

# A novel geophysical method to monitor ultra-shallow reservoirs: mapping of soil moisture content in subsiding peatlands to forecast drought effects and CO<sub>2</sub> emissions

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## Abstract

Managed peatland deterioration by microbial oxidation is a worldwide process that leads to the gradual disappearance of these highly organic and fertile soils. Peat oxidation is often the result of aerated top soils by artificially kept low groundwater levels, which enhances aerobic microbial breakdown of organic carbon. This process leads to both subsidence and large quantities of CO<sub>2</sub> emissions. Furthermore, artificially drained peatlands are vulnerable to salinisation when proximal to coastlines, and fires when situated in dry and warm climatic zones.

The decrease of the soil moisture content (SMC) and groundwater level (GL) during drought episodes can cause both subsidence and accelerated CO<sub>2</sub> emissions, both of which are big issues in the Netherlands. Severe drought results in salinisation of groundwater and greenhouse gas emissions by oxidising peat, and therefore is a societal burden to the Netherlands and worldwide. Furthermore, in coastal lowlands drought accelerates subsidence, leading to relative sea-level rise.

Both SMC and GL are proven to be mappable using geophysical methods. Multi-coil offset Electro-Magnetic Induction (EMI) has high potential to map peat properties for managed peatlands from apparent electrical conductivity (ECa). Studies show that by using EMI, it is possible to obtain ECa for different depth intervals, which are used to estimate soil organic carbon. Furthermore, EMI has a long application history of non-invasive SMC mapping, although obtained ECa also depends on other factors, such as variations in soil composition, density, and pore water conductivity ( $\sigma_w$ ).

TNO and SoilMasters, an expert EM company, employ a mobile electromagnetic mapping system to recover the soil moisture content, a crucial ingredient in these issues. These innovative Electro Magnetic Induction (EMI) measurements of the soil moisture content are used in combination with geodetic and CO<sub>2</sub> measurements to forecast subsidence and CO<sub>2</sub> emissions.

We present a time-lapse pilot study for SMC and GL employing EMI in a managed peatland in the central peat-rich delta plain of the Netherlands, near the city of Gouda. Furthermore, we use

soil moisture probe and GL measurements at fixed point locations to confront the obtained ECa. We also link the obtained calibrated soil moisture maps to observed subsidence, and CO<sub>2</sub> NEE (Net Ecosystem Exchange) flux. The resulting highly correlated measurements and observations can be well explained by precipitation and drought patterns. This makes our findings good proxies for spatio-temporal prediction of subsidence and CO<sub>2</sub> emissions for dry and wet spells by monitoring measurements of EMI.

## Introduction

Recently, elongated periods of drought in the Netherlands, particular challenges for vegetation on higher sandy soils. The peat areas in the western Netherlands also suffer from drought and low groundwater tables, which leads to peat oxidation and consequently to accelerated CO<sub>2</sub> emissions and subsidence (Boonman et al., 2022). Also, sea- and river-dykes that are less cohesive start to leak saline and fresh water in undesired locations via quells and ‘piping’. Additionally, urban infrastructure faces problems like sink holes and wash-outs due to the drought. Recent examples of structure collapses include quay collapses in the city of Amsterdam and observed peat subsidence and CO<sub>2</sub> emissions at the city of Gouda. Waterboards, agricultural areas, cities, building/construction companies and home-owners all require stable ground without subsidence, instability and salinisation problems.

The Netherlands has substantial acreage of peatlands as seen in Figure 1a. In northwestern Europe, peatlands are expected to become more susceptible to deterioration as climate models predict increased periods of extreme droughts (Figure 1b). For example, the managed peat areas in the Netherlands endured a rainfall deficit of 250 to 350 mm in the drought of spring and summer 2018, causing local phreatic groundwater levels to drop 150 to 200 mm below the average lowest phreatic groundwater level of the summer of 2017 (Sluijter et al., 2018). This increases the depth at which aerobic microbial organisms potentially could peat, and consequently increases CO<sub>2</sub> emissions and subsidence during periods of drought (Figure 2a).

