A novel geophysical method to map soil moisture in subsiding peatlands to forecast drought effects and CO2 emissions

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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 CO2 emissions. Furthermore, artificially drained peatlands are vulnerable to salinization when proximal to coastlines, and fires when situated in dry and warm climatic zones. The Netherlands has substantial acreage of peatlands as seen in Figure 1.

In northwest Europe, peatlands are expected to become more susceptible to deterioration as climate models predict increased periods of extreme droughts. 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 of 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 breakdown peat, and consequently increases CO2 emissions and subsidence during periods of drought.

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 oxidation process 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.

Both SMC and GL have proven to be mappable using geophysical methods. Multi-coil offset electromagnetic induction (EMI) has high potential to map peat properties for managed peatlands from apparent electrical conductivity (ECa) (Altdorff et al., 2016). 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 (σw).

We present a time-lapse study for SMC and GL employing EMI in a managed peatland in the central peat-rich delta plain of the Netherlands. 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 CO2 NEE (Net Ecosystem Exchange) flux, precipitation and subsidence measurements.

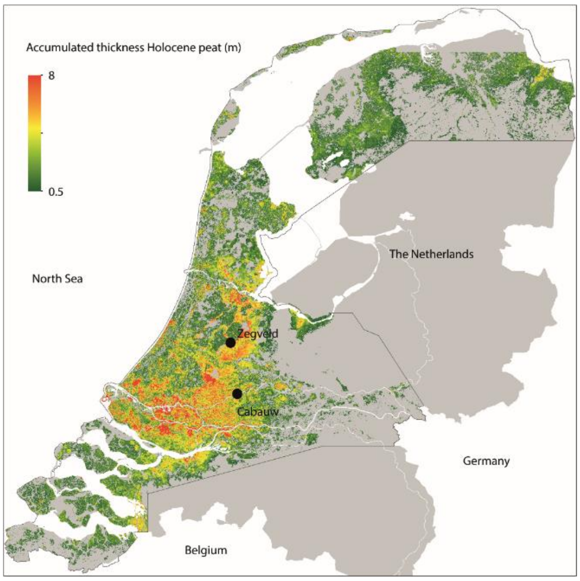

Figure 1 Accumulated thickness of Holocene peat distributed over the Netherlands (after Koster et al., 2020), and the locations of the Zegveld and Cabauw sites.

Approach and outcomes

In this study we conducted three time-lapse EMI field experiments on the Zegveld peat observatory site and one at a test field in Cabauw to ascertain the correlation to SMC (Figure 1). 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) (Figure 2). Too much interference by electromagnetic devises that are permanently present at the Cabauw test field for other monitoring studies resulted in the abandonment of this location after the March measurement campaign.

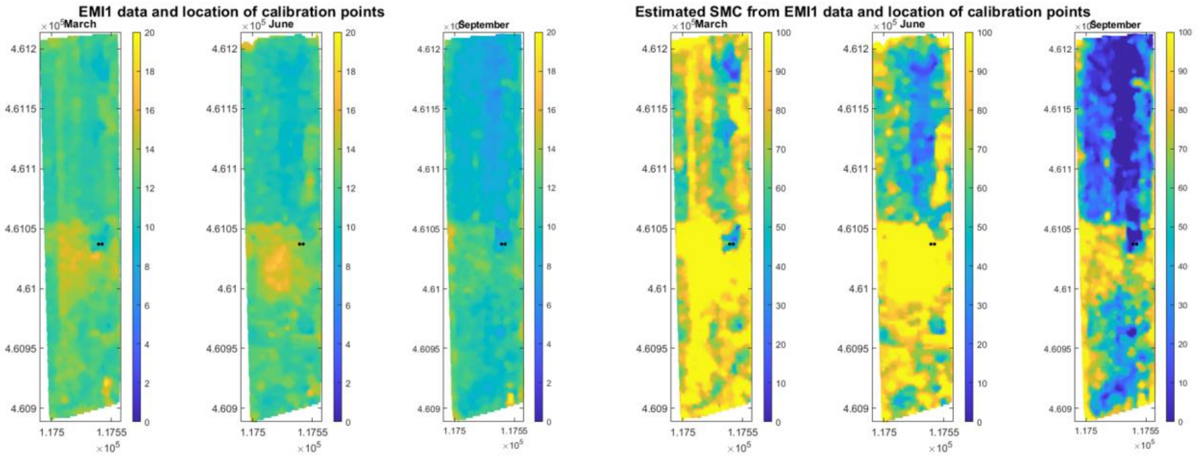

Figure 2 SMC time-lapse maps from Zegveld at 0.3m depth (right) derived from the observed variations in ECa at 0.3m (left).

The EMI field data is subsequently confronted with monitoring data that was previously collected for different studies: InSAR (Sentinel-1), soil moisture (KNMI for Cabauw, NOBV for Zegveld), and CO2 flux (KNMI for Cabauw, NOBV for Zegveld). These datasets are used in data assimilation procedures to predict soil moisture content (Fig. 3).

