for an extensively managed hillslope area for which soil properties and θ dynamics are known. For the investigated site, i) ECa showed small temporal variations whereas θ varied from very dry to almost saturation; ii) temporal changes of the spatial pattern of ECa differed from those of the spatial pattern of θ; and iii) the ECa-θ relationship varied with time. Results suggest that i) depending upon site characteristics, stable soil properties are can be the major control of ECa measured with EMI, and ii) for soils with low clay content, the influence of θ on ECa may be confounded by changes of the electrical conductivity of the soil solution θ itself has little influence on the measured ECa unless the electrical conductivity of the soil solution changes significantly. Further, our this study provides the opportunity to discusses the complex interplay between factors controlling ECa and θ, and the use of EMI-based ECa data with respect to hydrological applications.

1 Introduction

Electromagnetic induction (EMI) methods are widely used for soil mapping, as they allow fast and relatively low-cost surveys of soil apparent electrical conductivity (ECa) over areas up to several km^2 in size (McNeil, 1980). The main strength of the EMI method is that the induction principle does not require ~~a~~ direct contact with the ground. Consequently, a survey carried out using EMI sensors can be accomplished faster than an equivalent survey carried out with other instruments. Normally, surveys can be performed by a single operator, and a GPS receiver connected to the instrument allows collecting georeferenced ECa data. Measurements of ECa using EMI are in use since the 1970's, initially having been ~~developed~~ used for applications related to soil salinity. Since then, various environmental questions have been addressed using the EMI method, as discussed in the recent review of Doolittle and Brevik (2014). Although the use of non-invasive geophysical techniques for soil mapping is very attractive, the dependence of the measured ECa on a number of parameters complicates any interpretation to determine soil properties or states (Robinson et al., 2012). A firm understanding of the spatial and temporal variability of soil electrical conductivity (EC) and an appreciation for its highly complex interactions with static ~~and dynamic~~ soil properties and dynamic state variables, particularly at low-salt concentrations, is needed (Sudduth et al., 2001; Sudduth et al., 2005; McCutcheon et al., 2006), and it is helpful for understanding when EMI can be applied, as it is not applicable under all circumstances (Robinson et al., 2012).

The theory and basic principle of EMI ~~refers to the mechanistic soil EC model proposed by Rhoades et al. (1989)~~ are based on the soil equivalent resistance model (Sauer et al., 1955). Soil EC is assumed to arise from three conductance pathways through the soil: i) a conductance pathway traveling through a continuous soil solution, ii) a conductance pathway traveling through the solid particles, and iii) an alternating solid-liquid pathway (Rhoades et al., 1989). In this formulation, the total soil water content is separated into the fraction of water content in the fine pores (mostly adsorbed by the clay minerals, contributing to the alternating solid-liquid pathway) and the water content in the large pores (which contributes to the continuous liquid pathway). The soil EC is influenced by the volumetric water content (θ), the EC of the fractions of soil solution (EC_w), as well as by the volume of the solid particles and their EC (EC_s). As a consequence, several factors influence EC (Friedman, 2005). A higher clay content and/or higher organic matter content usually correspond to a higher content of adsorbed water (i.e., higher θ), higher EC_s, and higher cation exchange capacity (CEC~~, which in turn has the potential to increase the EC_w~~), thus potentially leads to higher EC (e.g., Hudson, 1994; Dingman, 2002; Lal and Shukla, 2004; Roth, 2012). Moreover, of particular importance is EC_w, which often increases with higher CEC~~,~~: as soil water interacts with the soil minerals (especially clay) and with soil organic matter (SOM), ions from the soil minerals can be released into the soil solution and, conversely, free ions can be adsorbed to equilibrate the mineral surface charges. In this respect, the initial EC of rain water~~,~~ and its residence time in the soil ~~and the mineralogical composition of the soil~~ may play a key role along with the mineralogical composition of the soil. Soil compaction affects EC due to the reduced porosity and increased soil particle-to-particle contact (Corwin et al., 2008; Brevik and Fenton, 2004). Soil temperature also affects EC, which increases approximately 1.9 % per degree centigrade (USDA, 1954; Corwin and Lesch, 2005). All these mechanisms

contribute to the complexity of EC and soil property relationships. Corwin et al. (2008) and Farahani et al. (2005) highlighted that the EC versus soil property functions are expected to be temporally variable unless EC_w and θ remain relatively unchanged, assuming EC_s to be stable at the temporal scale of observation.

5 ~~In the last decades, a number of sensors were developed for field measurements of ECa, based on the electromagnetic induction theory (Keller and Frischknecht, 1966). Technically, a transmitter and a receiver coil are placed on (or near) the soil surface at a fixed distance from each other, and the transmitter coil is energized with an alternating current. This generates a time-varying magnetic field, which induces electric fields in the soil, which in turn induce a secondary magnetic field. Such phenomena are described by Ampere's and Maxwell's laws. Both the primary and the secondary magnetic fields are sensed by the receiver coil and, under certain geometric conditions indicated as "low induction number" (McNeill, 1980;~~

10 ~~Callegary et al., 2007; Callegary et al., 2012), the ratio between the primary and the secondary magnetic field can be used to estimate the ECa of the volume of soil under investigation. As the final reading~~ The parameter measured by EMI sensors refers to a certain volume of soil material according to a complex depth-weighting, thus it is indicated as apparent electrical conductivity ECa. ~~Several factors influence the physical process described above. As the intercoil spacing s increases, the EM field propagates through a larger volume of soil. As the operating frequency increases, the EM field is more attenuated~~

15 ~~and therefore penetrates less into the soil, reducing the volume of investigation. Transmitter and receiver coils are commonly adjusted in coplanar configuration. Vertical coplanar coils (VCP) generate a horizontal magnetic dipole orientation (HDP), whilst the horizontal coplanar coil configuration (HCP) generates a vertical magnetic dipole (VDP). The coil configuration has implications for the volume of investigation. McNeill (1980) provided the relative response versus depth for an EMI device in both HDP and VDP and the "cumulative response" for homogeneous and layered soils. According to that, the~~

20 ~~response of an EMI device in HDP has larger sensitivity close to the soil surface (or, more precisely, immediately below the coils), with monotonic decay with depth, whilst the VDP configuration provides maximum sensitivity to the depth of ca. 0.4·s (i.e., 40% of the intercoil spacing). Additionally, the effective depth of exploration, defined as the portion that contributes with 70% to the measured value of ECa, is 0.75·s for the HDP and 1.50·s for the VDP configuration.~~ Callegary et al. (2007 and 2012) discussed ~~these concepts~~ this concept using a forward model of electromagnetic field propagation, and

25 found that the sensitivity of any EMI sensor ~~to soil ECa~~ as well as the depth of investigation can differ significantly from those suggested by McNeil (1980). Nevertheless, it appears clear that the final ECa reading of any EMI device is a complex physicochemical measurement which results from the propagation of the EM field within the volume of investigation and its interaction with stable and transient soil properties/states, and that the effective measurement depth and volume of investigation of an EMI sensor may vary at different times and locations (Sudduth et al., 2001; Corwin and Lesch, 2005;

30 Farahani et al., 2005; Callegary et al., 2007; Corwin et al., 2008; Werban et al., 2009; Zhu et al., 2010; Robinson et al., 2012; Callegary et al., 2012).

The fact that ECa measured with EMI responds to variations of several soil properties encouraged its use for a broad range of scopes. Examples of the application of EMI-based ECa measurements include soil salinity (e.g., Doolittle et al., 2001; Heilig et al., 2011), spatial pattern of soil texture (e.g., Abdu et al., 2008; Heil and Schmidhalter, 2012), lateral boundaries

between soil types (e.g., Anderson-Cook et al., 2002; James et al., 2003), depth to clay-rich layers (e.g., Saey et al., 2009; Doolittle at al., 1994), clay content (e.g., King et al., 2005; Weller et al., 2007), soil compaction (e.g., Al-Gaadi, 2012; Islam et al., 2014), soil CEC (e.g., Headley et al., 2004; Triantafilis et al., 2009), soil organic carbon (e.g., Martinez et al., 2009; Altdorff et al., 2016), assessment of soil quality (e.g., Johnson et al., 2001; Corwin and Lesch, 2005), detection of buried

5   services (e.g., Won and Huang, 2004; El-Quady et al., 2014), and mapping of active layer thickness in permafrost areas (e.g., Hauck and Kneisel, 2008; Dafflon et al., 2013). ECa measurements ~~is~~ are widely used in the context of precision agriculture for, e.g., refining existing soil maps (e.g., Doolittle et al., 2008; Martini et al., 2013), precision farming (e.g., Lück et al., 2009; Scudiero et al., 2015) and harvest zoning (e.g., Frogbrook and Oliver, 2007; Priori et al., 2013).

EMI has become widely used to determine soil water content or to study hydrological processes within the field of

10   hydrogeophysics (Binley et al., 2015; Huang et al., 2016; Huang et al., 2017). In a recent work, Calamita et al., (2015) listed 20 of the papers which address the use of EMI sensors for the determination of spatial and temporal patterns of θ. This summary provides a clear illustration of the differences among ECa-θ studies: estimation of θ was attempted for different soils and under varying climatic conditions, from the plot to the small catchment scale, with different temporal resolutions, and with different measurement schemes. The temporal resolution varied between one measurement date up to several days

15   or years. Soil water content was estimated with a variety of probes down to different depths of the soil profiles and sometimes total water storage down to a certain soil depth was inferred. However, discrepancies exist between the depth of soil moisture measurements and the theoretical investigation depth of the EMI sensor in use.