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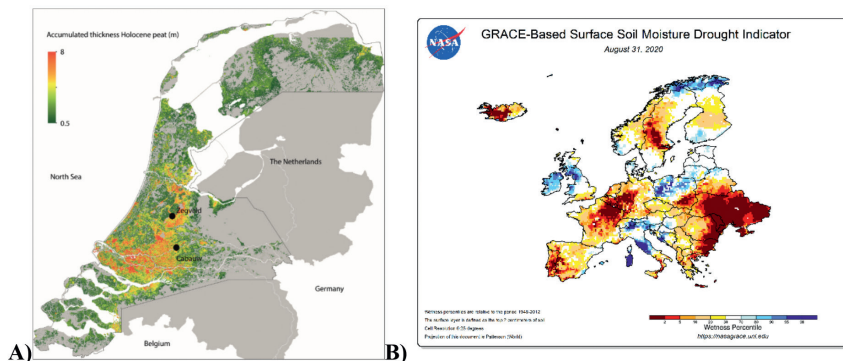
Peat oxidation is dependent on several soil properties, such as soil moisture content (SMC) and temperature. Atmospheric-controlled high soil temperature is the main driving force of oxidation processes at the top of peat soil layers. Whereas in the lower part of the unsaturated zone soil moisture is an important driver of oxidation, as soil temperature tends to decrease with increasing depth (Kechavarzi et al., 2010). Furthermore, changing elevation of the phreatic groundwater level (GL) controls the vertical interval of the oxidation prone unsaturated zone, making this an essential property for understanding local peat oxidation and consequently subsidence and salinisation (Figure 2b).

Key factors controlling the negative effect of drought on CO<sub>2</sub> emissions, subsidence and salinisation are (1) the soil moisture content (SMC) and (2) the groundwater table, also known as groundwater level (GL) or phreatic water level (FL). The Dutch national groundwater table modelling system accurately captures the fluctuations in groundwater level in dry periods. However, the understanding of soil moisture content in the layers above the groundwater table is less comprehensive, particularly regarding the spatial distribution of soil moisture. Consequently the forecasting of subsidence and CO<sub>2</sub> emissions is difficult. We introduce cross-domain technology to address this issue by using an Electro-Magnetic Induction (EMI) mapping system supported by InSAR, GPS, in-situ probes, CO<sub>2</sub> flux data and improved prior shallow geological models. Shallow EMI is a high-resolution version of this for ultra-shallow application (Altdorff et al., 2016). InSAR derived displacement estimates result in a millimetre-scale resolution of surface movement timelapse measurements. The combination of land-based and airborne EMI with InSAR enables the surveying of huge patches of land in short time.

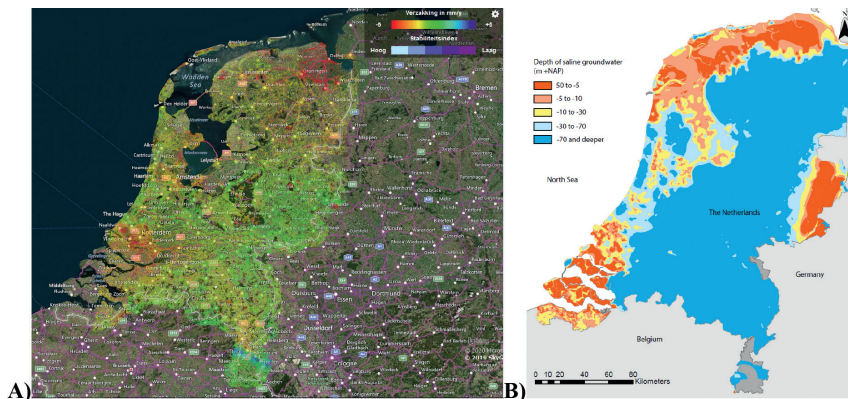
The aim of this project is to monitor ultra-shallow Dutch reservoirs by time-lapse EMI mapping of groundwater level and soil moisture content at a pilot peat area in western Netherlands and to couple these new geophysical measurements into predictive models in order to forecast and possibly mitigate CO<sub>2</sub> emissions and subsidence.

