The relation between land subsidence and CO_2 emission in peatlands

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Abstract

There are two crucial factors that need to be considered when using land subsidence data to establish CO_2 emissions from drained peatlands: i) not all land subsidence is the result of microbial decomposition of peat, and ii) a conversion value to express land subsidence (volume change) in CO_2 emissions (mass). This paper assesses how previous studies have dealt with these two factors and supplements existing values and experiences with new data and insights gathered over the last couple of years.

Introduction

Drainage of peatlands leads to double trouble: it causes land subsidence and carbon dioxide (CO_2) emission (cf. Erkens et al., 2016). The former increases local flood risk in these often already wet and flood-prone environments, whereas the latter contributes to the increased levels of greenhouse gasses in the atmosphere and thus to global climate warming.

Land subsidence and CO_2 emission are not just happening both in drained peatlands, in fact a relation exists between land subsidence and CO_2 emission. Both originate from the same process, namely the decomposition of organic matter by microorganisms such as bacteria, archaea, and fungi (Stephen and Johnson, 1951). This happens mostly under the influence of oxygen that can enter the unsaturated part of the soil following drainage. Carbon dioxide is a product of the decomposition process of organic material by microorganism. The same decomposition results in mass loss by itself which may lead to volume reduction which is noticeable as land subsidence at the surface. Additionally, decomposition of the organic matter forming matrix may lead to a decreased strength of the peat layer. When the loss of strength is severe, it may result in compaction of the layer and thus to land subsidence.

A relation between the degradation of peat layers, greenhouse gas emissions, and subsidence by volumetric loss was already identified by Neller (1944). Using this relation, land subsidence has been used as a proxy for greenhouse gas emission from drained peatlands (Hooijer et al., 2012; Erkens et al., 2016), or the other way around (Deverel et al., 2016). Particularly for studies on larger spatial scale, land subsidence has been used as a proxy, because methods to measure land subsidence over larger areas were readily available, such as spirit levelling or extensometers, whereas regional or nation-wide measurements of greenhouse gas emission are more complex and demanding. For the Netherlands for instance, the official national LULUCF (Land Use, Land Use Change and Forestry) reporting of CO_2 emission from peatlands (Arets et al., 2019) is based on a relation between measured land subsidence and CO_2 emission (Van den Akker et al., 2008a).

There are two crucial factors that need to be considered when using land subsidence data to establish CO_2 emissions from drained peatlands: i) not all land subsidence is the result of microbial decomposition of peat, and ii) a conversion value to express land subsidence (volume change) in CO_2

emissions (mass). This paper assesses how previous studies have dealt with these two factors and supplements existing values and experiences with new data and insights gathered over the last couple of years. The results contribute to the increasing need to establish large-scale greenhouse gas emission values from drained peatlands, driven by the greenhouse gas reduction aims agreed on in the Paris Agreement (2015).

Methods

This study mainly used existing published results from previous studies from around the world. These are put in the context of the Netherlands, where land subsidence is used as a proxy for CO_2 emissions in the national reporting. Results from published studies are complemented with recently acquired results from the Netherlands Research Programme on Greenhouse Gas Dynamics of Peatlands and Organic Soils (NOBV). The NOBV is measuring and monitoring land subsidence and CO_2 emissions from the drained Dutch peatlands and collects data on relevant soil parameters (Erkens et al., 2021).

Results

A major issue when converting land subsidence values into CO_2 emission values for drained peatlands is that not all land subsidence is related to the decomposition of peat and thus to emissions. There are four steps that need to be taken to convert land subsidence data to CO_2 emissions: i) isolate the deeper-rooted subsidence below the soft soil layer from the total subsidence, ii) discriminate between permanent and non-permanent processes in the soft soil layer, iii) establish how much subsidence is related to physical processes and how much to peat decomposition, iv) use a conversion factor to calculate CO_2 emissions from land subsidence as a result of peat decomposition. These steps will be presented in this section.

First, we distinguish between land subsidence processes that happen below the soft soil layer (peat, clay) and land subsidence processes that happen within the soft soil layer. Naturally occurring land subsidence and human-induced land subsidence rooted in deeper layers below the soft soil deposits, for instance because of extraction of water, gas, salt, or oil or isostatic and tectonic movements, need to be isolated from the total land subsidence at the surface (e.g. Erkens et al., 2015; Minderhoud et al., 2015) as these components are unrelated to the decomposition of peat. Usually this is possible when land subsidence in peatlands is measured opposed to a benchmark or reference level that is rooted in the underlying (Pleistocene) deposits. In this way all movement as a result of the processes below the soft soil layer are also in the reference level.