Because factors affecting ECa readings are complex and often interrelated, accurate interpretations have been a challenge (Zhu et al., 2010). In particular, the transient nature of soil water content and soil temperature was found to complicate the

20   characterization of ECa variability by altering its response to a given soil property during a given mapping event (McCutcheon et al., 2006), such that the spatial and temporal variance of θ explained by EMI-ECa data is strongly unstable (Calamita et al., 2015). Repeated EMI measurements at one site (which require accounting for temperature changes between different dates) allow inferring the dynamic component of the signal, based on the assumption that changes of ECa are related to changes in the volume of water in the soil pores and/or changes in the concentration of ions in the soil solutions.

25   Zhu et al. (2010) conducted repeated EMI measurements under varying moisture conditions on a 19.5 ha agricultural field in Central Pennsylvania, and found that the spatial pattern of standardized ECa remained relatively stable over time. In their study, the R^2 values between ECa and θ measured at different depths varied between 0.24 and 0.47. The authors argued that, because of the spatial ~~variability~~ heterogeneity of soil and hydrologic properties across the landscape, "the effect of soil moisture on ECa could have been masked by other variations of soil properties and terrain attributes". Soil ECa was strongly

30   influenced by soil moisture during wetter periods and at wetter locations, whilst other factors masked the effect of soil moisture on ECa variations during drier periods and at drier locations. They also remarked that the relationship between temporal variations of the soil ECa and soil water dynamics has not been thoroughly investigated for different soil moisture conditions and drying–wetting cycles, because simultaneous soil moisture measurements and EMI surveys were conducted only three times in this study.

Martinez et al. (2010) measured soil ECa during 13 occasions over three years in Vertisols to map temporal changes of the spatial pattern of θ. They used a principal component analysis to detect the main sources of variation of ECa, and found that the EM38-DD could successfully identify changes in soil properties due to tillage (i.e., changes of soil porosity) and formation of cracks within the soil profile. In fact, the first three components (90% of the ECa variability explained) were

5   related to soil spatial variability heterogeneity, soil management, and topography. Soil water dynamics reflected temporal variations of the above mentioned factors, and could therefore be identified only as a less important signal.

Robinson et al. (2012) conducted EMI measurements on 9 occasions within five months in a small forested catchment with contrasting soil textures. Similar to the finding of Western et al., 2003, they found that two distinct patterns are present in the ECa and modelled θ maps: in the wet state, the spatial pattern of ECa correlated well with the spatial pattern of clay content,

10   which, in turn, correlated well with θ, whilst the pattern in the dry state shows a smaller degree of organization and reasonable uniformity in θ across the catchment. They proposed a differencing approach to estimate θ from ECa, which improved the correlation from $R^2 = 0.28$ to $R^2 = 0.48$.

Recently, Shanahan et al. (2015) used repeated EMI measurements and electrical resistivity tomography to model soil EC, combined with laboratory estimates of gravimetric soil water content (θ_g), to investigate more specifically the effects of θ on

15   EC in soils with contrasting texture and under different wheat genotypes. They documented difficulties of relating soil EC to θ_g; in fact, they observed that the correlation between changes in soil EC and changes in θ_g varied with time and that the correlation was better for the investigated loamy sand soil than for the clay loam. The authors concluded that in soils where the effect of EC_w appears to be larger, "changes in bulk EC, measured by EMI, may be confounded by increased pore water conductivity and less closely associated with changes in θ_g".

20   Findings of the studies summarized above show clearly the need for a more in-depth examination of the ECa-θ relationship for soils under field conditions, with specific attention to the physical principles suite of physicochemical properties and states controlling the EMI measurements. The complexity of EMI data is too often ignored and the numerous issues related to the use of EMI for mapping of soil moisture are not always illustrated clearly. This may generate confusion due to the fact that proximal soil sensing techniques are used for a variety of scopes in several disciplines and there is a risk to interpret ECa

25   data beyond the limits of its applicability, resulting in misinterpretation.

This study aims to further investigate the potential of repeated EMI measurements with wide spatial coverage to capture field-scale soil water dynamics. To this end, we compare a time series of EMI measurements with high-resolution data from a wireless soil moisture and soil temperature monitoring network for a hillslope area in the Schäfertal catchment (Harz Mountains, Central Germany) for which spatial soil properties and soil moisture dynamics are known in detail. This gives us

30   the opportunity to discuss the complex interplay between factors controlling ECa and θ, and the use of EMI-based ECa data with respect to hydrological applications.

2 Material and methods

2.1 Site description

The study was carried out on a hillslope at the Schäfertal experimental site, a small headwater catchment (1.44 km^2) located in the Lower Harz Mountains, Central Germany (51°39'N, 11°03'E) (Borchardt, 1982; Reinstorf et al., 2010; Martini et al., 2015). The Schäfertal is a highly instrumented intensive research catchment within the TERENO "Harz/Central German Lowland Observatory" (Zacharias et al., 2011; Wollschläger et al., ~~in revision~~ 2017).

The catchment receives an average precipitation of 630 mm per year (of which a large fraction may be falling as snow, according to the annual winter conditions) and has an average annual air temperature of 6.9°C ~~with a subcontinental superimposed~~. The slopes of the Schäfertal catchment are formed by Devonian argillaceous shales and greywackes of the so-called Tanner Zone, which are covered by periglacial sediments (Borchardt, 1982). Cambisols and Luvisols are the dominant soil types on the slopes of the catchment, and Gleysols occupy the valley bottom (e.g., Ollesch et al., 2005). Interflow is known to play a relevant role within the runoff processes (Borchardt, 1982), and part of it can result in return flow. The slopes of the catchment are intensively used for agriculture, whilst meadow occupies the valley bottom (Schröter et al., 2015).

The hillslope site investigated for this study is a grassland transect beside the agricultural fields at the outlet of the catchment and consists of a north and a south exposed slope and a valley bottom where the creek Schäferbach lies (Figure 1). The spatial extent is ca. 250 m by 80 m. The detailed soil mapping for the Schäfertal hillslope site is described in Martini et al. (2015) and revealed low textural variations. The site is extensively managed, i.e. neither irrigation nor fertilizers are applied, which might alter EC_w and effect the measured ECa. Overall, the site characteristics (low textural ~~variability~~ heterogeneity, extensive land use) and the experimental setup of the Schäfertal hillslope site provide a rare opportunity to assess the suitability of repeated EMI surveys for mapping soil moisture at the field scale.

2.2 Hydropedological site characterization

Intensive investigation of the vadose zone water dynamics on the hillslope (Martini et al., 2015) was recently conducted with the aid of a wireless soil moisture and soil temperature monitoring network (*SoilNet*; Bogena et al., 2010). The positions of the 40 measurement nodes of the network (Figure 1) were determined by Weighted Latin Hypercube Sampling with Extremes (wecLHS, Schmidt et al., 2014) using information from geophysical surveys (EMI and gamma-ray spectroscopy) and topographic data. More detailed information can be found in Martini et al. (2015). For each of the network nodes, six sensors were permanently installed in the soil, with two repetitions at three depths (5, 25 and 50 cm), measuring soil moisture and soil temperature with hourly resolution. The sensors in use (*SPADE*, *sceme.de GmbH* i.G., Horn-Bad Meinberg, Germany; Hübner et al., 2009) are based on a ring oscillator. A sensor-specific seven-point-calibration in reference media with well-known dielectric permittivity (Kögler et al., 2013) was conducted to improve the θ measurement accuracy. Additionally, a sensor-specific calibration was performed for the soil temperature sensors. Volumetric soil

moisture content was estimated based on the CRIM formula according to Roth et al. (1990), where the dielectric permittivity of soil and air were assumed to be 4.6 and 1, respectively, and the dielectric permittivity of water was calculated based on the measured soil temperature (Kaatze, 2007). Porosity was estimated using volumetric soil samples and ranged between 0.45 and 0.80. More details can be found in Martini et al. (2015).

At each of the 40 sampling locations (Figure 1), the soil profile was described down to the depth of ca. 0.60 m (at the ridgetop, stoniness of the soil due to shallow bedrock limited the investigation to ca. 0.50 m), and the grain size distribution was determined for each node-position and each soil horizon. Four soil topographic units (STUs) were identified: silty loam Cambisols were found on the slopes (namely STU 1, STU 2 and STU 4), with little textural and morphological differences according to the topographic positions.; Ccharacteristic hydromorphic features were identified in the valley bottom as indicators of distinct wet state of the loam and silty loam stagnic Gleysols (STU 3). Here, in winter and spring seasons, where soils are frequently water saturated in winter and spring seasons. A summary of soil textural data relevant for the present work is provided in Table 1, additional details of the soil characteristics can be found in Martini et al. (2015).

The hydrological behaviour of the Schäfertal hillslope site was characterized by Martini et al. (2015) using the daily average soil moisture values for each measurement point of the monitoring network at the depths of 5, 25 and 50 cm ($\theta_{d,05}$, $\theta_{d,25}$ and $\theta_{d,50}$, respectively, also named topsoil, intermediate soil horizon and deep soil horizon, as they refer to three distinct soil layers). The monitoring period (from 15 September 2012 to 14 November 2013) comprises different states of soil moisture in response to varying atmospheric conditions (Figure 2). Soil moisture increased during the fall of 2012, when rainfall events were frequent and evapotranspiration (ET) decreased. The winter season was characterized by low precipitation (P) and low ET, followed by the spring season (April to June 2013), dominated by strong dynamics of soil moisture in response to increasing ET and extreme rainfalls up to 49 mm/d. Large areas of Central Europe were flooded at that time, and soils at the Schäfertal site were observed to be saturated in swales and depressions. During the summer period, ET exceeded P and the soil remained drier than the annual mean. The wetting transition started at the beginning of September 2013, with intense rainfalls and decreasing ET.