Key takeaway points in this study are:

- Severe drought results in salinisation of groundwater and greenhouse gas emissions by oxidising peat, and therefore is a societal burden.
- Drought accelerates subsidence, leading to relative sea-level rise.
- Peat areas in the western Netherlands suffer from drought and low groundwater tables, leading to peat oxidation CO<sub>2</sub> emissions and subsidence.
- Urban infrastructure faces problems like sink holes and wash-outs due to the drought.
- Key effects of drought on CO<sub>2</sub> emissions, subsidence and salinisation are: (1) soil moisture content (SMC) and (2) groundwater level (GL).
- Soil moisture content SMC in the layers above the groundwater level GL is not well known, knowledge of the spatial extent of soil moisture falls short.
- Consequently the physics-based forecasting of subsidence, salinisation and CO<sub>2</sub> emissions is difficult.
- Cross-domain TNO technology is used for this problem by using an Electro-Magnetic Induction (EMI) mapping system, InSAR, GPS, CO<sub>2</sub> data and geological models.
- We have mapped time-lapse groundwater level GL and soil moisture content SMC in a pilot peat area, coupling geophysical measurements with predictive models to forecast and possibly mitigate CO<sub>2</sub> emissions, subsidence.

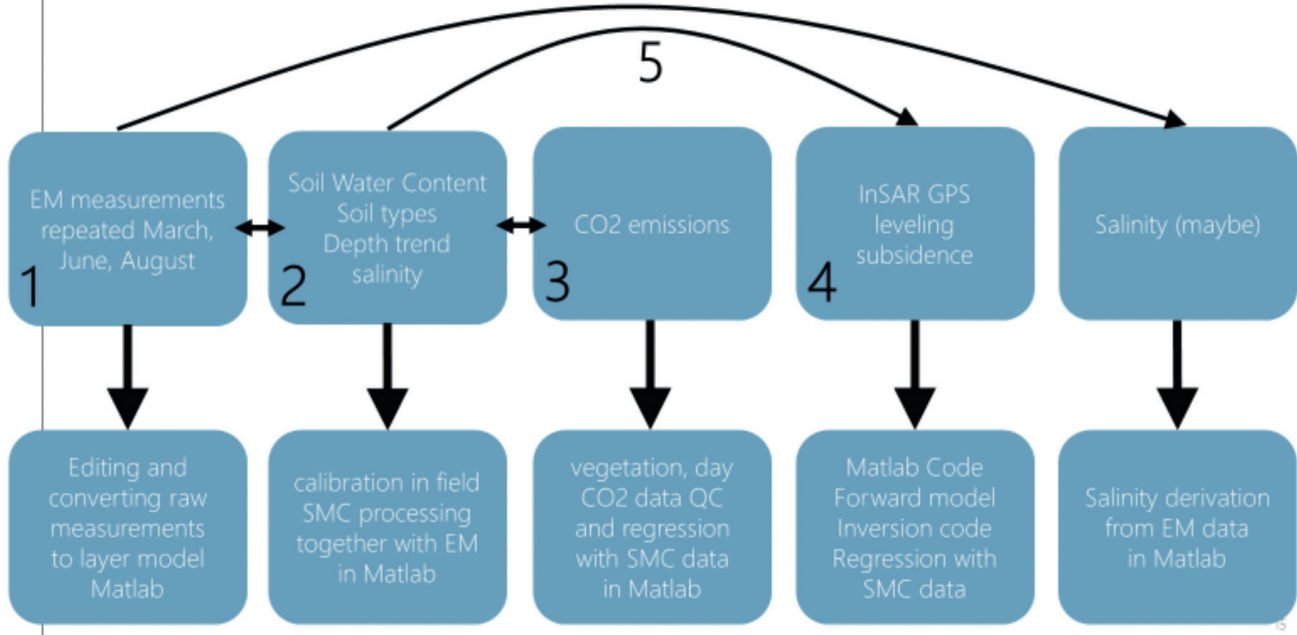


**Figure 1** a) Accumulated thickness of Holocene peat distributed over the Netherlands (after Koster et al., 2020), and the locations of the Zegveld and Cabauw sites. b) Map of Surface Soil Moisture Drought indicator by inference on NASA GRACE satellite data (<https://nasagrace.unl.edu/>). The drought situation is displayed for Europe in the record hot year of 2020.



