Towards process-based modeling of land subsidence due to peat oxidation in the Netherlands

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Abstract

Land subsidence in peatlands is a significant problem in the Netherlands. In the Dutch peat meadow areas oxidation, compaction and consolidation are the most important contributors to land subsidence. Oxidation is the decomposition of organic matter when oxygen is introduced into the soil, which causes land subsidence. Oxidation is strongly related to groundwater level lowering (drainage) and is identified as the most important process causing land subsidence in Dutch peat meadow areas. Furthermore, peatlands are currently under increased pressure due to climatic warming. Increased temperature and longer droughts increase peat decomposition rates.

This study aims to determine land subsidence due to peat oxidation in the Dutch peat meadow areas. Existing CO_2 model SOMERS is extended with a module that converts CO_2 emissions to volume loss and thus land subsidence due to oxidation (SSOM). SOMERS uses the relevant boundary conditions for oxidation, such as soil moisture, soil temperature and organic matter content. Moreover, it uses laboratory measurements of potential respiration rates to determine CO_2 emission. SSOM computes land subsidence due to oxidation based on existing relations between bulk density, organic matter content and volume loss. Measured groundwater levels on a daily basis are used as input for the computation. The model outcomes are compared with oxidation rates based on subsidence measurements and literature on two parcels at two study locations: Zegveld and Rouveen.

The average modeled yearly oxidation-induced subsidence rates are 2.8 mm/y and 6.4 mm/y at the Zegveld parcels, whereas at the Rouveen sites the modeled rates are 2.2 mm/y and 4.9 mm/y. These rates are in the same order of magnitude as oxidation related subsidence values extracted from measurements and from the literature. Subsidence due to oxidation by SSOM is currently larger than the oxidation rates based on subsidence measurements. The difference between modeled and measured subsidence due to oxidation implies either an overestimation of the model or an underestimation of the oxidation based on measurements. The most important identified uncertainties in SSOM are (1) the absence of scaling for density changes, (2) the oxygen availability is not accounted for in the AAP, (3) the basal respiration is not yet determined with long-term measurements. Despite the difference in subsidence rate between the modeled SSOM results, measurements and literature, the modeling method looks promising. It provides a strong basis for further modeling efforts and it is now possible to compute the effects of mitigating measures on future land subsidence due to oxidation in the Netherlands.

Keywords: land subsidence, peat oxidation, peat meadow areas, modeling oxidation, groundwater levels, peat density, volumetric soil loss, the Netherlands

Contents

1. Introduction

Land subsidence is a significant problem in the Netherlands, which leads to increased flood risks, water management issues, and damage to infrastructure with an associated cost of 1 billion euros in rural areas and up to 5 billion euros in urban areas (PBL, 2016)[1]. Land subsidence is especially persistent in the Dutch peatlands, where large scale drainage has led to subsidence due to oxidation. Oxidation occurs when oxygen is introduced in organic soil (by e.g. drainage), which results in conversion of organic matter into CO_2, and thus land subsidence. Drainage also results in subsidence via consolidation, which is the compression of saturated soil due to a decrease in pore water pressure. Furthermore, peat soils are now under pressure by ongoing drainage and climatic changes, because increased temperatures result in higher peat decomposition rates (Van Den Akker et al., 2008; Waddington et al., 2001).

Peat and peaty soils that are currently present at the surface in the Netherlands are shown (Figure 1), including the two study locations: Rouveen (province of Overijssel) and Zegveld (province of Utrecht). The Dutch peat meadow areas are predominantly situated in a coastal plain, where peat was able to grow during the last 8000 years under influence of relative sea level rise (Berendsen and Stouthamer, 2000). Inland lagoons gradually transitioned to quiet freshwater environments where, without significant sediment supply, thick layers of peat could form. In time, the influence of the sea or rivers may have increased locally, leading to some clayey and sandy deposits. Over the last 1000 years peatlands have been drained for human use (first for crops, now for dairy farming). This has on average led to 1.9 m of land subsidence, resulting in a landscape that is for 26% situated below the sea level (Erkens et al., 2016).

The problem of subsidence in peatlands is maintained by periodical lowering of drainage levels for land use purposes, which induces a new cycle of subsidence (Bootsma et al., 2020). Moreover, climatic warming will lead to an increased peat loss due to drier summers and increased temperatures, causing higher peat decomposition rates. Furthermore, peat oxidation is reported to be the dominant process leading to land subsidence in the Netherlands. According to Erkens et al. (2016), 72% of the subsidence in the Dutch peat meadow areas in the last 1000 years can be attributed to oxidation. Because of this dominance and the fact that peat soils are under increased pressure due to climate change, the focus in this research is on peat decomposition.

To mitigate subsidence due to oxidation effectively, reliable prediction tools are required for e.g. subsidence adaptation measures and spatial planning. Currently, subsidence due to oxidation is modeled using an empirical relationship relating the Deepest Ground Water Level (DGWL) to land subsidence and CO_2 emission (see Figure 2; Kuikman et al., 2005; Van Den Akker et al., 2008). This principle is widely used, such as in national subsidence prediction maps (Bootsma et al., 2020), policy reports (PBL, 2016) and local studies (Hoogland et al., 2012). The use of this empirical relation, however, has several disadvantages (for an extensive explanation, see NOBV report (2022)). These can be summarized as follows:

- By definition, empirical relations hold only under the specific circumstances where the measurements of the relation were done. They are thus not readily applicable to other locations or (hydrological) changes, such as a groundwater level lowering (Boonman et al., 2021)
- Seasonal dynamics are not considered when using the DGWL, and the effects of extreme dry or wet years are not accounted for. The DGWL's calculation is based on groundwater

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[1] PBL: Dutch Environmental Assessment Agency (Planbureau voor de Leefomgeving)

levels of an eight-year timespan, so differences in seasons or between years are not reflected in the DGWL.

- Large datasets of accurate measurements are required, which are currently not available for the Netherlands. The relation found by Van Den Akker (2008) is based on the only long-term subsidence dataset in the Netherlands that exists, which is measured between 1970 and 2020 at Zegveld. The dataset is, however, not sufficient to use for the entire Netherlands.