2.3 Repeated soil-ECa mapping

In the last decades, a number of sensors were developed for field measurements of ECa, based on the electromagnetic induction theory (Keller and Frischknecht, 1966). Technically, a transmitter and a receiver coil are placed on (or near) the soil surface at a fixed distance from each other, and the transmitter coil is energized with an alternating current. This generates a time-varying magnetic field, which induces electric fields in the soil, which in turn induce a secondary magnetic field. Such phenomena are described by Ampere's and Maxwell's laws. Both the primary and the secondary magnetic fields are sensed by the receiver coil and, under certain geometric conditions indicated as "low induction number" (McNeill, 1980; Callegary et al., 2007; Callegary et al., 2012), the ratio between the primary and the secondary magnetic field can be used to estimate the ECa of the volume of soil under investigation.

Generally, EMI systems consist of a transmitter and a receiver coil spaced *s* and operating at a certain frequency *f*. As *s* increases, the EM field propagates through a larger volume of soil. As *f* increases, the EM field is more attenuated and therefore penetrates less into the soil, reducing the volume of investigation. Transmitter and receiver coils are commonly adjusted in coplanar configuration. Vertical coplanar coils (VCP) generate a horizontal magnetic dipole orientation (HDP),

5 whilst the horizontal coplanar coil configuration (HCP) generates a vertical magnetic dipole (VDP). The coil configuration has implications for the volume of investigation. McNeill (1980) provided the relative response versus depth for an EMI device in both HDP and VDP and the "cumulative response" for homogeneous and layered soils. According to that, the response of an EMI device in HDP has larger sensitivity close to the soil surface (or, more precisely, immediately below the coils), with monotonic decay with depth, whilst the VDP configuration provides maximum sensitivity to the depth of ca.

10 $0.4 \cdot s$ (i.e., 40% of the intercoil spacing *s*). Additionally, the effective depth of exploration, defined as the portion that contributes with 70% to the measured value of ECa, is $0.75 \cdot s$ for the HDP and $1.50 \cdot s$ for the VDP configuration.

For this study, ~~s~~Soil ECa was measured using an EM38-DD device (*Geonics Ltd.*, Ontario, Canada), widely used for environmental studies hence severely tested under various conditions. The system is composed by two units mounted perpendicularly to each other, both consisting of a transmitter and a receiver coil ~~spaced~~ (*s* = 1 m~~.~~), which ~~This~~ allows

15 simultaneous measurements of ECa over two depths for every measurement location. ~~The measured data for the two dipole configurations have a different sensitivity response. For the vertical dipole configuration (VDP), this results in a theoretical maximum sensitivity at the depth of ca. 0.40 m and a theoretical maximum investigation depth of ca. 1.50 m at the operating frequency (*f*) of 14.5 kHz. The sensitivity in the horizontal dipole configuration (HDP, *f* = 17 kHz) decreases with depth (i.e., maximum sensitivity to very shallow structures), with a theoretical maximum investigation depth of ca. 0.75 m (according to~~

20 ~~the cumulative sensitivity function by McNeill, 1980).~~ In VDP, given the operating frequency *f* = 14.5 kHz, the theoretical maximum sensitivity corresponds to the depth of ca. 0.40 m and the theoretical maximum investigation depth to ca. 1.50 m. In HDP (*f* = 17 kHz), the sensitivity of the device decreases with depth down to a theoretical maximum depth of investigation of ca. 0.75 m (McNeill, 1980).

Surveys were conducted on seven measurement dates within the soil moisture monitoring period (Figure 2), with three

25 measurement dates (19 September, 18 October and 20 November 2012) during the wetting transition; two dates (18 April and 28 May 2013) during the dynamic spring period; and two dates (31 July and 29 August 2013) during the dry summer season. The surveys were conducted with the EMI device mounted on a sledge (made of wood and plastic, in order to avoid conductivity anomalies) at ca. 0.05 m above ground and pulled by one operator at constant walking speed. The study area was divided into three fields: northern slope (i.e., STUs 1 and 2), valley bottom (i.e., STU 3) and southern slope (i.e., STU

30 4), and each field was measured separately. A fixed location next to the study area (Figure 1), was used as calibration point for instrument nulling (McNeill, 1980) before each survey, and according to the recommendations of, e.g., Robinson et al. (2004), a warm-up period of at least 30 minutes was ensured before measurements were started. Before and after the surveys, ECa was measured along the reference profile (i.e., a fixed 40 m-transect, Figure 1) in order to assess and correct a possible drift in the data (e.g., Sudduth et al., 2001; Abraham et al., 2006). ECa was measured along survey lines spaced ca. 5 m with

a rate of 5 records/s, resulting in an approximate resolution of 0.2 m along the main direction. Towards the end of each of the surveys, crossing lines (Simpson et al. 2009) were measured in order to use the cross-over points for drift correction (CWA 16373, 2011; Delefortrie et al., 2014).

2.4 Processing and integration of time-lapse ECa measurements

5   Data collected using the HDP configuration showed strong noise. This caused critical problems in data processing and hindered a purposeful data interpretation. As the datasets of ECa measured in VDP did not show significant noise or drift, only those data were used for the present work.

Similar to Rudolph et al. (2016), data points located within a 2-m circular buffer area around each of the soil moisture monitoring network nodes were removed in order to exclude any possible data alteration induced by the magnetic
10   components of the network nodes. By plotting the measured ECa data over time, a limited number of additional outliers could be identified as isolated extreme and unrealistic values.

Data collected with EMI devices may be affected by drift due to instability of the calibration or to temperature changes (Robinson et al., 2004). The measured crossing lines were used to identify and correct the drift: with the help of the interfaces of normal profiles and crossing-lines, a linear drift function was derived for ~~each~~ the data sets which required this,
15   and used for drift correction. On average, the observed drift was as low as 1.14 mSm^{-1}. In this step, we assumed that ECa along the reference profile remains constant during the time of survey, i.e., ca. 45 min for the south-facing slope (STU 1 and STU 2 in Figure 1), ca. 15 min for the valley bottom (STU 3) and ca. 30 min for north-facing slope (STU 4), hence that the reference profile measured at the beginning and at the end of each of the surveys must show similar values of ECa.

Due to the sensor nulling performed prior to each survey, a small offset may occur between the data sets collected at
20   different measurement dates, e.g. because of differences in weather conditions which may affect the measurement signal (e.g., Triantafilis et al., 2000). For this reason, we refrain from comparing absolute values from different measurement dates in this study and concentrate i) on the analysis of differences in spatial patterns of θ and ECa identified using the Spearman rank correlation coefficient and ii) on differences in the relationship between ECa and θ for the individual measurement dates. By doing so, we are well able to discuss the data in terms of hydrological processes and do not attempt quantifying
25   temporal changes of θ from the EMI measurements, which would not be supported by the dataset.

ECa data measured along the reference profile ~~within~~ for the same day were plotted against time and, if necessary, field-data were corrected by applying a shift (on average as low as 0.86 mSm^{-1}) based on the mean ECa of the reference profiles. We tested that this did not produce artefacts in the spatial pattern of ECa. Based on the assumption that ECa along the reference profile does not vary within the duration of the measurement (i.e., a few hours), such procedure ensured the data collected
30   with different surveys within the same day to be quantitatively comparable. Measured ECa data were standardized to the reference temperature of 25 °C using the correction factors provided by USDA (1954). Three different reference soil temperatures were calculated (one for the valley bottom and one for each of the two slopes with opposite exposition) averaging all available temperature values measured hourly at the depths of 25 and 50 cm between 9 am and 4 pm on each

EMI measurement date (i.e., the time frame in which the surveys were carried out). Except for the topsoil, temperature variations within such time interval are negligible. Among the different measurement dates, the lowest soil temperature was recorded for the EMI survey in November 2012 (i.e., 4 °C on the south-exposed hillslope), and the highest in July 2013 (i.e., 19 °C in the valley bottom).

5 For each measurement date and for each independent dataset, the experimental variogram was calculated for the temperature corrected ECa and fitted using a linear model for comparability. The fitting parameters were used to ~~spatialize~~ interpolate the data using block kriging with a cell size of 1 m. The choice of using linear variogram models was supported by the fact that, despite not all experimental variograms showed a linear behaviour at larger lag distances, linear behaviour is always given for the 1-m distance used later on for ~~spatialization~~ interpolation (data not shown). Afterwards, for each measurement date,

10 the three data sets for the northern slope, the valley bottom, and the southern slope were aggregated, and ECa values of the kriging cell corresponding to the location of each network node were extracted for each measurement date, similar to Zhu et al. (2010). For the following analysis, extracted ECa values (ECa_e) for the seven measurement dates were used in combination with the daily averaged soil moisture (θ_d) at the depths of 5, 25 and 50 cm (based on the available hourly measurements between 9 am and 4 pm) at each single network node for the same measurement dates. As the two methods

15 refer to very different measurement volumes (i.e., integrated ECa values from EMI vs. local soil moisture estimation from the SPADE sensors which compose the monitoring network), an integrated soil moisture value ($\theta_{d,CS}$) was calculated for every measurement date and for every node of the monitoring network ~~based on the cumulative sensitivity function for horizontal coplanar orientation (McNeill, 1980)~~:

20 $$\theta_{d,CS} = \theta_1 \left[4\left(\frac{z_1}{s}\right) + 1 \right]^{-1/2} + \theta_2 \left[4\left(\frac{z_2}{s}\right) + 1 \right]^{-1/2} + \theta_3 \left[4\left(\frac{z_3}{s}\right) + 1 \right]^{-1/2}$$ (1)

$$\theta_{d,CS} = \sum_{i=1}^{n} \frac{\theta_n [CS(z_{i-1}) - CS(z_i)]}{\sum_{i=1}^{n} CS(z_i)}$$

~~where θ_1 and z_1 are the soil water content and measurement depth (i.e., 0.05 m) for the topsoil; θ_2 and z_2 are the soil water content and measurement depth (i.e., 0.25 m) for the intermediate soil horizon; θ_3 and z_3 are the soil water content and measurement depth (i.e., 0.50 m) for the deep soil horizon; s is the coil separation of the EMI device (i.e., 1.0 m).~~ where θ_n are the soil moisture measurements at the three depths of monitoring and $CS(z_i)$ refers to the cumulative sensitivity function of the EMI (McNeill, 1980).