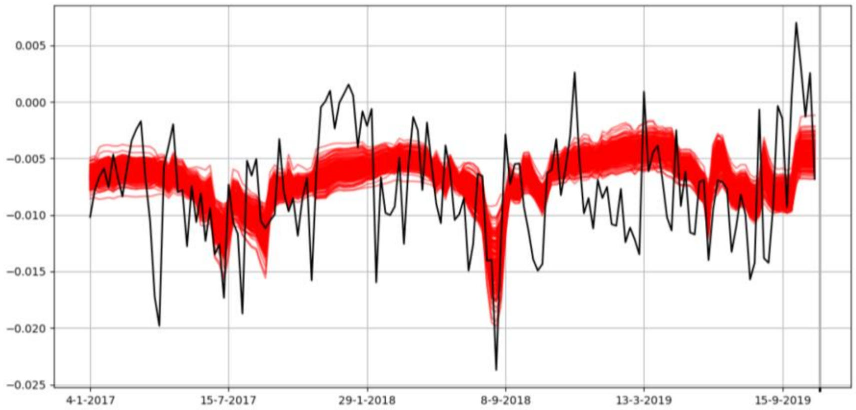

Figure 3   In red the ensemble members after 4 assimilation steps. In black the InSAR data. For the fit with SMC data a seasonal trend with flattened tops and some peaks is visible. The peak in the dry summer of 2018 stands out the most. Chi-square is 1.63.

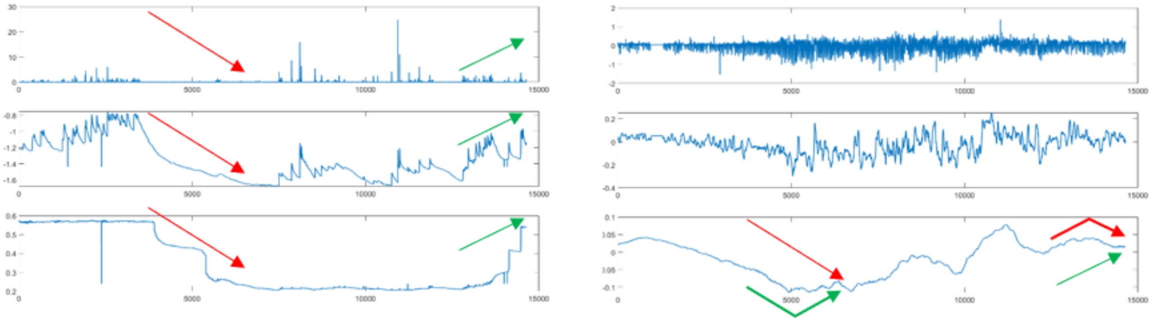

Figure 4   2020 yearly CO2 flux curves at Cabauw (KNMI). From top to bottom left: precipitation, groundwater level (GL), Soil Moisture Content (SMC) at 20 cm depth; right: CO2 Net Ecosystem Exchange (NEE) flux 30 minutes interval, CO2 NEE flux 2-daily moving average, CO2 NEE flux 2-monthly moving average.

We found that in-situ located SMC point measurements after calibration correlates 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.

Additionally, it was found at the Zegveld site that both SMC and ECa followed intimately the behavior 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 make assessments of how the SMC will react after a 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 meters of soil and causative precipitation events. Figure 3 demonstrates that subsidence or in general soil movement from InSAR is seen to correlate well to SMC at the Cabauw site. The relation of InSAR movements to precipitation is weaker, possibly due to the delay factor.

At Cabauw, we have also observed strong indications that net CO2 emission is closely related to the SMC and GL in the upper 0.5 meters of the soil and causative precipitation events (Figure 4). The analysis of net CO2 emission is a delicate procedure, involving much 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 CO2 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 CO2 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 as well for net CO2 emission through SMC.

When looking in Figure 4 at the 2020 upcoming drought period marked by the red arrows and looking at the upcoming wet season marked by the green arrows, an interesting response is seen in the CO2 NEE flux curves. When looking at the 2-months average curve, a phase delayed response occurs in the CO2 curve where the drought causes an increase in the NEE net CO2 emission and the wet season decreases the NEE net CO2 emission. This is a clear indication of the drought-induced peat processes that emit CO2. 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 CO2 emissions and subsidence through empirical relations.

Look forward

We have found 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. Soil moisture content in the layers above the phreatic groundwater table is by de facto not so well known and especially knowledge of the spatial extent of soil moisture falls short.

This study confirms that the key factors controlling the negative effect of drought on CO2 emissions and subsidence are (1) the content of soil moisture (SMC) and (2) the groundwater level (GL), also known as phreatic water level. The upper +- 0.5 meters of Dutch soil is found to be a highly dynamic component of the subsurface which acts as a conduit and mirror of atmospheric processes toward the subsurface and vice versa. In case of events of drought or highly wet conditions the upper +- 0.5 meters of soil responds, albeit with a delay, strongly on these events by changing its electrical conductivity, its soil moisture content, its groundwater table, soil movement and net CO2 emission.

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