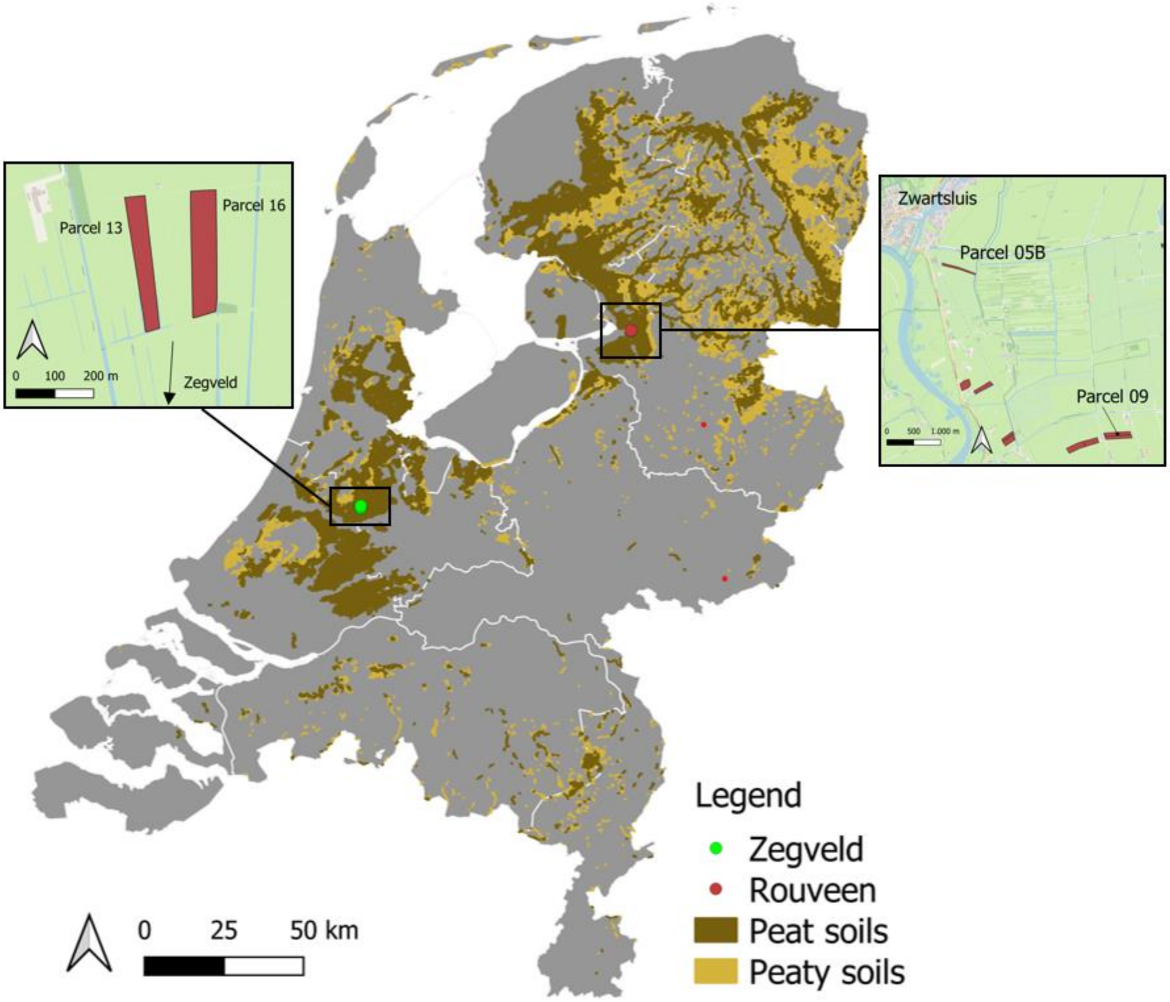

Figure 1. An overview of peat and peaty soils at the surface in the Netherlands. Peat soils contain at least 50% organic matter in the top 80 cm of the soil, whereas peaty soils contain less than 50% organic matter in the top 80 cm but contain cumulatively more than 5 cm organic matter (Deltares, 2020). Model locations Rouveen and Zegveld are indicated in respectively red and green. At both study locations two parcels were modeled .

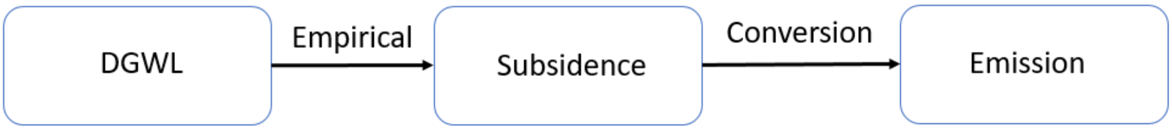

Figure 2. The relation between Deepest Ground Water Level (DGWL), subsidence and CO_2 emission (Van Den Akker et al., (2008).

Consequently, at present subsidence due to peat oxidation cannot be predicted accurately, which is especially problematic now that there is the need to assess measures (i.e. changing hydrological parameters). Models with predictive power are required, such as a process-based model that includes multiple parameters instead of one. A process-based model regarding subsidence due to peat oxidation is here defined as a representation of several processes characterizing the functioning of a system. This does not necessarily mean that there are no empirical relations present to represent a single process. There is, however, a requirement for dynamics in the parameters in order to model changing conditions.

Recently, a process-based model to estimate CO_2 emissions due to peat decomposition (SOMERS 1.0) is developed. This model is developed within the framework of the Dutch national research program on greenhouse gasses in peatlands (NOBV). SOMERS estimates the relevant boundary conditions (such as soil moisture, soil temperature and organic matter content) and uses laboratory measurements of potential respiration rates to determine CO_2 emission. Groundwater dynamics (modeled or measured) have a central role in SOMERS. This is essential to compute the effects of mitigating measures because they often consist of groundwater level changes. The phreatic groundwater levels are calculated on a daily basis, which is a high temporal resolution when compared to the yearly values of the relationship between DWGL and land subsidence (Van Den Akker et al., 2008). This implies that the results of SOMERS are sensitive to e.g. changes in weather, within and between years, in contrast to the current relationship (Figure 2).

This study uses CO_2 model SOMERS 1.0 and is extended with a new model (SSOM: SOMERS Subsidence Oxidation Model) to simulate subsidence due to peat oxidation. CO_2 emissions, computed by SOMERS, are converted to organic matter mass. From this, land subsidence is calculated using existing relations between bulk density, organic matter and the amount of volume that is lost per unit mass.

1.1 Research aim

This study aims to determine land subsidence due to peat oxidation for the first time using a process-based model and assess its quality by comparison with measured and literature subsidence data for two locations in the Netherlands, Zegveld and Rouveen (Figure 1). The peat decomposition potential of SOMERS is used to model peat oxidation. The eventual goal is to make the model spatially available for all Dutch peatlands and to use it for different climatic scenarios and water management strategies. The addressed research questions are:

(1) What is the reliability and accuracy of SSOM? To assess the quality of the model, the outcome has been compared to (1) oxidation-caused subsidence values deduced from measured land subsidence data for both study locations (see Fig. 1), and (2) oxidation-caused subsidence values from literature. The model quality is essential in order to determine how well the model functions. Model results are expected to be within the same order of magnitude as deduced oxidation and oxidation caused subsidence rates in the literature. Furthermore, a sensitivity analysis is done for key model parameter basal respiration to assess its sensitivity to changes.

(2) What explains deviation of modeled oxidation-induced subsidence from measured and literature subsidence due to oxidation? Knowledge of model quality is essential to determine possible missing model parameters and uncertainties.

(3) What is the influence of organic matter density differences in peat soils on the amount of land subsidence due to oxidation, i.e. volumetric soil loss? How is this reflected in the amount of subsidence due to oxidation? SSOM is currently independent of organic matter density (see Methods for the full model description). To answer this question, an analysis is made of a large dataset of samples containing organic matter density and organic matter content.

This report is structured as follows. The approach is first presented, and consequently the subsidence processes and research methods are described (Chapter 2). The model structure and equations are explained here as well. Subsequently, the results of SSOM and oxidation analysis are described in Chapter 3, and they are discussed in Chapter 4 (Discussion), Finally, the conclusion of the research is presented in Chapter 5.

2. Methods

2.1 General approach

Land subsidence due to oxidation is modeled at the Zegveld and Rouveen sites by developing an oxidation model (SSOM: SOMERS Subsidence Oxidation Model) adding to an existing CO_2 model SOMERS 1.0, see NOBV report (2022). The central idea is to calculate volume loss and thus subsidence due to oxidation based on the peat decomposition potential scaled to the conditions in the field. Measured groundwater levels are used as input for model runs. In addition, measured land subsidence data is analyzed in order to extract solely the oxidation component. Measured, modeled and literature values of subsidence due to oxidation are compared to assess model performance. Lastly, a sensitivity analysis for key model parameter basal respiration is done.

2.2 Process definitions and model set-up

2.2.1 Process definitions

SSOM is a process-based model and revolves around the relation between peat oxidation and land subsidence. When modeling subsidence caused by oxidation, it is essential to understand all shallow (<2 m) subsidence mechanisms acting in the topsoil. The shallow subsidence processes that are distinguished in this study are: oxidation, shrinkage, compaction, and consolidation:

- Oxidation is the decomposition of organic matter by microbes, mainly occurring in the aerated zone and leading to CO_2 emission into the atmosphere. Factors controlling the oxidation rate are (1) availability of organic matter, (2) oxygen availability, (3) soil temperature, (4) soil moisture content, (5) the presence of soil bacteria, and (6) pH value (Brouns et al., 2016). Aerobic decomposition is approximately ten times faster than anaerobic decomposition. Peat decomposition thus occurs primarily above the groundwater table (Scanlon & Moore 2000). According to Hooijer et al. (2012) peat oxidation itself does not increase bulk density. Peat decomposition leads to mass loss by converting the organic matter into CO_2 and water (H_2O). The question of how this loss of mass leads to volume loss is essential to determine the amount of subsidence as a result of peat decomposition.
- Shrinkage refers to the volume loss caused by the contraction of plant fibers and pores when peat is exposed to air under the influence of e.g. evaporation and high temperatures. A part of it is reversible, i.e. the initial volume can return when wetting occurs, but on long timescales of centuries most of it is irreversible (Erkens et al., 2016). Shrinkage takes place only above the phreatic groundwater level and is very hard to distinguish from oxidation when measuring land surface elevation changes. Shrinkage leads to an increase in bulk density, because the mass remains the same, while the initial volume decreases.
- Compaction refers to volume reduction of peat or clay in the unsaturated zone resulting from pressure applied on the peat surface, the weight of the soil itself (autocompaction) or because of strength loss due to e.g. oxidation. The bulk density will increase after compaction.
- Consolidation is the compression of peat in the saturated zone due to groundwater table fluctuations and lowering. Water table lowering lead to a decrease in pore water pressure and an increase in effective stress, resulting in the grains being pressed together. Consolidation is directly linked to applying a load, whereas creep (or secondary consolidation) is the visco-plastic deformation of the soil grains that persists for decades after applying of the initial pressure. Both processes lead to an increase in peat bulk density (Hooijer et al., 2012).