25 Although this simple approach neglects vertical changes of soil properties within the soil profile (i.e., soil horizons which may affect the vertical distribution of θ), we assume that the integrated soil moisture values $\theta_{d,CS}$ provide representative information about the weighted θ within the volume of soil sensed by the EMI device.

2.5 Analysis of the temporal stability of soil moisture and ECa patterns

The Spearman rank correlation coefficient was used to investigate the temporal stability of the spatial pattern of ECa_e and θ_d over the seven dates of survey. This coefficient was proposed by Vachaud et al. (1985) as a measure of similarity between two data sets, based on the comparison of the rank of spatially distributed observations between two times, and is defined as:

$$r_s\,(j_1, j_2) = \frac{6\sum_{i=1}^{N}[R(i,j_1) - R(i,j_2)]^2}{(N_s - 1)Ns(N_s + 1)} \tag{2}$$

where N_s is the total number of spatial observation locations, $R(i,j_1)$ is the rank of the observation for the position i and for the time j_1, and $R(i,j_2)$ is the rank of the observation for the same position, but for the time j_2. The r_s coefficient ranges

10   between -1 and 1, and describes the statistical dependence between the two ranked variables: $rs = 1$ when there are no changes in the rank of the observations and decreases proportionally to the number of observations for which the rank varies and the number of position changed both toward a higher or lower rank. In other words, the Spearman rank correlation coefficient shows the qualitative similarity between spatially distributed observations.

3 Results and discussion

15   **3.1. Observed spatial patterns of ECa and soil moisture**

In contrast to results from other sites (Martinez et al., 2010; Robinson et al., 2012; Lausch et al., 2013; Martini et al., 2013), ECa measured on the Schäfertal hillslope was low ranging between 0 and 24 mSm^{-1} during the complete measurement period and showed a very small range of spatial variation, which we attribute predominantly to the small ~~variability~~ heterogeneity of soil texture. The range in ECa_e measured along the slopes varied between 7.6 mSm^{-1} in August 2013 and

20   11.8 mSm^{-1} in November 2013. This small range makes the interpretation of the dynamics in ECa challenging. Nevertheless, the low soil textural variation along the slopes provides the opportunity to evaluate the effect of soil moisture on the measured ECa without the need to account for significant influences of soil texture.

For the seven measurement dates, the overall spatial pattern of measured ECa as well as the extracted apparent electrical conductivity at the positions of the network nodes (ECa_e) showed highest values in the valley bottom (STU 3) and on the

25   footslope (STU 2), whereas the hillslopes (STU 1 and STU 4) showed lower values (Figure 3a-b). Similar spatial patterns were observed for soil moisture (Figure 3c-e) at the three depths of monitoring. Absolute values of measured ECa were lowest in September 2012, May and July 2013 and highest in October 2012, April and August 2013.

For the dates of the EMI surveys, the overall spatial distribution of soil moisture measured at the nodes of the monitoring network showed similar distributions (Figure 3c-e), with the lowest θ_d being measured in summit and backslope positions of

30   the south-exposed slope, and highest θ_d in the valley bottom. The topsoil's daily average moisture ($\theta_{d,05}$) exhibited the largest temporal variability, with overall hillslope minimum in September 2012 and July and August 2013 (i.e., 0.15, 0.16 and 0.10

m^{3}m^{-3}, respectively; Figure 2) and maximum in April and May 2013 (i.e., 0.41 and 0.43 m^{3}m^{-3}, respectively). Daily average soil moisture of the intermediate soil horizon ($\theta_{d,25}$) ranged between 0.17 (measured in August 2013) and 0.37 m^{3}m^{-3} (in April and May 2013). The deep soil horizon showed less variable daily average soil moisture ranging between 0.23 and 0.25 m^{3}m^{-3} except for the measurement dates of April and May 2013 ($\theta_{d,50}$ = 0.35 m^{3}m^{-3}).

5 The fact that, during the monitoring period, soil moisture values covered the complete annual range from very dry (in August 2013) to near-saturation (in May 2013), while little variations were observed in the range and absolute values of ECa for the different measurement dates gives a first, strong indication that, for the Schäfertal hillslope site, soil moisture has little influence on the measured ECa.

3.2 Temporal persistence of the spatial patterns

10 To further analyse the temporal persistence of the generally similar spatial patterns of ECa and soil moisture, the Spearman rank correlation coefficient (r_s) was used. To this end, we investigated the temporal persistence of the spatial pattern of ECa$_e$ as well as the temporal persistence of the spatial pattern of θ_d at the three depths of observation. The overall spatial pattern of ECa$_e$ exhibited a similar distribution for all measurement dates (higher values in the valley bottom, lower values on the slopes), whilst the spatial organization of the values within the site showed some differences. Two distinct spatial patterns

15 (Table 2, $r_s \geq 0.9$) of ECa$_e$ were highlighted: one being present in September, October and November 2012 and May 2013, and another one in April, July and August 2013.

The spatial pattern of soil moisture in the topsoil ($\theta_{d,05}$) showed low persistence with r_s decreasing proportionally to the time between two measurement dates (Table 3). The intermediate and deep soil horizons ($\theta_{d,25}$ and $\theta_{d,50}$; Tables 4 and 5) showed a similar evolution of the pattern, however, as expected, with higher persistence than observed for the topsoil moisture. Three

20 groups ($r_s \geq 0.9$) of spatial distribution could be identified: i) transition from dry to wet state (September, October and November 2012); ii) wet state (April and May 2013); and iii) dry state (July and August 2013).

The direct comparison of the spatial patterns of ECa$_e$ and θ_d showed a clear difference for all three measurement depths. This again supports the observation that, for the Schäfertal hillslope site, soil moisture has little influence on the measured ECa.

3.3 Correlation between ECa and soil moisture at the measurement node positions

25 Figure 4 shows the relationship between ECa$_e$ and θ_d for the different EMI measurement dates and depths of soil moisture monitoring. The plots in the bottom panels relate ECa$_e$ to the θ values calculated based on the cumulative sensitivity function ($\theta_{d,CS}$) proposed by McNeil (1980). As discussed earlier in the text, intrinsic limitations exist in the EMI measurement technique which may limit the comparability of absolute ECa values; thus we did not attempt to interpret the temporal changes of ECa$_e$ from one measurement date to the other, but rather we focus on the ECa$_e$-θ_d relationship for every single

30 measurement date and depth of monitoring which, however, provides useful hints about the strength and persistence of the relationship.

Taking a closer look at the ECa-θ relationship shown in Figure 4, the topsoil moisture ($\theta_{d,05}$) generally showed an overall poor correlation with ECa, with the exception of the survey in April 2013. Nevertheless, the EM38-DD in VDP has little sensitivity to shallow structures (Callegary et al., 2007, 2012; McNeil, 1980). For the depths of 25 and 50 cm, very poor correlation was found during the wetting transition (i.e., September, October and November 2012, with $p > 0.05$) and for May 2013. Better correlation was found for the measurements in April 2013 and in the dry state (July and August 2013). In particular, $R^2 > 0.50$ was found for the ECa_e-θ_d relationship for both the intermediate and the deep soil moisture measurements in April and July 2013, as well as for the 25 cm depth in August 2013. The same is well summarized by the ECa_e-$\theta_{d,CS}$ relationship, as expected. Overall, when the entire hillslope area is considered, ECa_e was observed to show some correlation with θ_d for only one of the two measurement dates in the wet state and on both measurement dates in the dry state. Nevertheless, no unique correlation between ECa_e and θ_d could be identified for the complete time series which clearly shows that ~~observed stronger relationships on some measurement dates must be attributed to factors other than soil moisture and that~~ ECa_e cannot be used as a proxy for quantitative spatial soil moisture distribution at the investigated site.

~~For most of the cases, measurement points within the same STU clustered within a limited region of the scatter plot to form point clouds, as highlighted by the different colours in Figure 4. This observation supports the concept of STUs, which may facilitate the interpretation of soil moisture and ECa dynamics along the field site. Therefore, useful~~ Deeper insights into the factors controlling the temporal dynamics of the ECa_e-θ_d relationship ~~are provided~~ can be gained by considering the relative position of the point clouds of the four STUs (represented with different colours in Figure 4)~~, which can be interpreted based on the knowledge of the factors controlling the soil moisture dynamics (gained with the hydrological monitoring as described in Martini et al., 2015) and ECa (from the basic principles already discussed)~~. The fact that measurement points within the same STU clustered within a limited region of the scatter plot illustrates the rather low within-STU variability of the soil bulk electrical conductivity at the site.