More complex is the discrimination between other processes that lead to land subsidence within the (Holocene) peat layer itself or surrounding (Holocene) soft soil deposits (clay). Processes that lead to permanent soil deformation happen both in the unsaturated and saturated zone (Table 1).

In the unsaturated zone increased stresses by suction (negative pore water pressure) will cause permanent shrinkage. In the saturated zone, increased effective stress, either by reduced pore water pressure or increased total stress, may cause consolidation and viscous behavior of the material under constant pressure conditions (creep) leads to compaction. These three physical processes lead to volume reduction and compaction of the deposits, but not to greenhouse gas emissions. Peat decomposition and the occurrence of physical processes leading to soil deformation may be linked, because decomposition of organic matter may impact the supportive skeleton consisting of plant material and fibers, decreasing strength of the peat, and eventually causing peat compaction. This relationship still needs to be established with laboratory geotechnical testing on samples in their original form and decomposed form.

Result	Position in subsurface	Process	Driver	Causing CO_2 respiration?
Permanent deformation	Unsaturated zone	Organic matter (peat) decomposition	Microbial activity	Yes
		Shrinkage (irreversible)	Pore water suction	No
	Saturated zone	Consolidation	Effective stress	No
		Viscous behaviour (creep)	Viscosity	No
Non-permanent deformation	Unsaturated zone	Shrink/swell behavior (reversible)	Pore water suction	No
	Saturated zone	Poro-elastic behaviour	Effective stress	No

Table 1 Processes leading to deformation in drained peatlands. Only one of the identified processes leading to land subsidence is related to CO_2 emissions

Reference	Location	Reported value of contribution of physical compaction	Timescale of study
Erkens et al., 2016	Netherlands, peatlands	28%	1000 years
Van Asselen et al., 2018	Netherlands, urban/rural environment	17-65%	10-1000 years
Schothorst, 1977	Netherlands, rural	35-48%	6 years
Stephens et al. 1984)	Everglades, Florida, USA	47%	years-decades
Van den Akker et al., 2008a,b	Rural peatlands, Netherlands	0% (at 1,00 m depth), ~10% overall	30 years
Hooijer et al., 2012	Southeast Asia	25% (5 years); 8% (18 years)	20 years
Deverel & Leighton, 2010	Sacramento Delta, California, USA	43/45/69%	80 years (modelled)
Kasimir-Klemedtsson et al., 1997	Sweden, the Netherlands	30%	years

Table 2 Reported contribution of physical compaction to total land subsidence. The selected studies are focusing on peat layers at the surface.

Contributions of physical compression processes versus peat decomposition to total land subsidence of stacks of peat and clay layers have been reported in literature (Table 2).

The values reported in Table 2 show that the contribution of physical processes to total land subsidence may differ substantially. Note that shrinkage, happening in the unsaturated part of the soil, is often neglected as the shrunk soil will experience decomposition after shrinkage. There is however an overall trend observed that on longer time scales the contribution of physical processes to total land subsidence decreases. This is the result of the short-term nature of shrinkage and consolidation (but not of creep) that happen specifically during the first years following an increase in effective stress, for example due to a drainage event (see results from Hooijer et al., 2012 and van Asselen et al., 2018 in Table 2). After a single drainage event, the contribution of physical processes will become small after decades. In case of multiple consecutive drainage or loading events, like in the Netherlands, this contribution may remain higher, as shown by Erkens et al. (2016). Overall, the contribution of physical processes to land subsidence in drained peatlands will be larger than 0%, and most studies indicate a contribution of ~20-50%. For the Netherlands, the value of ~30% on the time scale of decades seems realistic (Table 2).

In the NOBV research programme, several extensometers have been installed to monitor land movement over time (hourly measurement) in Dutch drained peatlands. Figure 1 shows a preliminary result for a drained peatland in Zegveld, the Netherlands, that there is highly dynamic surface movement over the 2,5-year measurement period (see also Van Asselen et al., 2020). Permanent deformation let alone the contribution of peat decomposition to total deformation, is not clear from these measurements. This is the result of the difference in scale and magnitude of the non-permanent processes shrink/swell and poro-elastic response (Table 1) over permanent deformation processes. Note that this measurement field has a long-lasting history of drainage and did not see a recent change in drainage depth. With total land movement of up to 10 cm over a year (Figure 1), it will take years (minimum 5 years) before permanent deformation (in the order of mm per year) may be derived from such measurements. This shows the great challenges that using land subsidence measurements as a proxy for CO_2 emissions brings. The most practical measurements to isolate land subsidence due to microbial decomposition are long-lasting (> 5 years) land movement measurements, preferably with an extensometer, that enables separating the saturated from the unsaturated zone processes (Van Asselen et al., 2020), in a situation wherein the drainage depth remains constant over time (so non-permanent processes remain as constant as possible).