2.2.2 Model set-up

The main input parameters to determine land subsidence due to oxidation are measured soil temperature, measured groundwater level, relative organic matter content, measured basal respiration and the fraction of carbon present in organic matter (see Figure 3).

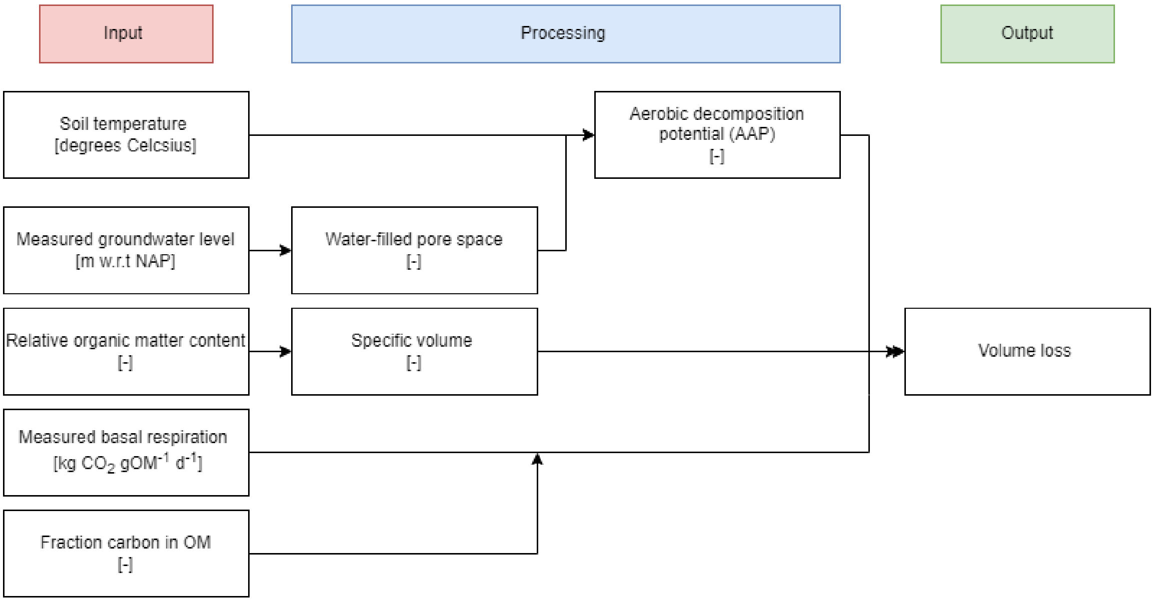

Figure 3. Schematic overview of the components in the SSOM model. The groundwater level is measured with respect to the Dutch Ordnance Datum (NAP).

Basal respiration [expressed in kg CO_2 gOM^{-1} d^{-1}] is a material property, and it gives the maximum rate at which peat can decompose in units of the amount of CO_2 that can respirate per gram organic matter per day. It was measured in the laboratory by NOBV researchers under optimal temperature and soil water, which are respectively 20 degrees Celsius and 70% of the field capacity. Also, the samples were perturbed to reach a state where the soil sample was not limited by oxygen availability or CO_2 diffusion.

The basal respiration was measured in samples from three different soil zones: the oxidation zone, oxidation/reduction zone and in the reduction zone. In the oxidation zone, organic matter from plants respirates alongside peat and thereby disturb the peat respiration measurements. This plant respiration is part of the short-term carbon cycle, whereas we are interested in the long-term carbon cycle (peat decomposition). In the reduction zone, it is assumed that no aerobic peat decomposition takes place. In the oxidation/reduction zone plant roots are minimal and at least a part of the year, when the zone is oxygenated, prone to peat decomposition. Therefore, only the oxidation/reduction zone measurements are used to determine the basal respiration parameter (see NOBV, 2022).

The peat decomposition amount is determined by scaling the maximal decomposition rate (basal respiration) relative to the environmental conditions (AAP). The AAP (Aerobic decomposition potential) scales between 0 and 1, compared to the reference circumstances for optimal decomposition (20 degrees Celsius and water content of 70% of the field capacity). Afterward, the outcome is corrected based on organic matter percentage and carbon content in the peat. The calculation described below was done at 1/3 of the parcel width for 5 cm soil intervals, which are summed to obtain total land subsidence due to oxidation per unit time. For a full overview of model discretization and further determination of AAP (soil temperature and water-filled pore space) see the SOMERS Documentation (NOBV, 2022; Deltares, 2020).

To calculate the volume loss due to peat decomposition, the basal respiration is multiplied with the aerobic decomposition potential (AAP), specific volume loss, and the fraction of carbon in organic matter (OM) (Equation 1):

$$R_{ox} \;=\; AAP * BR * \rho_{bulk} * \; F_{org} * \; \hat{V} * \; F_c \qquad \text{Equation 1}$$

Where R_{ox} $[m^3_{bulk}\; m^{-3}_{bulk} d^{-1}]$ is relative volume loss, AAP [-] is the aerobic decomposition potential, BR $[g\; CO^2 g\; OM^{-1} d^{-1}]$ is the basal respiration, ρ_{bulk} is the soil bulk density $\left[\frac{kg}{m^3}\right]$, F_{org} is the mass-based organic matter percentage [kg OM / kg solid mass], $\hat{V}$ $[m^3/kg]$ is the specific volume of oxidation and F_c is the conversion factor of CO_2 to organic matter. The conversion factor formula can be written as:

$$F_c\;[-] \;= fCinCO_2 \left[\frac{kg\;C}{kg\;CO_2}\right] * \frac{1}{f_{CinOM}\left[\frac{kg\;C}{kg\;OM}\right]} \qquad \text{Equation 2}$$

Where firstly, the fraction of C (carbon) in CO_2 (fCinCO2) is calculated using the molar mass of carbon (12 g/mol) and dividing this by the molar mass of CO_2 (44 g/mol). Secondly, the fraction of carbon in the soil is converted to the amount of organic matter using the assumption that 50% of OM consists of carbon (Erkens et al., 2016; Alterra Wageningen University, 2003). Other atoms, such as nitrogen, phosphorus and sulfur, are present in organic matter. They make up, among other substances, the 50% of OM that is not carbon.

The AAP consists of two components: one for soil temperature and one for water-filled pore space (amount of water in the soil pores). Both are calculated relative to their optimal values for respiration, the same as the basal respiration measurement conditions (see also NOBV, 2022; Boonman et al., 2021). The water-filled pore space is based on HYDRUS model runs of the unsaturated zone at representative peat meadow conditions for every groundwater level between land surface and 1.2 m depth (Šimůnek et al., 2016). Soil temperature is based on NOBV measurements (NOBV, 2022). Specific volume of oxidation ($\hat{V}$) is a quantity that relates the reduction of soil volume (in m^3) to units of organic mass (in kg) degradation due to oxidation (Deltares, 2021; Equation 3).

$$\hat{V} = \frac{0.5}{F_{org} * \rho_{bulk}} * \left(1 + \operatorname{erf}\left(\frac{F_{org} - 0.2}{0.1}\right)\right) \qquad \text{Equation 3}$$

Where *erf* represents the calculation of an error function. For example, organic clays have a lower specific volume of oxidation than highly organic peats. The amount of volume that is lost per unit mass that is oxidized is higher when the soil is dominated by organic matter components. Direct measurements of specific volume do not exist.

Note that the organic matter mass percentage and bulk density are present in Equation 1 and 3. In equation 1, $F_{org} * \; \rho_{bulk}$ is present in the numerator (Eq. 1) and it is present in the denominator in Eq. 3. When plugging equation 3 for specific volume ($\hat{V}$) into equation 1, the bulk density and organic matter mass percentage cancel each other out. The resulting calculation of specific volume in the volume loss equation is now calculated as follows:

$$\hat{V}_{scaled} = 0.5 \;\left(1 + \;\operatorname{erf}\left(\frac{F_{org} - 0.2}{0.1}\right)\right) \qquad \text{Equation 4}$$

The net relative volume loss equation becomes:

$$R_{ox} \;=\; AAP * BR * 0.5\,(1 + \mathrm{erf}\left(\frac{F_{org}-0.2}{0.1}\right)) \quad * \; F_c \qquad \text{Equation 5}$$

Where the relative volume loss is independent of peat density. The scaled specific volume of equation 4 now becomes a scaling factor ($\hat{V}_{scaled}$) based on the organic matter percentage (Figure 4). The curve basically describes whether the peat decomposition leads to full volume loss (40-100% Forg) or to decreased volume loss (Forg < 40%). At first, going from right to left, $\hat{V}_{scaled}$ does not decrease as F_{org} decreases. The relative effective volume loss is maximal (scaling factor = 1). The mineral fraction (at e.g. 50% OM) is present in the pore spaces of peat. Therefore, according to this model, peat mass loss directly translates to volume loss on a 1:1 scale. For low organic matter percentages (organic clays) the mineral fraction forms most of the bearing capacity of the soil. Consequently, loss of organic matter does not directly lead to volume loss. Because of this, the scaled specific volume ($\hat{V}_{scaled}$) line decreases, and the volume loss thus decreases according to equation 1.