For some of the measurement dates, the point clouds of the different STUs occupied different positions relative to each other following changes of ECa and, especially, θ. A distinction, in terms of moisture content, can be observed (Figure 4) between the soils on the slopes (STU 1 and STU 4, south- and north-exposed, respectively, but with similar soil texture), which can be referred to differences of ET on the north and south exposed slopes leading to lower ET and higher soil moisture values for the north exposed STU4. Such an effect was evident at the beginning of the monitoring period (measurement date in September 2012) as the result of the summer period during which ET is presumed to have led to persistently different moisture values, which remained visible during the rest of the wetting transition (October and November 2012). Similarly, the two measurement dates in the dry season (July and August 2013) showed higher θ_d values for STU 4 than for STU 1 at all depths of measurement. ET is also presumed to have had important effects on the topsoil moisture in the valley bottom ($\theta_{d,05}$ blue dots in Figure 4), which has high porosity and remained rather dry in the summer period. This circumstance was inferred as favourable for the occurrence of preferential flow through the topsoil in the valley bottom (STU 3) at the end of the dry seasons in 2012 and 2013 (Martini et al., 2015). Higher θ_d compared to the slopes persisted in the valley bottom during the winter period, due to the combination of local soil properties (i.e. higher porosity), topographic position and

presence of a shallow groundwater table. In particular, the latter allowed the soil to reach saturation in the valley bottom, locally, according to the local topographic features. This is evident in Figure 4 for the measurement date in April 2013, represented by five network nodes (out of seven in STU 3, blue dots) which are now well separated from the rest of the data points showing soil moisture values as high as 0.72 m^3m^{-3}. At the same time, the groundwater-distant soils on the slopes

5 received water only from snowmelt and from rainfall. The flood event with strong rainfalls at the end of May 2013 is responsible for the overall high θ_d measured at the site. Large areas within the valley bottom were saturated due to shallow groundwater level, and patches of ponding water were observed; local emergence of return flow was observed at footslope positions within the catchment. In the summer period (measurement dates in July and August 2013 in Figure 4) ET plays an important role in conjunction with local soil properties. Thus, the different moisture content between the soils on opposite

10 slopes (STU 1 and 4) is visible, as well as the higher θ_d in the subsoil in the valley bottom (STU 3).

Based on this, the three distinct spatial patterns of soil moisture observed in Tables 3, 4 and 5 can be attributed to distinct factors: local soil properties and ET in the dry state (July and August 2013); local soil properties, topography and shallow groundwater table in the wet state (April and May 2013); and local soil properties, progressive reduction of ET and progressive rise of groundwater table in the valley bottom during the transition from dry to wet (September, October and

15 November 2012).

In a similar manner, the two distinct spatial patterns of ECa_e (Table 2) can be discussed referring to (Figure 4). Under dry soil conditions (July and August 2013), the higher ECa measured in the valley bottom (STU 3) compared to the slopes can be attributed to the presence of loam and silty loam stagnic Gleysols, with finer texture and high organic matter content. The silty loam Cambisols on the slopes (STU 1, 2 and 4) showed similar values of ECa in response to overall similar textural

20 characteristics. In April 2013, an important contribution to the high moisture content on the slopes came from snowmelt. Thus, a large volume of water within the volume of soil sensed by the EMI device was likely to have low EC_w leading to overall low ECa_e values being comparable to the dry state, when the pores were air-filled. Furthermore, the influence of more conductive water (from groundwater which drains the fertilized agricultural fields of the Schäfertal catchment) enhanced the higher ECa_e values for the valley bottom compared to the slopes. This is evident from the gap, in terms of

25 ECa_e, between the blue dots and all other points in Figure 4. As a consequence, the spatial pattern of ECa_e for the measurement date in April 2013 was substantially similar to the spatial pattern observed in the dry season (Table 2). This is not the case for the measurement date in May 2013, when there was no contribution of water from snowmelt. As a consequence, a higher concentration of ions in the soil solution can be assumed, causing a higher EC_w that is presumed to have contributed significantly to the ~~soil ECa~~ bulk soil electrical conductivity for the entire study area, with the effect of

30 masking the textural differences between the valley bottom and the slopes. Therefore, the spatial pattern of ECa_e for the measurement date in May 2013 did not reflect those of July, August and April 2013. Similarly, the spatial pattern of ECa_e during the wetting transition (September, October and November 2012) is presumed to reflect the contribution of water with different EC_w due to subsurface flow through the soil, where the solid matrix can be enriched with ions due to the process of evaporation and consequent precipitation of ions. Furthermore, the poor correlation between ECa_e and θ_d for the

measurement dates in May 2013 and during the wetting transition was determined by the facts that the soil in the valley bottom did not show significantly higher θ_d as compared to the soils on the slopes, as it occurred, instead, for the measurement dates in April, July and August 2013 (Figure 4). This can be explained with the lower θ_d in the topsoil and intermediate soil horizon ($\theta_{d,05}$ and $\theta_{d,25}$, respectively) for the valley bottom (Martini et al., 2015); and with the occurrence of

5   the flood event in May 2013, when the soil reached saturation in large portions of the entire Schäfertal catchment, locally with overland flow. Under such conditions, EC_w could be altered by the flushing of soil organic matter, nutrients and ions released from the solid matrix of the soil from the catchment. Another reason for the different ECa_e patterns observed (measurement dates in September, October, and November 2012 and May 2013, on one hand, and April, July and August 2013, on the other hand, Table 2) lies in the varying relative position of STU 1 and STU 4 along the x-axes (i.e., in terms of

10   ECa). Based on the interpretation discussed above, such differences can be attributed to the occurrence of different water infiltration and transport processes which may take place at different positions according to local soil properties and nonlocal factors such as topography and therefore influence the within-field variability EC_w. It is important to remark that measurements of EC_w are not available for the Schäfertal hillslope site with adequate spatial coverage. However, for the different states of soil moisture, distinct hydrological processes were described to take place at different locations within the

15   hillslope area and at different soil horizons. This knowledge based on high resolution monitoring of soil water content, combined with information on spatial ~~variability~~ heterogeneity of soil characteristics, enabled inferring spatial and temporal changes of variables (including EC_w) relevant for ECa data interpretation.

The spatial pattern of ECa_e (Table 2) appears to ~~represent~~ mirror primarily the spatial ~~variability~~ heterogeneity of soil ~~texture~~ textural properties, i.e. higher ECa for the valley bottom (STU 3) than for the slopes (STUs 1, 2 and 4). The occurrence of

20   different hydrological processes (e.g., water infiltration and transport through the vadose zone as well as dynamics of the groundwater level) which take place at different positions along the slope can modify EC_w differently and, in turn, induce small changes in the ECa pattern. In summary, our observations suggest that static soil properties (such as texture, porosity and organic matter content) and~~, of secondary importance,~~ superimposed temporal variations of EC_w, control the spatial pattern of ECa measured with EMI at our site. Soil moisture itself has only a minor effect on ECa, although it is clear that it

25   acts as the carrying agent for transporting the ions leading to EC_w. Given the proven site-specific nature of EMI applied to soil studies and the relatively strong correlations that have been recorded between soil water content and ECa at some other locations, it seems important to acknowledge that this statement is not necessarily valid at all sites. However, the strength of the relationship between ECa and soil moisture can only be evaluated if data measured during different hydrological states are available. This is also obvious from our data since it must be considered that if EMI surveys would have been conducted

30   only on measurement dates in April, July and August 2013, ECa would have been interpreted as a reasonable proxy for θ (Figure 4), which clearly shows the importance of time-series data for proper interpretation of EMI. It is evident from Figure 4 that the range of ECa remained ~~relatively~~ rather constant for the seven measurement dates although θ varied significantly. The variability of ECa within a single STU was rather small, especially for the soils on the slopes, and the ECa_e-θ_d relationship in Figure 4 is controlled by the relative position of the STUs-clusters. As a consequence, the correlations

between ECa_e and θ_d may become more evident when applied to a site with more contrasting soil properties: for instance, if only STU 1 and STU 3 would be considered, for the Schäfertal hillslope site, rather high R^2 values would be found, simply because the two soils show constantly lower ECa_e and lower θ_d, and consistently higher ECa_e and higher θ_d, respectively. In contrast, if soils with similar texture would be considered (e.g., only the soils on the slopes, excluding the STU 3), no correlation would be found between ECa_e and θ_d throughout the monitoring period, because there are no clear differences in ECa_e among STUs 1, 2 and 4 (Figure 4), and because changes of θ_d do not affect ECa_e, unless they are responsible for significant variations of EC_w. But the latter effect in turn would lead to comparable changes on both slopes.

4 Using EMI for mapping soil moisture and implications for soil mapping

It is widely acknowledged that EMI surveys offer the potential to map the soil spatial variability over large areas within relatively short time, non-invasively and with high spatial resolution (e.g., Doolittle and Brevik, 2014). This makes EMI methods an important aid for optimizing the number of soil samples required to generate a soil map, and for the numerous applications which require detailed soil maps. Results of this study show the importance of repeated surveys in order to capture the dynamics of the spatial pattern of ECa. This, combined with a sound interpretation of the factors controlling such dynamics, allows obtaining the most reliable information from the ECa maps. With respect to that, EMI-based ECa maps can certainly be important supports for hydrological studies, as repeated EMI surveys at one site provide the opportunity to identify stable patterns of soil ECa controlled by the spatial ~~variability~~ heterogeneity of soil properties, which in turn have important effects on the soil water dynamics.

Similar to our findings, Zhu et al., 2010 observed that "wetter sites were generally distributed in the areas with lower elevations, gentler slopes, and depressional landscape positions. These areas also corresponded to a shallower water table and deeper depth to bedrock. These observations suggest that soil ECa is more soil moisture dependent in wetter landscape positions than in drier positions". For the Schäfertal site, the increase in soil EC can be related to two different reasons i) to the wetting of the shallower sections of the soil profile with higher clay content and higher organic matter content (peat soils of the valley bottom) which leads to a release of adsorbed ions from the mineral and organic surfaces and thus releases ions to the soil solution or ii) to the flushing of the valley bottom by groundwater with higher electrical conductivity which also would lead to an increase in soil ECa .