**Figure 2** a) Map of Bodemdalings Kaart Nederland provided by Skygeo in 2021 on <https://bodemdalingskaart.portal.skygeo.com/portal/bodemdalingskaart/u2/viewers/basic/>. b) Map of salinisation in the Netherlands in 2021 from <http://www.grondwatertools.nl>.

## WORKFLOW PREDICTIVE MODEL SUBSIDENCE AND CO2



**Figure 3** Schematic of the workflow and software tools for the predictive model for subsidence and CO2 emission due to drought.

### Method

In this study we develop a workflow with the following steps (Figure 3):

- Derive soil moisture content and groundwater level from time-lapse EMI and probe in-situ data using empirical relations, initially from literature and models, subsequently from pilot site field data
- Collect the time-lapse measurements EMI, InSAR, GPS, probes with in-situ SMC and GL, CO2 flux at a pilot site
- Calibrate predictive model of subsidence and CO2 emissions with geophysical measurements and to groundwater models and improved shallow geologic models
- Generalise the model such that land-based and airborne EMI, InSAR and GPS systems can forecast subsidence and CO2 emissions at desired locations on a feasible continuous, on-demand basis.
- Achieve a pilot on the target site of peat land in the western Netherlands, where ground-truth is available through existing monitor-wells

To run and validate this workflow, in 2021 we have conducted three time-lapse EMI field experiments (Figure 4) on the Zegveld peat observatory site (Figure 1a) and one at a test field in Cabauw (Figure 5, Figure 1a) to ascertain the correlation to SMC and GL. To capture as much as possible variations in soil moisture content the three field experiments were conducted in different seasons (spring – March, summer – June, autumn – September 2021). In the end, too much interference by electromagnetic devices that are permanently present at the Cabauw test field (Figure 5) for other monitoring studies resulted in the abandonment of this location after the March measurement campaign. We continued with the Zegveld pilot site (Figure 1a).

The EMI field data is subsequently confronted with monitoring data that was previously collected for different studies (Boon-



**Figure 4** Field measurements of EMI at Cabauw site.

man et al., 2022): InSAR (Sentinel-1), probe-based in-situ soil moisture content (Royal Dutch Meteorological Institute (KNMI) at Cabauw, National Research Programme on Greenhouse Gas Dynamics in Peatlands and Organic soils (NOBV) at Zegveld), and CO2 flux (KNMI at Cabauw, NOBV at Zegveld). These datasets are used in data assimilation and calibration procedures to predict soil moisture content.

We will estimate soil moisture content (SMC) over a large area employing electromagnetic induction methods (EMI). We now provide some background on EMI methods, their calibration and their relation to soil moisture.

EMI methods are well established and do not require major research. Over the past decades EMI has been explored as a tool in ‘precision agriculture’ or ‘site specific management’. The prime parameter in EMI is often the so-called apparent conductivity (ECa). ECa can sometime be interpreted in a more specific layer of electrical conductivity (ECI). Various studies were performed to study the relation between ECa and other soil parameters, such





Figure 5 Field layout at Cabauw site.