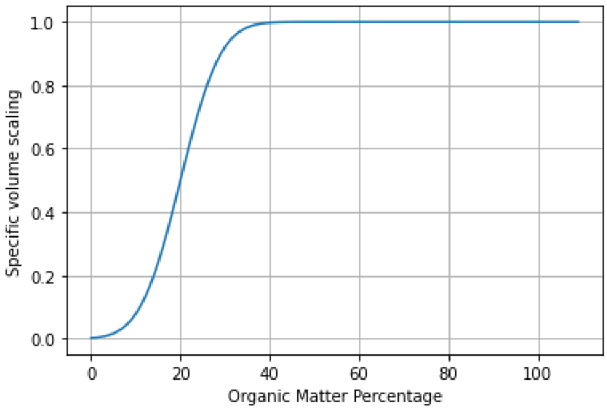

Figure 4. The relation between specific volume and organic matter percentage used in SSOM.

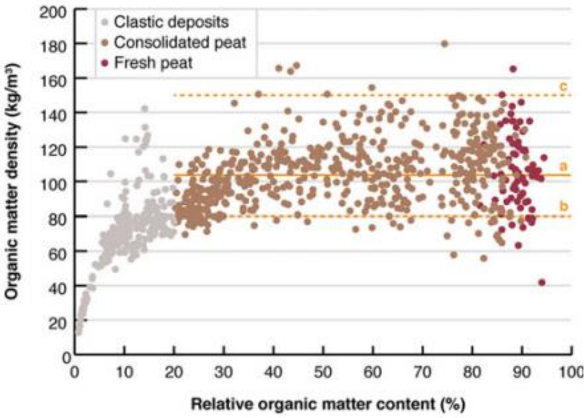

Figure 5. The relation between relative organic matter content (%) and organic matter density (kg/m³) taken from the Dutch coastal and deltaic peatlands (Erkens et al., 2016).

The reasoning behind the shape of this curve is based on the soil density dataset taken in the Dutch coastal plain described by Erkens et al. (2016), where relative organic matter content is plotted against organic matter density (see Figure 5). From this can be concluded that the organic matter density is largely independent of the organic matter content for values larger than roughly 20%. A range is visible within the organic matter density, which reflects variations in porosity and different degrees of peat consolidation, e.g. at a relative organic matter content of 60% the organic matter density ranges between roughly 70 and 150 kg/m^3. Because of this density independence at higher organic matter mass percentages, it is assumed that the volume that oxidizes per unit mass is constant with increasing organic matter percentages, as is shown by the curve in figure 4.

Lastly, relative volume loss $[m^3_{bulk}\, m^{-3}_{bulk} d^{-1}]$ is converted to land subsidence due to oxidation $[mm\ d^{-1}]$ for a set parcel area using the relationship $V = A * H$ where V = volume loss [m^3], A = parcel area [m^2] and H = land subsidence [m].

2.3 Data overview

2.3.1 Zegveld

Two parcels are modeled at the Zegveld study site: parcel 13 and 16 (Figure 1). The groundwater regime of the area is characterized by infiltration and the subsurface composition is dominated by peat. Fortnightly manually measured phreatic groundwater levels between 1994 and 2020 are provided by KTC Zegveld. The corresponding monitoring wells are located in the middle of the parcel and the water level is measured by hand with respect to the surface level. The tubes are about 2 m long and are not founded in the Pleistocene sand layer. As a result, the tubes can move along with the land surface changes during the year, causing an uncertainty in the exact vertical position of the phreatic groundwater level up to several centimeters in a year.

As SOMERS 1.0 model requires daily groundwater values, the fortnightly measured groundwater values are linearly interpolated to obtain daily levels for the period between the 1st of January 1994 and the 31st of December 2019 (Figure 6). The aim of this study is to determine the quality of SSOM. Therefore, measured groundwater levels are used as input, because this contributes to reducing uncertainty of the model outcome. It is, however, also possible to run SSOM with modeled groundwater levels.

The groundwater measurements are relative to the land surface, whereas the model requires groundwater levels relative to the Dutch Ordnance Datum (NAP). Therefore, the groundwater levels have been converted to NAP using the original land surface elevation of 1994. As the original freeboard (compared to the surface level) of 1994 was maintained over the period between 1994 and 2020, and the land surface in SSOM is not corrected for the effects of land subsidence, this simplification does not introduce an error. Moreover, an assumption underlying this method is that the soil composition remains the same, because new soil columns are oxidized due to subsidence and subsequent periodical groundwater level lowering. The organic matter percentage and soil composition must be similar, so that hydrological conditions do not change. This is the case for Zegveld and therefore this method can be used.

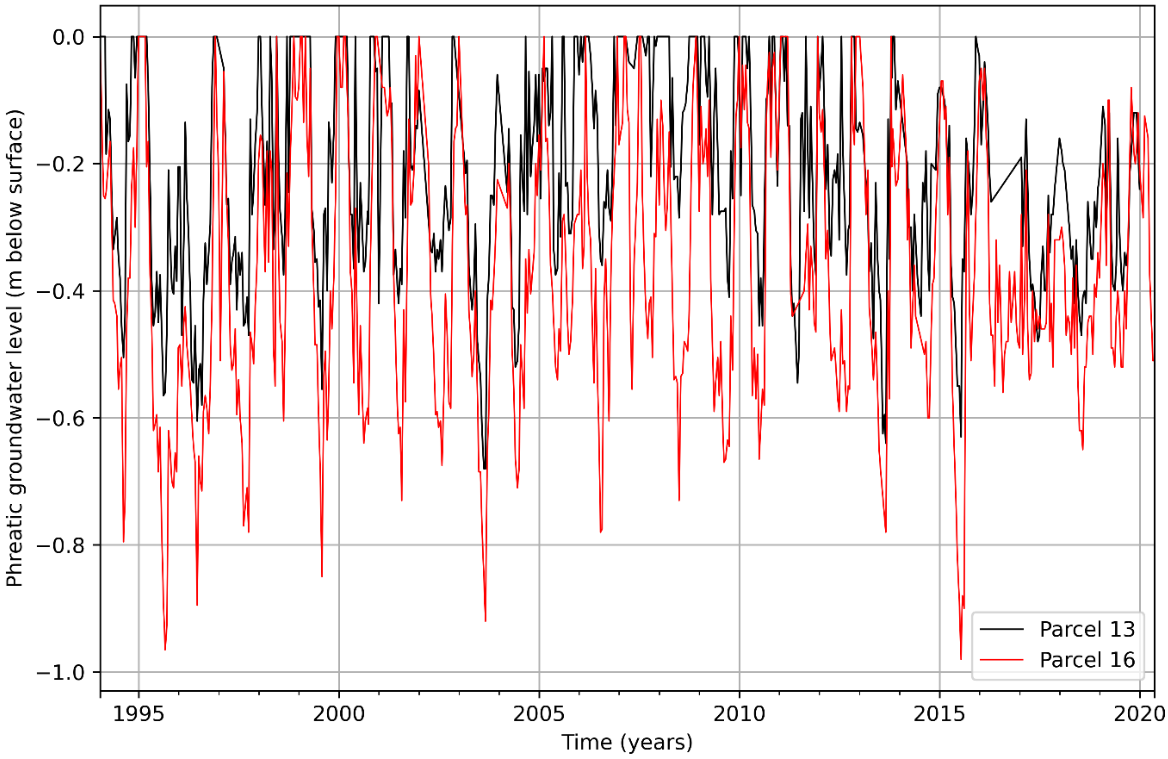

Figure 6. Interpolated phreatic groundwater levels of parcel 16 and 13, Zegveld. Parcel 16 is characterized by lower average groundwater levels than parcel 13. Seasonal fluctuations are clearly visible. The deepest water levels at parcel 13 occur around 60 cm below the land surface. The deepest water levels at parcel 16 are present up to 100 cm, but generally occur around 60-70 cm below the land surface.