The observed temporal variations of the ECa_e-θ_d relationship showed clearly that soil moisture at the Schäfertal site is not the major control on the measured ECa values, and temporal changes of the ECa pattern are to a large extent unrelated to changes of soil moisture. For EMI measurements conducted at different dates and for different moisture conditions, Farahani et al. (2005) found that higher θ does not necessarily correspond to higher ECa values, which is in good agreement with our observations. Furthermore, Zhu et al. (2010) described that the wetness condition was not the only factor influencing the spatial variability of ECa at their site, and that terrain and soil properties masked the effects of soil moisture on ECa during dry periods, whereas soil ECa was strongly influenced by θ during wetter periods and at wetter locations. Shanahan et al.

(2015) found different ECa-θ relationships between a sandy clay loam and a loamy sand, but for both, soil EC decreased with depth, although gravimetric soil water content at depth was higher than or similar to that at the surface.

Referring to the soil equivalent resistance model (Rhoades et al., 1989) on the physical principle behind the ECa measurements, Corwin et al. (2008) discussed the complexity of ECa measurements as being influenced by any soil property

5 or state that influences electrical conductance pathways in soils, and explained that most of the soil properties that influence ~~ECa~~ bulk soil electrical conductivity exhibit co-dependency and thus provide overlapping information on ECa. Furthermore, our data clearly show that the relationship between ECa and a given soil property or state is time-of-measurement dependent, which results from the dynamic nature of e.g. groundwater levels, soil water content and concentration of pore water solution which influence the electrical conductance pathway. This is also confirmed by field data presented in Farahani et al. (2005),

10 and the authors argued that the relationship that they observed between ECa and θ can be partially explained by the dependency of θ on stable soil properties, such as clay content. Furthermore, they showed that such behaviour may produce the effect of magnifying the relationship between ECa and a given soil property at certain times. In the same direction, our results show clearly the difficulties of simply relating ECa to θ. The ~~low variability~~ little differences of soil texture and the rather low clay content at the Schäfertal hillslope site are responsible for the small range of measured ECa.

15 Corwin et al., 2008 observed that, at sites where dynamic variables (e.g., salinity) dominate the ECa measurement, temporal changes in spatial patterns exhibit more fluidity than systems that are dominated by static properties (e.g., soil texture). Other studies (Zhu et al., 2010; Robinson et al., 2012; Calamita et al., 2015) observed larger spatial variability of soil ECa during the wetter periods and stronger correlation of ECa with clay and topography patterns, and poor spatial organization under dry conditions, supporting the concept of preferred soil moisture states as described in Grayson et al. (1997).

20 In addition to that, important aspects to be considered in the interpretation of EMI-based ECa data~~,~~ are the volume of investigation of the EMI instrument and its spatial sensitivity. Callegary et al. (2007) found that the instrument vertical sensitivity varied significantly ~~with changes in ECa~~ both for homogeneous and heterogeneous soils~~,~~ although the general shape of all cumulative sensitivity distributions was similar to those predicted by McNeill (1980)~~. According to their results, the depth of investigation indicated by McNeill (1980)~~ , which holds true only for non-conductive soils~~,~~ and decreases with

25 increasing ECa. ~~In particular, they reported deviations of 10% or more already at ECa of 3 mSm⁻¹, with depth of investigation reduced to 0.51·s and 0.80·s for the HDP and the VDP configurations, respectively, for the case of the most conductive soil they simulated.~~ In a more recent study (Callegary et al., 2012), the same authors simulated the distribution of the EM field in a 3D space, and found that the sensitivity pattern has a highly complex shape, including areas of negative contribution (i.e., conductive anomalies may contribute negatively to the instrument ECa reading)~~, and that the HDP and~~

30 ~~VDP volumes of investigation are not as different as assumed from previous studies, although depth sensitivity functions are different~~. This implies that caution is required when the ECa data are to be used quantitatively, as the volume of soil sensed by the EMI device may change spatially and temporally. Such an effect may not be a severe limitation for the Schäfertal site, where ~~ECa~~ bulk soil electrical conductivity is low, but may be significant for ~~sites with~~ ~~higher ECa~~ more conductive soils or with more contrasting soil textures.

Given the complexity of the EM field propagation through natural soils (hence, with a certain degree of heterogeneity) any quantitative interpretation of ECa data (e.g. for estimating θ or solute concentration) is difficult to prove with field data from EMI measurements only. In fact, for every point in space where EMI measurements are conducted, measured ECa resembles the bulk conductivities of all sources contributing to ECa. These are EC_s, and EC_w for the actual volume of investigation of

5   the EMI sensor, which changes according to variations in the electrical conductivity profile. The water itself does not contribute to the soil EC. However, it is the carrying agent for ions released into the pore water, and it is responsible for the thickness of water films around the minerals which themselves control the mobility of ions therein and, consequently affect soil EC (Friedman, 2005).

Interdisciplinary combination of expertise and the use of well-constrained numerical models can certainly improve our
10   ability to extract reliable information from EMI-based ECa datasets. This is not trivial, and involves the fields of pedology, hydrology, soil physics, soil chemistry, and geophysics, as it must account for the propagation of the EM field through the heterogeneous soil material, where complex interactions between stable soil properties and transient state variables take place and are spatially and temporally dynamic. Furthermore, such models need to be trained with time series of highly resolved spatial data.

15   Benefits to the use of EMI-based ECa data may arise from the use of multiconfiguration EMI systems and calibration procedures, as they allow collecting ECa data from multiple depths at the same time. Following the original work of Lavoué et al. (2010) and its further improvement by Mester et al. (2011), recent studies (e.g., Von Hebel et al., 2014; Shanahan et al., 2015) promoted the calibration of ECa, collected using multiconfiguration EMI, based on inverted electrical resistivity tomography (ERT) data. This is probably the most advanced approach available nowadays for calibrating EMI
20   measurements collected at different points in space and in time. Nevertheless, the reliability of this calibration procedure appears still limited due to a number of fundamental issues which are not solved yet. Among others, a major source of uncertainty is due to the fact that the solution of ERT inversion is non-unique (e.g., Keller and Frischknecht, 1966; Koefoed, 1979; Sharma and Kaikkonen, 1999; Dafflon et al., 2013). Consequently, the risk exists to adjust the EMI-based ECa data to soil EC profiles which do not match reality, and little control is offered about the uncertainties. Furthermore, existing
25   calibration approaches rely on the standard vertical sensitivity function of EMI (McNeill, 1980), which is only valid for homogeneous and nonconductive soils and not easily applicable to natural soils, as clearly illustrated by the works of Callegary et al. (2007 and 2012). However, even if all issues would be solved, multi-depth calibrated ECa data from ERT inversion can provide depth-resolved information on soil electrical conductivity, only. The separation of soil moisture from all the other properties and states that influence the EMI measurement will still remain a challenge. In a recent study, Michot
30   et al. (2016) illustrated some of the issues related to the use of ERT for soil moisture estimation. Soil spatial heterogeneity was found to be responsible for the nonstationariety of the relationship between electrical resistivity (ER) and θ in a heterogeneous a soil system. Moreover, the authors argued that changes of ER were probably related to changes of EC_w (controlled by soil-plants interactions and infiltration processes), as θ remained unchanged.

As soil and consequently also water and solute dynamics are spatially heterogeneous, ideally it would be required to calibrate every single measurement point within a study site for each measurement date. A proper calibration of ECa~~,~~ ~~suitable~~ for soil moisture monitoring would only be possible if the temporal variations of all other state variables that induce co-dependencies on ECa (such as temperature and EC_w) ~~would not change over time or their temporal changes~~ could be

5 ~~measured~~ determined and if the influence of the water content on ECa would be strong enough to ~~significantly change ECa~~ ~~in a way that it is~~ make it measurable with EMI. This would be an enormous effort and to our knowledge there are no published works which attempted such an ambitious site characterization. We consider the dataset presented in this study as one of the most complete with respect to EMI-θ studies; nevertheless, this is still not adequate to provide data suitable for proper calibration of ECa.

10 Similar difficulties exist for multi-frequency EMI sensors. Tromp-van Meerveld and McDonnell (2009) could not resolve the θ depth profile using an EMI sensor comprising six frequencies, which provided similar responses for six different frequencies although the distribution of θ with depth was non-uniform due to rain events. The study of Calamita et al. (2015) showed similar limitations, and the authors highlighted that a number of factors can make the interpretation of ECa data with respect to θ challenging, and that the use of the EMI method for hydrological applications can be better understood when

15 considering the effects of EC_w and clay minerals.

Shanahan et al. (2015) remarked that in ECa-θ studies it is commonly assumed that a change in soil EC is simply due to a change in the volume of the fluid. Nevertheless their study showed that, under certain circumstances, changes in EMI-based ECa may be confounded by increased EC_w and less closely associated with changes in θ. Cassiani et al. (2015) remarked the need for more consideration for EC_w, which may play an important role. Our study confirms this, at least for the case of low

20 conductive soils, and shows that the large changes of θ at the Schäfertal site have negligible effects on the measured ECa. Different results may be found for different soil types. In fact, larger ECa response to changes in θ was observed for clay-rich soils (e.g., Martinez et al., 2010; Robinson et al., 2012; Shanahan et al., 2015). Good relationships between ECa and soil moisture may be achieved locally and for certain soil conditions, triggered by co-dependencies between most of the properties and states that influence ECa.