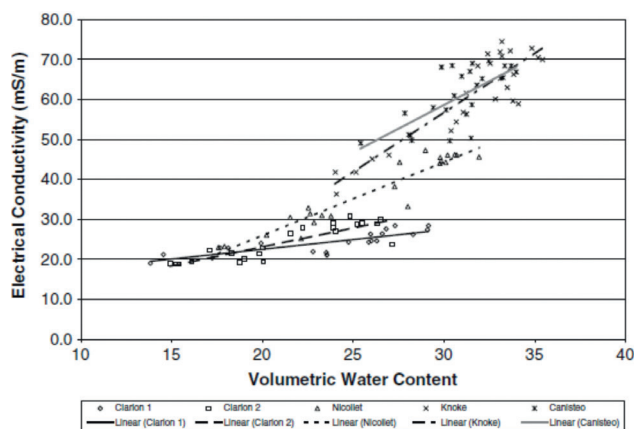


Figure 6 Relation between EC and volumetric water content, also known as soil moisture content, for various soil types (after Brevik, Fenton and Lazzari, 2006).

as SMC, but also soil texture, pH, organic matter content, which on their turn are interrelated. ECa generally correlates well with SMC in previous studies that were performed over rather varying conditions regarding soil and climate. Within the framework of this project the correlation between SMC and ECa or ECI must be confirmed (Figure 6) for typical Dutch conditions by a field test. For this, probe in-situ calibration measurements are also necessary and will be used at the sites Cabauw and Zegveld (Figure 1a, Figure 5).

The EMI methods generally use a transmitter loop and a receiver loop that receives a voltage that is induced from the transmitter loop plus the currents induced in the subsurface. Generally horizontal loop and vertical loop configurations are used. Each configuration has a specific weighting function that shows which part of the subsurface contributes to the total signal. By employing different loop configurations and different separations between source and receiver different parts of the subsurface are scanned. The more data points per location the better the subsurface model can be derived.

It is possible to calculate a simple layered model (ECI) for each measured location if multi offset and multi configuration

data is present (see e.g. De Smedt et al. 2013). The layered model allows more advanced estimation of SMC with depth, compared to the use of the ECa. The validation results show that to derive reasonably accurate regression models for predicting SMC from EMI measurements for field scale mapping of SMC, site specific calibration is required (Badewa et al. 2018). An example of the relation between ECa (Vertical Dipole) and SMC for five soil types (Iowa, USA) is shown in Figure 6 (taken from Brevik, Fenton and Lazzari, 2006).

## Results

We found that in-situ located SMC point measurements after calibration correlate well to the average ECa conductivities at those locations during the three timelapses. A solid empirical relation could be established between SMC and ECa allowing for spatial prediction of SMC on the Zegveld field into plausible maps (Figures 6, 7).

As seen in Figure 7, it was found at the Zegveld site that both SMC and ECa followed intimately the behaviour of precipitation and GL. The usual pattern arose that a short- or long-term precipitation event would take place, then with short delay the GL would rise and after more delay the SMC and ECa would rise. For a drought the opposite effect occurred with the same delays: first a period without precipitation, then GL drops, and subsequently the SMC and ECa. This is a helpful insight that enables us to not only spatially predict SMC from ECa, but also to make assessments of how the SMC will react after wet and dry period.

At Cabauw, we have observed strong indications that subsidence from InSAR is also closely related to the SMC and GL in the upper 0.5 of soil and causative precipitation events. Figure 8 demonstrates that subsidence or in general surface displacement estimates derived from InSAR (black curve) are seen to correlate well to calibrated SMC (red band) at the Cabauw site. The relation of InSAR displacements to coinciding precipitation is weaker, possibly due to the delay factor.

At Cabauw, we have also observed strong indications that net CO<sub>2</sub> emission is closely related to the SMC and GL in the upper 0.5 m of the soil and causative precipitation events (Figure 9). The analysis of net CO<sub>2</sub> emission is a delicate procedure, involving much use of statistics and calibration to separate the biomass intake, seasonal trends, atmospheric factors like wind etc. In this study, we could do only a crude estimation of the net CO<sub>2</sub> emission at the Cabauw site in 2020 using running average models on the raw data. Yet, these running averages do show a convincing delayed relation between precipitation, GL and SMC, similar to what we found at the Zegveld site from our ECa-SMC analysis. At Cabauw, net CO<sub>2</sub> emission increases with a delay after the start of a drought and decreases again with delay after a wet season commences. This is a promising result that translates the calibration at Cabauw to the Zegveld site and that allows for EMI data to be a proxy for subsidence and net CO<sub>2</sub> emission through soil moisture content SMC and groundwater level GL.