Shallow land subsidence measurements for both parcels were shared by the WEnR (Wageningen Environmental Research). Yearly measurements were done at various moments in spring between 1970 and 2020. Land surface elevations were measured with respect to the Dutch Ordnance Datum (NAP) on 20 cm intervals between the surface and 140 cm depth. Metal disks attached to a tube were placed at the vertical 20 cm soil intervals. The top of the tubes can be measured to obtain elevation data of the respective soil interval (STOWA, 2020). A model run requires (1) groundwater data as input and (2) subsidence data to compare to the model outcome. The Zegveld model runs are performed between 1994 and 2020 (26 years), because only for this period both data requirements are fulfilled.

2.3.2 Rouveen

At the Rouveen study site, two parcels are modeled: parcel 05B and parcel 09 (Figure 1). The groundwater regime of the area is characterized by seepage. In addition, a clay layer of about 35 cm thickness is present on top of the peat layer. Phreatic groundwater levels were shared by the NOBV. The groundwater tubes are founded in the Pleistocene sand layer to prevent the tube from moving along with soil movements. The water levels are measured automatically every hour relative to the land surface using an Ellitrack-D measurement device (NOBV, 2021). The monitoring well used for this study is placed at 50% of the parcel width and the measurement duration is about 3 years. The water levels are resampled from hourly to daily values to obtain the same measurement interval as the Zegveld water levels. The phreatic groundwater levels of Rouveen show a similar pattern compared to Zegveld's groundwater levels (Figure 7). The groundwater levels are originally recorded with respect to NAP, so the conversion is not an issue for these groundwater levels.

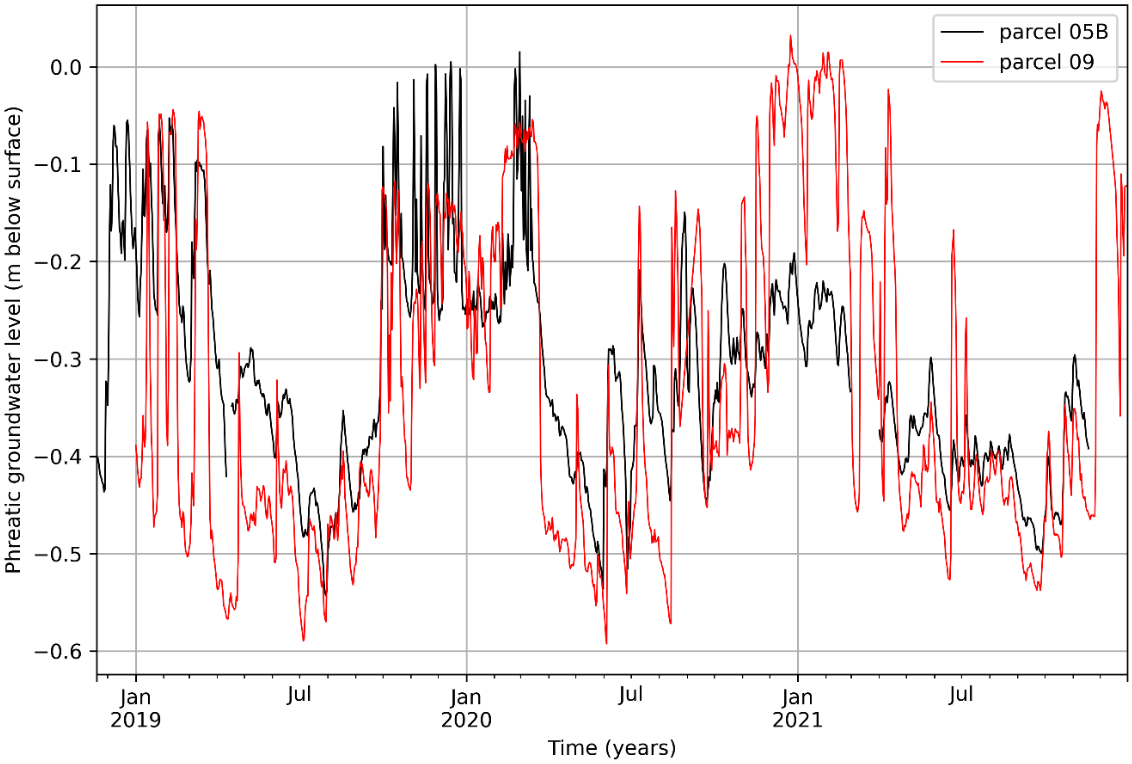

Figure 7. Interpolated phreatic groundwater levels of parcel 05B and 09, Rouveen. Note that the timespan is much shorter than at Zegveld: 3 years instead of 26. The accuracy of this figure is greater than figure 6 due to the significantly more frequent measurement interval. The water level is above the surface at times, which depicts a flooding of the land surface. Parcel 09 generally shows generally larger extremes than parcel 05B. In the key periods for oxidation (spring/summer) parcel 09 depicts lower groundwater levels. Furthermore, compared to the Zegveld study site the Rouveen water levels display shallower groundwater levels. Phreatic levels of 60 cm below the land surface are frequently exceeded on parcel 16, whereas these never occur at the Rouveen study site.

Shallow land subsidence measurements by extensometers were provided by the NOBV on an hourly basis between 2019 and the present. The extensometer is a device to measure vertical movement of the (sub)surface using different subsurface levels called anchors (Van Asselen et al., 2020). The lowest level is anchored in the Pleistocene sand and acts as the reference level. At parcel 05B the anchor depths are (1) at the land surface, (2) at the transition between clay and peat at 35 cm depth and (3) at 115 cm depth. At parcel 09 only the surface levels and the 115 cm depth level are equipped with an anchor. The Rouveen model runs are performed between 1-1-2019 and 31-12-2021 (3 years), because only for this period the data requirements (groundwater and subsidence data) are fulfilled.

2.4 Comparison to measured subsidence and literature oxidation

Land subsidence due to oxidation is modeled (SSOM). To assess the quality of the model, the outcome is compared with measured subsidence due to oxidation and oxidation values from literature. This section explains how to total measured subsidence and subsidence due to oxidation are separated. In addition, it describes which oxidation-related subsidence values reported in literature are used.

2.4.1 Oxidation analysis

The subsidence measurements described in section 2.3 reflect total subsidence of the soil. Therefore, an analysis is made wherein the oxidation component of the total land subsidence is separated. The groundwater table is used as the separator between oxidation (and possibly irreversible shrinkage) and consolidation because oxidation does not occur in the saturated zone (Hooijer et al., 2012). Peat compaction above the groundwater level also takes place but is assumed to be small because of the absence of loading due to e.g. buildings. After separating the oxidation and non-oxidation zone, a linear trend line is drawn through the land surface data and the separation depth (Figure 8). The difference between these trend lines is the land subsidence due to oxidation.

Furthermore, it is assumed that the ratio between subsidence due to oxidation and subsidence due to mechanical processes (e.g. consolidation) stays the same over time. This method yields an average oxidation contribution, while in reality the subsidence quantity changes due to groundwater level lowering. Shortly after water level lowering, the soil must find a new equilibrium, leading to more consolidation. The relative contribution of oxidation is lower in these periods. Oxidation is a constant process and therefore large timescales are required to make reasonable estimates. It is thus important to obtain information on the ditch water level adjustment to gain more insight in the land subsidence that has occurred as a result of consolidation shortly after water level lowering and the land subsidence due to oxidation.

Zegveld

For parcels 13 and 16 respectively, the 60- and 80 cm depth levels are taken as the separator between the oxidation and non-oxidation zone. The phreatic groundwater levels barely surpass this depth (Figure 6) and therefore it is considered a safe assumption that below this depth oxidation does not take place. Furthermore, the dataset contains about almost 50 measured years, whereas the model run is only 26 years. Some data points seem to be outliers, such as the last measurement point of the surface at parcel 13 and 16 (Figure 8). It is not certain if these outliers are measurements errors or natural deviations from the trend. The choice is made to do the analysis for both timespans: (1) the model run (1994-2020), and (2) the entire dataset. Together they form the upper and lower bandwidth of the results of this analysis. This way, the impact of measurement errors is minimized.