25 Our results apply to the Schäfertal site and to landscapes with similar soil characteristics (low conductive silty loam soils evolved on loess deposits are widespread over large areas of Central and Northern Europe) and call~~s~~ for proper interpretation of ECa, which ~~is a~~ respond to complex physicochemical ~~property~~ properties~~, due to the complex nature~~ of soil. To this end, an interdisciplinary approach combining pedological and hydrological expertise with solid understanding of the (geo)physical principles underlying the EMI method may certainly improve the results of future studies.

30 **5 Summary and conclusions**

Repeated EMI surveys were conducted on a hillslope site within the Schäfertal catchment, of which soil properties and soil moisture dynamics were known. Soil ECa was mapped on seven dates with different soil moisture states, comprising dry,

wet and transition from dry to wet. This allowed investigating the effects of θ on the measured ECa under field conditions and provided the opportunity to discuss the physical principles behind EMI measurements of ECa.

Although the range of θ variations was very large throughout the monitoring period, ECa showed a very small range of variation. Temporal changes in spatial patterns of ECa were found to differ from temporal changes in spatial patterns of θ.

5   The observations discussed in the present work support the conclusion that soil moisture is not the major control on ~~ECa~~ the bulk soil electrical conductivity measured with EMI, which is, indeed, controlled by a number of soil properties and states with a variable and time-varying relative contribution. It is worth remarking that time series data have the potential to reveal the limits of applicability of the EMI method with respect to the specific site conditions and to avoid overinterpretation of geophysical proxies.

10   Comparing repeated EMI measurements with high-resolution monitoring of soil water dynamics in the vadose zone allowed us to identify two distinct spatial patterns of ECa; the one representing the actual ~~spatial variability~~ heterogeneity of soil properties, i.e., under dry conditions (July and August 2013) or when EC_w was presumably low (April 2013); the other, when different processes, such as water infiltration and transport through the soil and dynamics of the groundwater from the catchment, modify EC_w and, in turn, ~~add to~~ change the signal from the stable pattern of soil properties (e.g., in September,

15   October and November 2012 and May 2013). Furthermore, our observations suggest that for soils with low clay content, θ itself has little influence on the measured ECa unless the electrical conductivity of the soil solution changes significantly.

The combination of repeated EMI measurements and distributed soil moisture monitoring at one site enabled us to provide a process based interpretation of the relationship between ECa measured with EMI and soil moisture, beyond the limits which we might be subject to if only one method would be available.

20   Experimental evidences and data interpretation provided with this research promote a careful use of the EMI method for any environmental application. Time-lapse measurements of ECa conducted with multiconfiguration EMI can enable to capture the spatial variation (including depth information) of soil properties as well as the temporal dynamics of the variables involved. Data sets with these characteristics, inverted based on well-calibrated physically based numerical models that are able to represent the spatial and temporal patterns of, ideally, all properties and states which influence soil ~~ECa~~ bulk

25   electrical conductivity, can certainly improve our ability to extract reliable information on environmental variables of interest that can be used quantitatively. However, this may not be feasible for all sites, as it requires large technical efforts and combined expertise in different fields of research. In such cases, repeated EMI mapping can still provide the opportunity to map noninvasively the soil ~~spatial variability~~ heterogeneity of the site, which makes EMI an important aid for any environmental research.

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Tables and captions

15 Table 1 – Soil texture (median values) of the Schäfertal hillslope site for the topsoil (ca. 0-15 cm) and for the subsoil (ca. 15-60 cm). More detailed information can be found in Martini et al. (2015).

Soil		% Clay	% Silt	% Sand
STU 1	topsoil	17	69	14
	subsoil	15	67	18
STU 2	topsoil	16	78	7
	subsoil	15	79	6
STU 3	topsoil	25	67	10
	subsoil	14	55	28
STU 4	topsoil	15	77	9
	subsoil	13	76	12

Table 2 - Spearman rank correlation coefficients (r_s) between spatial patterns of ECa_e. Values of $r_s \geq 0.9$ are highlighted in bold.

	Sep 2012	Oct 2012	Nov 2012	Apr 2013	May 2013	Jul 2013	Aug 2013
Sep 2012	**1**						
Oct 2012	**0.94**	**1**					
Nov 2012	**0.98**	**0.96**	**1**				
Apr 2013	0.54	0.66	0.60	**1**			
May 2013	**0.95**	**0.94**	**0.93**	0.59	**1**		

Jul 2013	0.55	0.66	0.59	**0.97**	0.58	**1**
Aug 2013	0.55	0.67	0.61	**0.96**	0.58	**0.98**	1

Table 3 - Spearman rank correlation coefficients (r_s) between spatial patterns of soil moisture ($\theta_{d,05}$) in the topsoil. Values of $r_s \geq 0.9$ are highlighted in bold.

	Sep 2012	Oct 2012	Nov 2012	Apr 2013	May 2013	Jul 2013	Aug 2013
Sep 2012	**1**						
Oct 2012	0.85	**1**					
Nov 2012	0.84	**0.95**	**1**				
Apr 2013	0.80	0.73	0.79	**1**			
May 2013	0.73	0.66	0.74	**0.99**	**1**		
Jul 2013	0.67	0.63	0.61	0.67	0.65	**1**	
Aug 2013	0.62	0.54	0.56	0.70	0.70	0.83	**1**

5   Table 4 - Spearman rank correlation coefficients (r_s) between spatial patterns of soil moisture ($\theta_{d,25}$) in the intermediate soil horizon. Values of $r_s \geq 0.9$ are highlighted in bold.

	Sep 2012	Oct 2012	Nov 2012	Apr 2013	May 2013	Jul 2013	Aug 2013
Sep 2012	**1**						
Oct 2012	**0.97**	**1**					
Nov 2012	**0.95**	**0.99**	**1**				
Apr 2013	0.81	0.81	0.81	**1**			
May 2013	0.80	0.80	0.80	**0.99**	**1**		
Jul 2013	0.86	0.88	0.82	0.80	0.80	**1**	
Aug 2013	0.87	0.88	0.83	0.76	0.76	**0.99**	**1**

Table 5 - Spearman rank correlation coefficients (r_s) between spatial patterns of soil moisture ($\theta_{d,50}$) in the deep soil horizon. Values of $r_s \geq 0.9$ are highlighted in bold.

	Sep 2012	Oct 2012	Nov 2012	Apr 2013	May 2013	Jul 2013	Aug 2013
Sep 2012	**1**						
Oct 2012	**0.99**	**1**					
Nov 2012	**0.96**	**0.98**	**1**				
Apr 2013	0.68	0.63	0.65	**1**			
May 2013	0.75	0.73	0.74	**0.97**	**1**		

| Jul 2013 | 0.63 | 0.82 | 0.63 | 0.72 | 0.69 | **1** | |
| Aug 2013 | 0.67 | 0.84 | 0.65 | 0.69 | 0.64 | **0.96** | **1** |