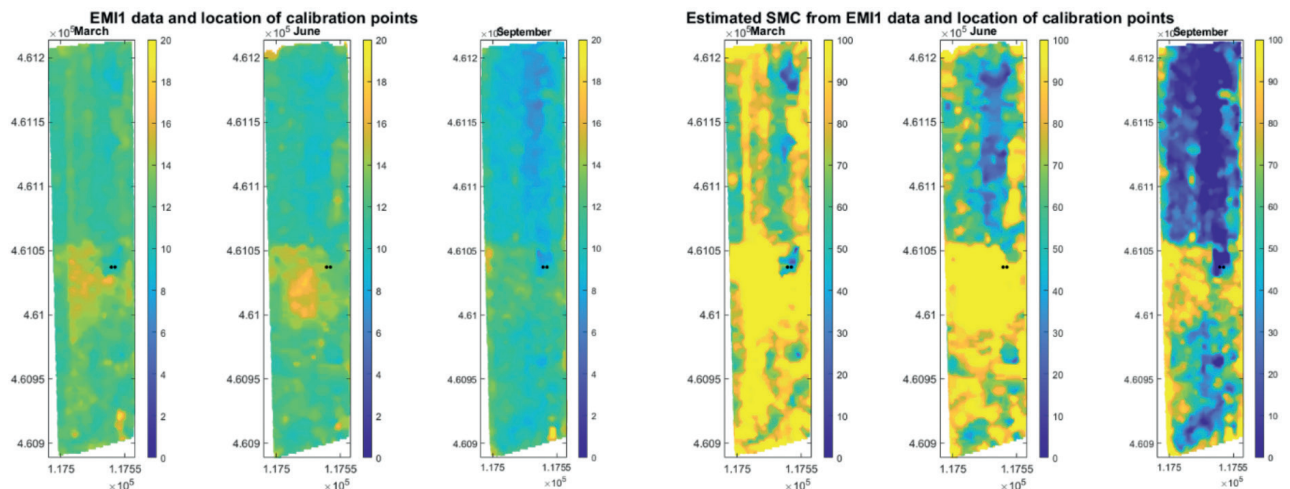
Figure 9 presents the 2020 precipitation, SMC, GL and NEE data for the Cabauw site (KNMI) with drought/drier periods marked by the red arrows and wet periods marked by the green arrows (Figure 9 a/b/c). An interesting response is seen in the CO<sub>2</sub> NEE curves if plotted as the 2-months average curve (Figure 9f). A phase delayed response occurs in the CO<sub>2</sub> NEE curve where the drought causes an increase in the CO<sub>2</sub> NEE curve (a net CO<sub>2</sub> emission, green upward arrow) and the wet period decreases the

CO<sub>2</sub> NEE curve (a relative uptake of CO<sub>2</sub>, red downward arrow). Although the balance of uptake and emission is more complicated than presented here it is a clear indication of drought-induced peat processes emitting CO<sub>2</sub>. Also, the precipitation appears to be a predictor for soil movement in the shallowest 0.5 m. Given that drought can be spatially predicted by EMI measurements, EMI can most likely also spatially predict CO<sub>2</sub> emissions and subsidence through empirical relations.