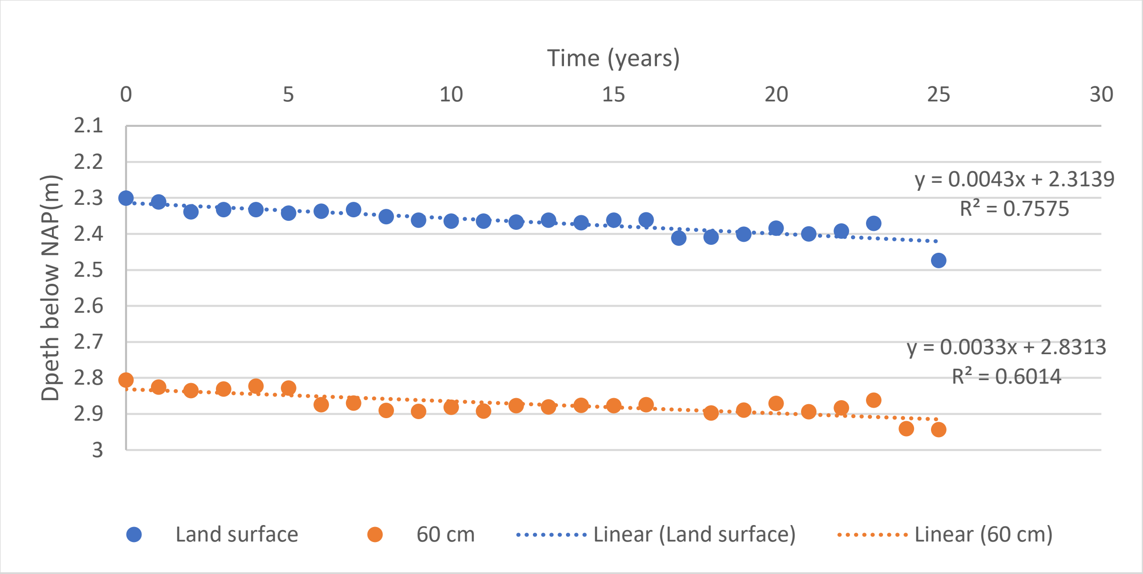

Figure 8. The land subsidence measurements of parcel 13 (Zegveld) with trend lines through the land surface elevation and the 60 cm depth level. The surface level decreases faster than the 60 cm depth interval. The difference between these trend lines is the subsidence due to oxidation. The R^2 of the trend lines show a reasonable correlation between time and land elevation in this dataset.

Rouveen

The Rouveen subsidence dataset differs from the Zegveld dataset in three ways that affect the oxidation analysis significantly, (1) the measurement length is only 3 years in contrast to almost 50 years, (2) the measurement frequency is much higher, and (3) a clay layer is present on top of the peat. Due to reason (1) and (2) the long-term trend cannot be drawn as accurate as for Zegveld, because the seasonal fluctuations have too much impact in this short measurement period (Figure 9). A linear trend line is drawn through the subsidence data, showing reduced land level elevations as outcome. The R^2 values of the linear trend lines indicate a less accurate correlation. This introduces a different type of uncertainty, which can in the future be solved with longer measurement series. Furthermore, the presence of a clay layer of roughly 35 cm on top of peat makes the previously described method not applicable for parcel 09, because the land movement is only measured at the surface and 1.15 m depth level. Subsidence due to oxidation between clay and peat layers cannot be distinguished at this parcel. At parcel 05B a clay layer on top of peat is present too, but the extensometer measures at the transition between clay and peat (0.35 m depth) and therefore an oxidation rate could be determined for this parcel.

Figure 9. Land elevation changes of parcel 05B (Rouveen). Trend lines are drawn through the curves to show that the trends between the surface and 115 cm depth interval differ in steepness. The linear correlation coefficients (R^2) are, however, not high on these short time scales due to the large seasonal variety. Source: NOBV measurements.

2.4.2 Oxidation-induced subsidence from the literature

Furthermore, an oxidation-induced subsidence value from the literature for both locations is determined using the measured linear surface level subsidence trend and oxidation percentages found by several authors in comparable areas (Schothorst, 1977; Erkens et al., 2016; Van Asselen et al., 2018). Schothorst (1977) found an oxidation contribution of 50% over 6 years. Erkens et al. (2016) found 72% as the best estimate scenario in the last 1000 years of peat oxidation in the Netherlands. Van Asselen et al., (2018) found a range of oxidation-caused subsidence values between 39% and 71% in the last 1000 years in the Netherlands, of which the 39% was in a similar area (agricultural loading). This value is therefore taken as the lower boundary for literature oxidation.

2.5 Sensitivity analysis and density analysis

2.5.1 Sensitivity analysis of basal respiration

The model outcome is compared to measured oxidation data and oxidation values from literature, but it is also valuable to have an idea of the sensitivity of the model for changes of a parameter. For example, one parameter may be measured or implemented incorrectly, with large effects on the model outcome. When looking at the governing equation of SSOM (Equation 5) the main model inputs are the soil temperature and soil water (both in AAP), organic matter mass percentage and the basal respiration. The aim of this study is to research how well the SSOM model performs assuming that the organic matter mass percentages and AAP calculation is correct, so these are not suited for the sensitivity analysis. The basal respiration is assumed to have a large influence on the model outcome and has a large uncertainty bandwidth (Figure 10). It is therefore picked for the sensitivity analysis. The lower and upper quartile are used as lower and upper boundaries of the basal respiration parameter. Model runs are done with these boundaries forming a bandwidth around the median basal respiration value to obtain an idea of how sensitive the model outcome is to changes in this parameter. The obtained bandwidth is compared to the oxidation values in the literature and the subsidence due to oxidation analyzed from measurements.

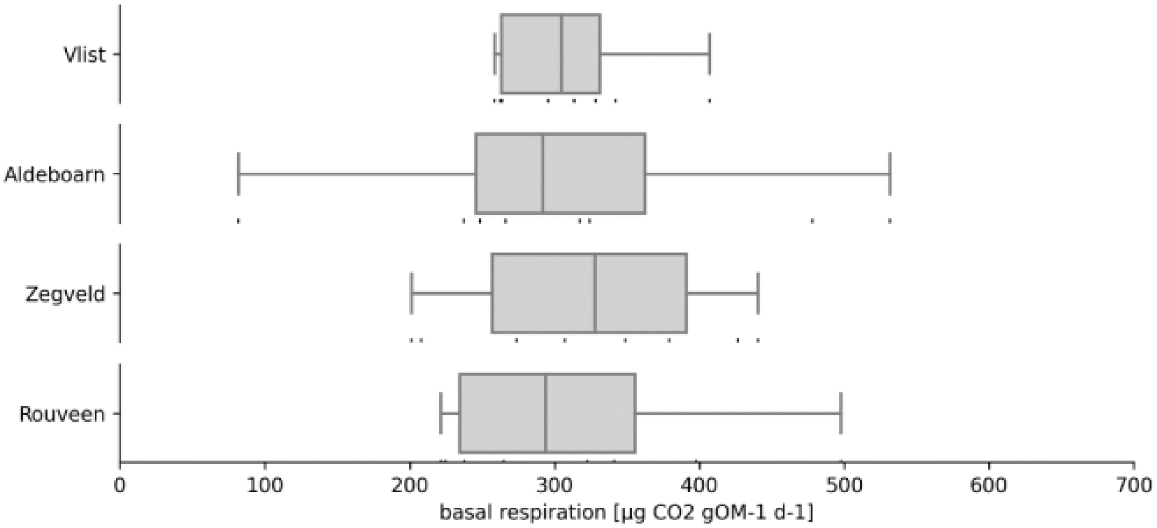

Figure 10. Measured basal respiration rates of peat samples collected from different NOBV measurement sites. The measurements are carried out under optimal conditions in the laboratory (Erkens et al., 2021). Note the large spread of data between the lower quartile (Q1) and the upper quartile (Q3) around the median (Q2).

2.5.2 Density analysis

To determine the influence of organic matter density different in peats soils on the amount of land subsidence due to oxidation, an analysis is done of a large dataset of peat densities. The dataset combines two measurements campaigns: (1) the data used by Erkens et al., (2016) taken in the Dutch coastal plain, and (2) data from the NOBV taken at the NOBV study sites in the Dutch peat meadow areas. The measurement method is described in NOBV (2021) and the measurement locations can be found at NOBV (2022). In the analysis, plots of organic matter density versus content are made to compare to the current relationship (Figure 5).

2.6 Model assumptions

The process-based modeling approach with relatively small run times requires several assumptions and simplifications. Key assumptions in SSOM are discussed here. Further assumptions made in the SOMERS 1.0 model about soil temperature, soil composition and water-filled pore space are described in the SOMERS Documentation (NOBV, 2022).

- The fraction of carbon in organic matter is assumed to be 50% (Erkens et al., 2016). This estimation is important to obtain the right amount of mass that respires per unit soil mass and ranges in literature. The value is supported by carbon density values found by Gorham (1991) and is important to estimate the amount of carbon in organic matter correctly (equation 2).