Figures captions
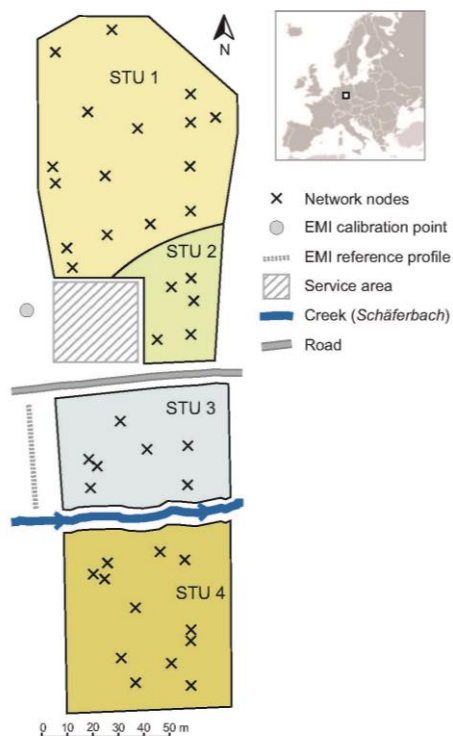
Figure 1- Schematic map of the Schäfertal hillslope site (Martini et al., 2015, modified): the position of the 40 nodes of the wireless soil moisture and soil temperature monitoring network is indicated, as well as the spatial extent of the four soil topographic units (STUs). EMI calibration point (grey dot) and reference profile (dashed line) are indicated in the eastern part of the hillslope.
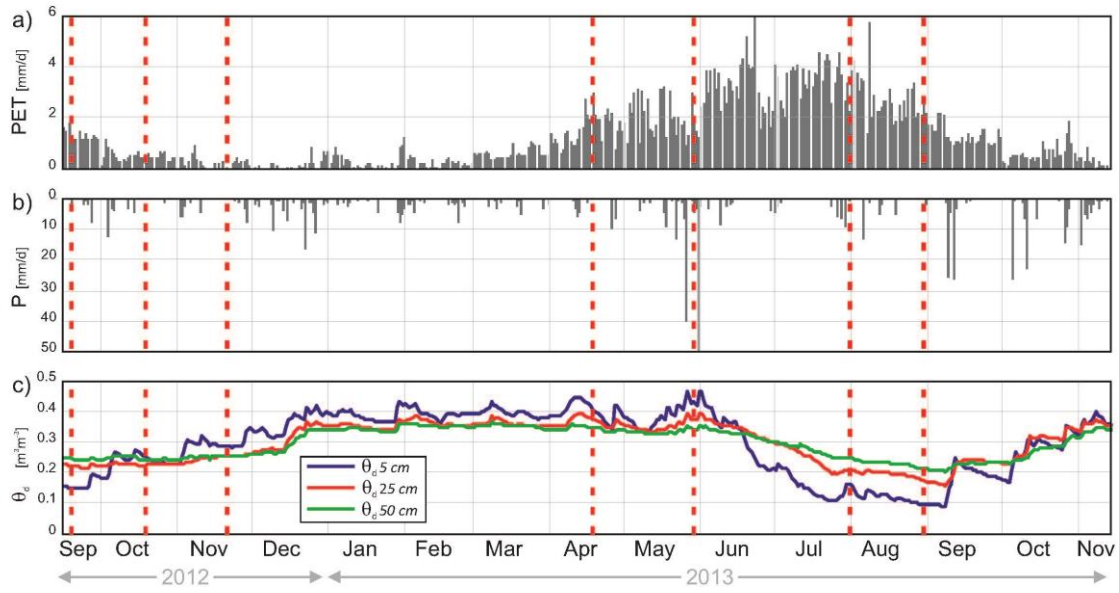
Figure 2 - Time series of a) daily potential evapotranspiration (PET), b) daily cumulative precipitation (P) and c) daily average soil moisture at the three depths of observation ($\theta_{d,05}$, $\theta_{d,25}$ and $\theta_{d,50}$, respectively). Vertical dotted lines indicate the dates of the EMI measurements: 19-Sep-2012, 18-Oct-2012, 20-Nov-2012, 18-Apr-2013, 28-May-2013, 31-Jul-2013 and 29-Aug-2013 (Martini et al., 2015, modified).
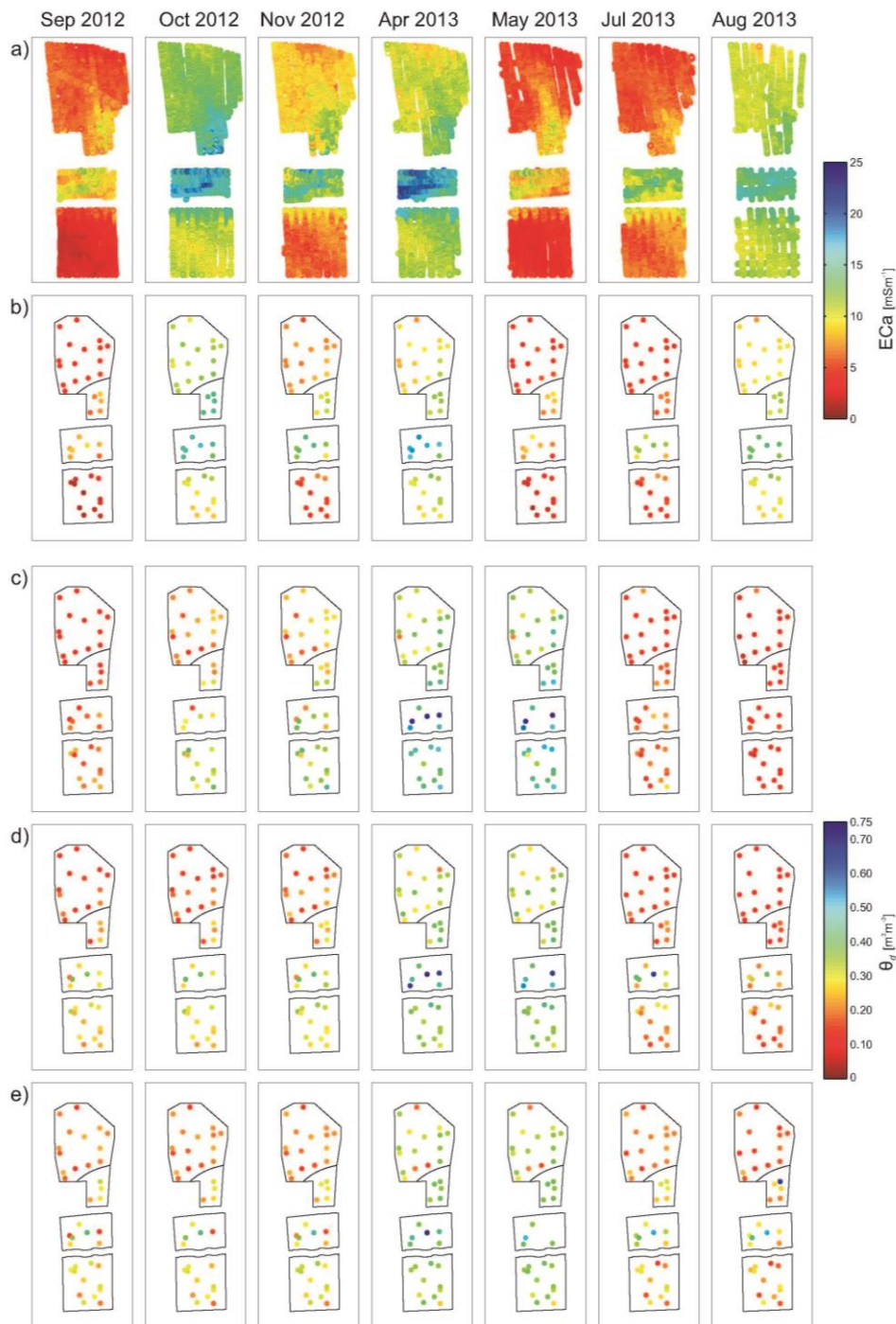
Figure 3- Spatial maps of a) measured ECa (after processing); b) extracted apparent electrical conductivity (ECa$_e$) for the positions of the 40 nodes of the soil moisture monitoring network; c) daily mean soil moisture at 5 cm ($\theta_{d,05}$); d) daily mean soil moisture at 25 cm ($\theta_{d,25}$); e) daily mean soil moisture at 50 cm ($\theta_{d,50}$).
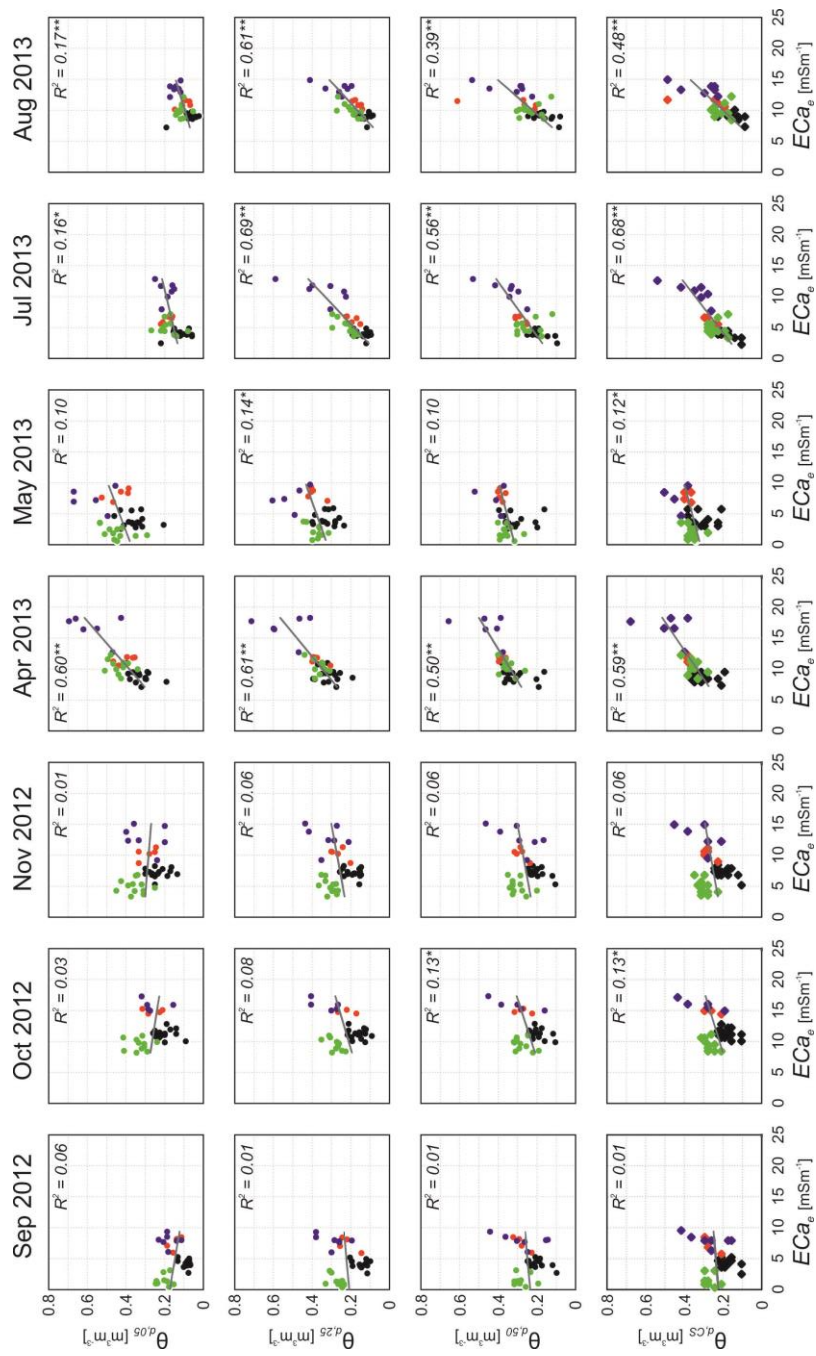
Figure 4 - Linear regression between ECa_e and θ_d for every EMI measurement date and every depth of soil moisture monitoring ($\theta_{d,05}$, $\theta_{d,25}$ and $\theta_{d,50}$, respectively), as well as for the integrated soil moisture calculated using the cumulative sensitivity function ($\theta_{d,CS}$). The different colours represent measurement points located within: STU 1 – black dots; STU 2 – red dots; STU 3 – blue dots; and STU 4 – green dots. Regression coefficients R^2 are indicated (; asterisks refer to the significance levels $p < 0.05$ and $p < 0.01$ are indicated as * and **, respectively).