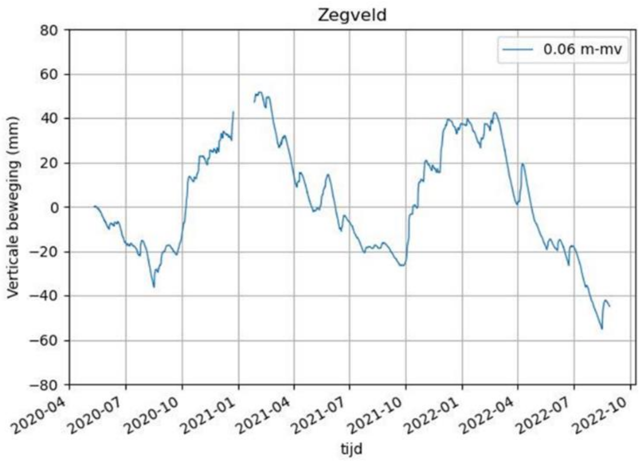

Figure 1 Preliminary results of the extensometer from Van Asselen et al (2020). Reported contribution of physical compaction to total land subsidence. The selected studies are focusing on peat layers at the surface.

To convert land subsidence attributed to organic matter decomposition to CO_2 emissions, a conversion factor needs to be established. The factor depends on the fraction of carbon in the organic matter (not discussed in this paper), the bulk density and the organic matter fraction (Van den Akker et al., 2008b). Erkens et al. (2016) found that there is no relation between the relative organic matter content and organic matter density for peats (>20% weight organic matter; Figure 2). Erkens et al. (2016) derived an average organic matter density of 103 kg/m^3 for all peats in the Netherlands, but the range in Figure 2 is considerable. This range is mainly the result of compaction of peat layers that increased their organic matter density. Van den Akker et al. (2008b) found that the organic matter density at 30 cm depth in a drained peat layer was 207 kg/m^3, whereas at 120 cm depth this was only 112 kg/m^3. These are unfortunately just two samples, whereas the values from Erkens et al (2016) are based on almost 1000 samples, but these are taken from many different depths. In order to convert land subsidence to CO_2 emission, there is therefore a need for an updated value. The NOBV research programme sampled per 5 cm 15 research sites throughout the Dutch peatlands (mostly drained). The average organic matter density for the upper 120 cm (considered the interval where peat decomposition happens) from the ca 360 samples is 147 kg/m^3. It is suggested that this value is used in the Netherlands for the conversion from land subsidence to CO_2 emissions. Using the formula from Van den Akker et al (2008b), we arrive at a value of 2965 kg CO_2 per ha per yr per 1 mm land subsidence due to peat decomposition, higher than the previously reported value of 2259 kg CO_2 per ha yr per mm land subsidence (Van den Akker et al., 2008b)

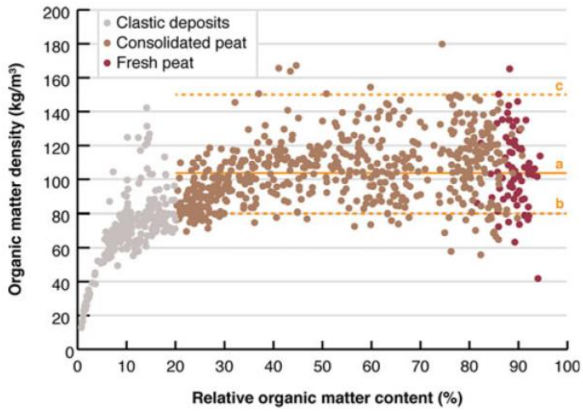

Figure 2 Relation from Erkens et al (2016) between relative organic matter content and the organic matter density. Above relative organic matter content of 20%, there is no relation with organic matter density, because for these samples the clastic content does not contribute to the volume of the sample.

Conclusion

- When land subsidence measurements are to be used as proxy for CO_2 emissions, it is imperative to separate the land subsidence rooted below the soft soil layer and to discriminate between permanent and non-permanent land deformation processes within the soft soil layer. The following step is to further subdivide the permanent deformation processes into physical processes and microbial decomposition, which is related to CO_2 emission. Research suggests that on longer timescales ~30% of the land subsidence in drained peatlands is the result of physical processes and may thus not be correlated to CO_2 emissions.
- Based on new data, the average organic matter density of the upper 120 cm of the drained Dutch peatlands contain 147 kg/m^3 organic matter. This value should be used, at least in the Netherlands, when using land subsidence rates as a proxy for CO_2 emissions by organic matter decomposition. When applied to the Netherlands, we arrive at a value of 2965 kg CO_2 per ha per year per 1 mm land subsidence to organic matter decomposition.

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