- Anaerobic peat decomposition is neglected. In reality, the anaerobic peat decomposition is estimated to be around 10% of the total decomposition (NOBV, 2022). This, however, differs largely per situation. Anaerobic peat decomposition can result in nitrous oxide (N_2O) and methane (CH_4) emission. NOBV research has found that nitrous oxide and methane emissions are mainly present under relatively wet conditions, respectively, with phreatic levels of 20 cm or 40 cm and less below the land surface. Little is known about (modeling) CH_4 and N_2O emission.
- The influence on pH is neglected. The pH is reported as a factor in peat decomposition (Limpens et al., 2008). However, temperature and hydrological conditions seem to play a more significant role in peat decomposition (Kluber et al., 2020; Deltares (NOBV, 2022)). Also, the exact relations between pH, peat type and the amount of decomposition are not yet known. For these reasons, the pH is not included in the model
- The organic matter content and initial land surface elevation do not change over time. This assumption adds to the paragraph where the groundwater conversion to values relative to NAP is described. The groundwater levels function because the initial land surface does not change. In addition, the organic matter content is static. This assumption only holds if the subsurface composition is of the same substance and organic matter percentage as the subsurface considered during the initial conditions. For example, the average groundwater level is 60 cm below the surface and during 20 years of oxidation 10 cm of soil subsidence has taken place. The groundwater is lowered to be at 50 cm below the surface, but a new part of fresh material, which was originally between 50 and 60 cm depth, is now prone to oxidation. The assumption holds as long as the subsurface composition does not change, and therefore limits the amount of time that can reliably be simulated by the model. The outcome of e.g. 500 years of model simulation will probably not hold.

3. Results

3.1 Analysis of oxidation component of the measured subsidence data

In this section, the results of the measured subsidence data analysis will be shown. The oxidation component is separated from the total subsidence to compare this with modeled subsidence due to oxidation, aiming to answer research question 1 and 2.

3.1.1 Zegveld

The correlation coefficients of the trend line that are drawn to separate the subsidence due to oxidation component from the total subsidence are relatively high (Table 1), especially the correlation coefficients relating the surface level change to time. It is noteworthy that the correlation coefficients are higher (more accurate) when the entire dataset is used instead of only the years 1994-2020. Remarkable is the outlier of parcel 16 where the division line R-value is only 0.07, which is because of many outliers and variations in the soil level at this depth. These outliers have significant less influence if the entire dataset is used for the trend line (0.79 instead of 0.07).

Table 1: An overview of correlation coefficients of the oxidation analysis at Zegveld. The surface R-value gives the correlation coefficient between the surface level change and time. The division line R-value is the correlation coefficient between the depth horizon just below the lowest groundwater level, used to separate subsidence due to oxidation from the other processes, and time. The oxidation trend shows the subsidence due to oxidation rate of the trend line that is drawn through the subsidence data points.

Location	Time period	Surface R-value	Division line R-value	Oxidation trend [mm/y]	Contribution of oxidation to total subsidence
Parcel 13	1973-2020	0.96	0.86 (60 cm depth)	1.9	44%
Parcel 13	1994-2020	0.87	0.77 (60 cm depth)	1	23%
Parcel 16	1970-2020	0.93	0.79 (80 cm depth)	2.5	57%
Parcel 16	1994-2020	0.69	0.07 (80 cm depth)	4.1	93%

3.1.2 Rouveen

The correlation coefficients of the trend lines, that are used to separate subsidence due to oxidation from total subsidence, are shown in Table 2. Note the very low surface subsidence rate at parcel 09, compared to the other parcels (all order of 5 mm/y) and the corresponding low correlation coefficient (0.37). The subsidence due to oxidation from literature is calculated as a percentage of the surface level (=total) subsidence from measurements. Therefore, the oxidation related subsidence rate from literature is also low. The low surface subsidence rate can be explained by the thickness of the saturated peat layer, which was thin compared to the saturated peat layer at parcel 05B. A large part of the yearly surface movements results from this layer. Thus, the surface elevation changes were small at parcel 09. Furthermore, the clay on top of the peat may slow down oxygen uptake and bacteria transport to the peat.

Furthermore, at parcel 05B the division lines at 35 and 115 cm depth showed low correlation coefficients, whereas the surface level showed a moderate correlation. This is because the measurement resolution is significantly larger (hourly to annually) than at Zegveld. Therefore, although there is a subsiding trend, there is no strong correlation between land level change and time. This is illustrated by Figure 9 where the land surface shows large seasonal variations and a linear trend is thus not readily found.

Table 2: An overview of correlation coefficients of the oxidation analysis at Rouveen. The surface R-value gives the correlation coefficient between surface level change and time. The division line R-value is the correlation coefficient between the depth horizon just below the lowest groundwater level, used to separate subsidence due to oxidation from the other processes, and time. The oxidation trend shows the subsidence due to oxidation rate of the linear trend line that is drawn through the subsidence data points. As described in the Methods section, the analysis could not be performed entirely at parcel 09 (indicated by not available (NA)).

Location	Surface trend R-value	Division line R-value	Oxidation trend [mm/y]	Surface level trend [mm/y]	Contribution to total subsidence
Parcel 09	0.37	NA	NA	1.75	-
Parcel 05B	0.51	0.31 (35 cm depth) and 0.33 (115 cm depth)	0.88	5.26	17%

3.2 Model results

3.2.1 Zegveld

The cumulative modeled land subsidence due to oxidation parcels show clear yearly patterns in terms of land subsidence rates (see Figure 11 and 12 for respectively parcel 13 and 16). Remarkable are the years 1995 and 2003 where the subsidence rate is the largest of the entire model timespan. It can be partly attributed to lower groundwater levels (Figure 6), which caused the conditions, such as the AAP, to be favorable for decomposition. Furthermore, the total subsidence due to oxidation is significantly higher at parcel 16 than 13 (Table 3), which is expected based on the lower average groundwater levels at parcel 16. 2007 stands out as a year with lower subsidence rates, up to almost 0. It was probably a wet year, causing shallow groundwater levels (Figure 6). The model shows a large variety between years based on e.g. climatic conditions. Moreover, within years seasonal fluctuations are visible. The subsidence trend is without question, but the rates clearly differ between summer and winter seasons. Every summer an oxidation caused subsidence jump takes place. The amount depends on the conditions in the field that vary between years due to, for example, climatic fluctuations or human-induced groundwater level changes.

Table 3: Descriptive statistics of the modeled subsidence due to oxidation for the Zegveld study area

Location	**Parcel 13**	**Parcel 16**
Average yearly oxidation caused subsidence	2.78 mm/y	6.38 mm/y
Standard deviation of the yearly oxidation caused subsidence	1.25 mm/y	1.93 mm/y
Total subsidence due to oxidation	71.4 mm	164 mm
Largest yearly subsidence due to oxidation rate	5.87 mm (2003)	11.6 mm (1995)
Smallest yearly subsidence due to oxidation rate	0.24 mm (2007)	3.4 mm (2007)

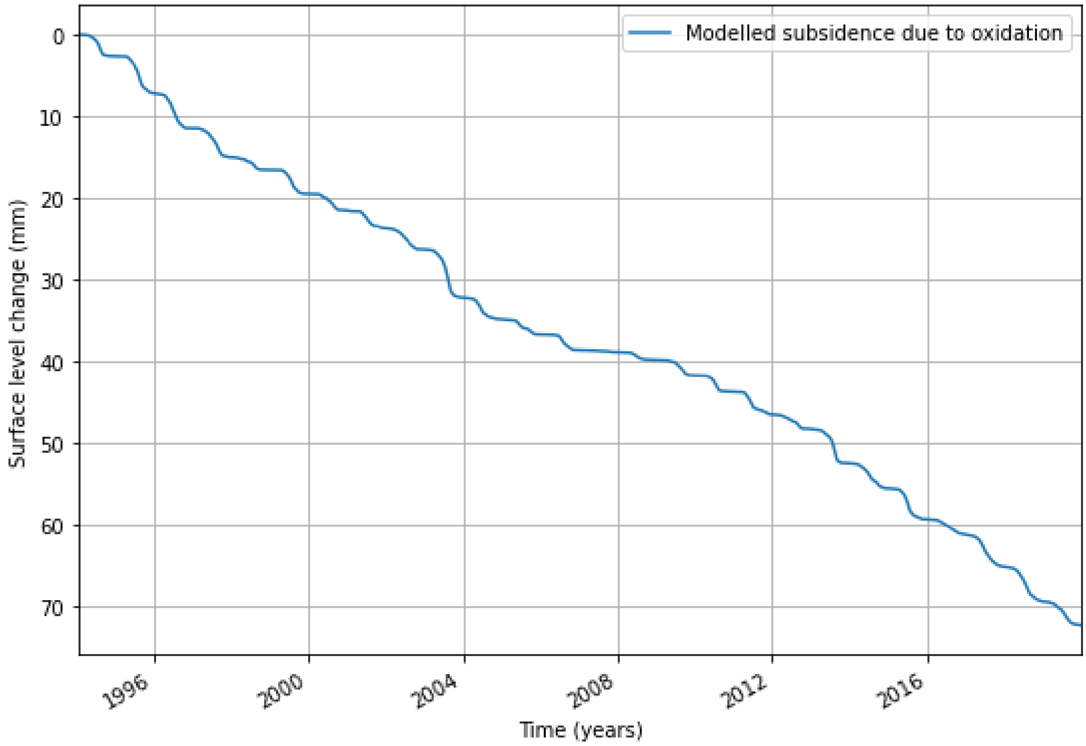

Figure 11. Cumulative modeled land subsidence due to oxidation (blue) at parcel 13 (Zegveld). Variations between years and within years are clearly visible. Every year shows a steep decline around the summer months in which significant subsidence occurs.