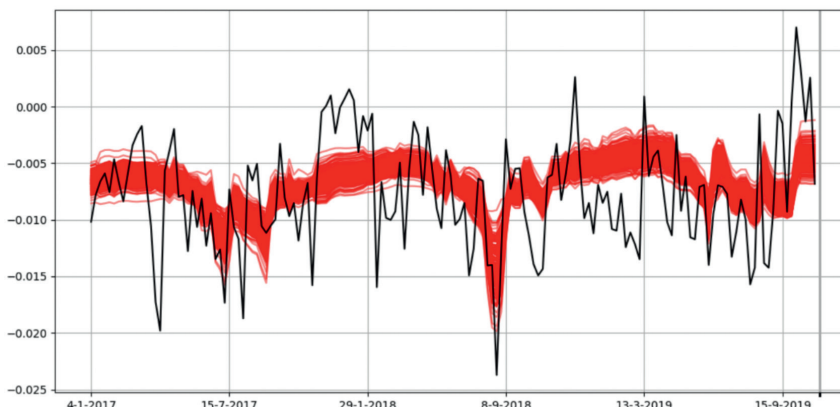
## Conclusions

This study confirms that the key factors controlling the negative effect of drought on CO<sub>2</sub> emissions, subsidence and salinisation are (1) the content of soil moisture (SMC) and (2) the groundwater level (GL). The upper  $\pm 0.5$  m of Dutch soil is found to be a highly dynamic part of the subsurface which acts as a conduit and mirror of atmospheric processes towards the subsurface and vice versa. In case of events of drought or highly wet conditions the upper  $\pm 0.5$  m of soil responds, albeit with a delay, strongly on these events by changing its soil moisture content, its groundwater table, its electrical conductivity, soil movement and net CO<sub>2</sub> emission.

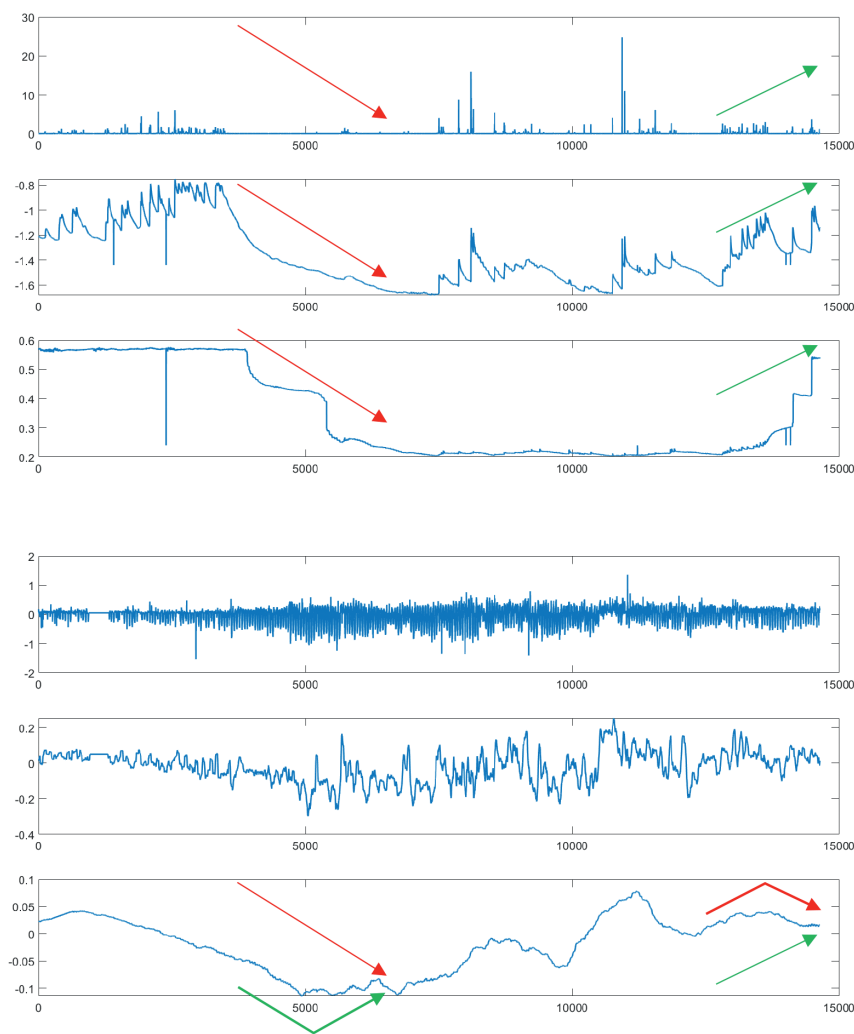
Especially in peat areas this is a strong effect. Soil moisture content in the layers above the groundwater table is by default not so well known and knowledge of the spatial extent of soil moisture falls short. We have found however that electrical



**Figure 7** SMC time-lapse maps from Zegveld in March, June and September 2021 at 0.3m depth (3 panels right) derived from the observed variations in ECa at 0.3m (3 panels left). X- and Y axis represent GPS coordinates in the Dutch RD coordinate system. The colorbar units in the left three panels represent conductivity ECa in mSiemens and in the right three panels SMC in percentage.



**Figure 8** In red the SMC ensemble members after 4 assimilation steps. In black the InSAR data. For the fit with SMC data a seasonal trend with flattened tops and some peaks is visible. The peak in the dry summer of 2018 stands out the most. Chi-square is 1.63. Y-axis is relative displacement in meters with respect to 01-01-2017, X-axis is time in days.



**Figure 9** 2020 yearly CO<sub>2</sub> flux curves at Cabauw (KNMI). 6 panels from top to bottom: precipitation, groundwater level (GL), Soil Moisture Content (SMC) at 20 cm depth, CO<sub>2</sub> Net Ecosystem Exchange (NEE) flux 30 minutes interval, CO<sub>2</sub> NEE flux 2-daily moving average, CO<sub>2</sub> NEE flux 2-monthly moving average. Y-axis is relative amounts of displayed properties, X-axis is number of half hour intervals in 2020.

conductivity (EMI) is an excellent proxy for soil moisture content and correlates well. In this study, we conducted tree timelapse EMI field experiments on the Zegveld peat observatory site. We found that in-situ located SMC point measurements after calibration correlated well to the average EMI conductivities at those locations during the three timelapses. A solid empirical relation could be established between SMC and EMI allowing for spatial prediction of SMC on the Zegveld field into plausible time-lapse monitoring maps.

Additionally, it was found at the Zegveld site that both SMC and EMI followed intimately the behaviour of precipitation and GL. The usual pattern arose that a short or long-term precipitation event would take place, then with short delay the GL would rise and after more delay the SMC and EMI would rise. For a drought the opposite effect occurred with the same delays: first a period without precipitation, then the GL drops and then the SMC and EMI drop. This is a helpful insight that enables us to not only spatially predict SMC from EMI, but also make assessments of how the SMC will react after a wet and dry period.

At the other large peat observatory Cabauw, we have observed strong indications that subsidence derived from InSAR is also closely related to the SMC and GL in the upper 0.5 m of soil and causative precipitation events. Subsidence or in general

soil movement from InSAR is seen to correlate well to SMC at the Cabauw site and another peat site in Friesland. The relation of InSAR displacement estimates to coinciding precipitation is weak, possibly due to the delay factor.

At the same peat observatory Cabauw, we have observed strong indications that net CO<sub>2</sub> emissions are also closely related to the SMC and GL in the upper 0.5 m of soil and causative precipitation events. The analysis of net CO<sub>2</sub> emission is a delicate procedure, involving many statistics and calibration to separate the biomass intake, seasonal trends, atmospheric factors like wind etc. In this study we could do only a crude estimation of the net CO<sub>2</sub> emission at the Cabauw site in 2020 using running average models on the raw data. Yet these running averages do show a convincing delayed relation between precipitation, GL and SMC, similar to what we found at the Zegveld site from our EMI-SMC analysis. At Cabauw, net CO<sub>2</sub> emission increases with a delay after the commence of a drought and decreases again with delay after a wet season commences. This is a promising result that may allow for EMI data to be a proxy for subsidence and net CO<sub>2</sub> emission through SMC.

We conclude that electrical conductivity (EMI) is an excellent proxy for soil moisture content and correlates well. This is promising for subsidence research worldwide, as EMI can also be conducted airborne and by satellite.

## Acknowledgements

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