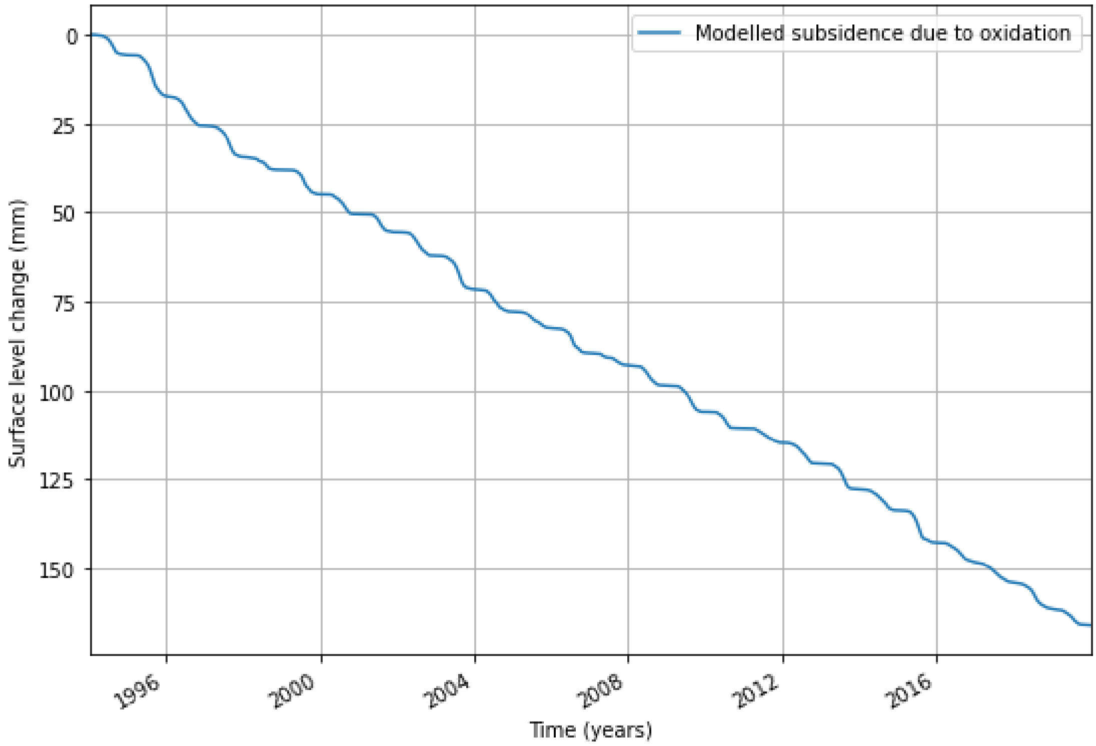

Figure 12. Cumulative modeled land subsidence due to oxidation (blue) at parcel 16 (Zegveld). Variations between years and within years are clearly visible. Every year shows a steep decline around the summer months in which significant subsidence occurs. The years 1997 and 2003 are noticeable because of their large surface level change.

3.2.2 Rouveen

The Rouveen modeled period is short (3 years), but also shows distinctive variations between seasons in more detail than the Zegveld results (Figure 13 and 14 for respectively parcel 09 and 05B). Despite the clay layer present in this area, the average yearly subsidence due to oxidation is in the same order of magnitude (Table 4). The timespan is too short to notice large differences between years. Note that the standard deviations are also very small because of the small sample size and small variety between the years. The months in which most subsidence occur are May until September, which is caused by high temperature and deep phreatic levels. In winter months, subsidence due to oxidation hardly occurs if the water levels are close to the surface and the temperatures are low. This is not always the case. For example, parcel 05B (Fig. 14) shows some subsidence due to oxidation in the winter of 2021. This can be related to relatively deep groundwater levels for the winter months (Fig. 7).

Table 4: Descriptive statistics of the modeled subsidence due to oxidation for the Rouveen study area.

Location	**Parcel 09**	**Parcel 05B**
Average yearly oxidation caused subsidence	4.88 mm/y	2.16 mm/y
Standard deviation of the yearly oxidation caused subsidence	0.64 mm/y	0.15 mm/y
Total subsidence due to oxidation	14.6 mm	6.5 mm
Largest yearly subsidence due to oxidation rate	5.58 mm (2019)	2.27 mm (2019)
Smallest yearly subsidence due to oxidation rate	4.32 mm (2021)	1.99 mm (2011)

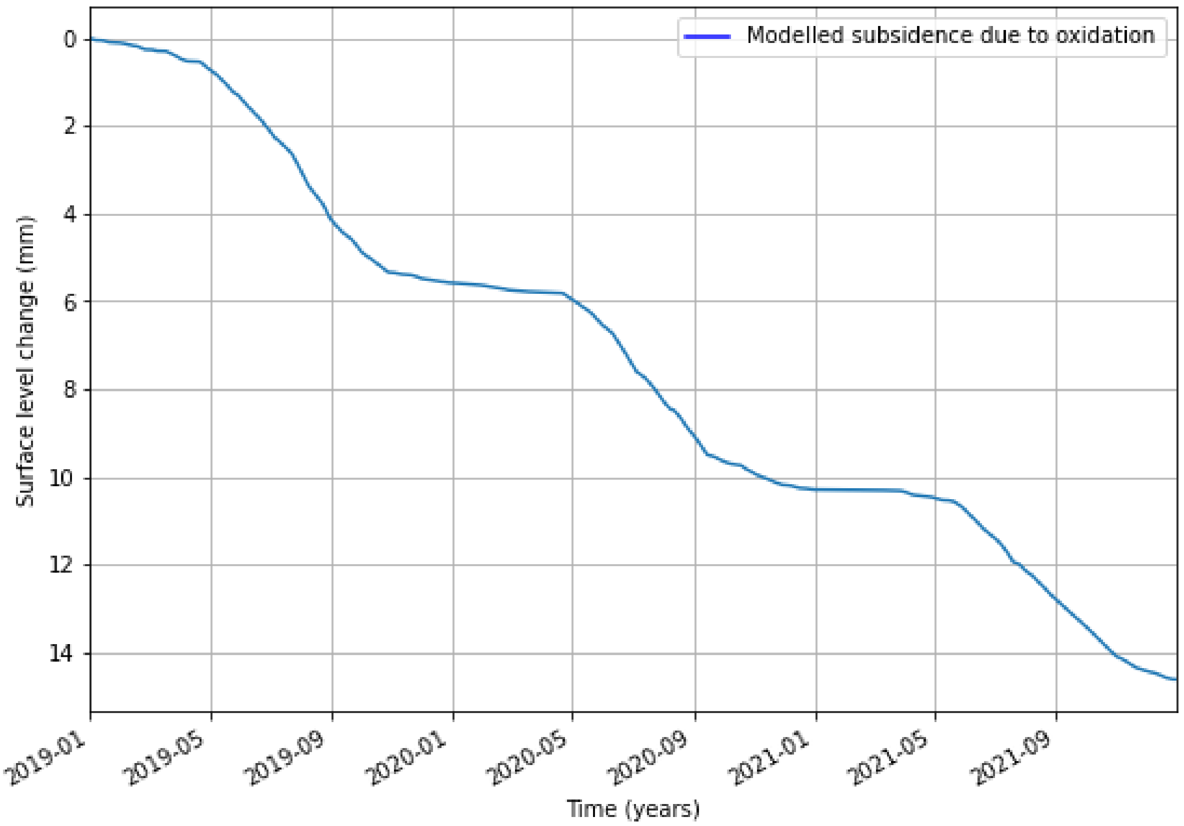

Figure 13. Cumulative modeled land subsidence due to oxidation (blue) at parcel 09 (Rouveen). Seasonal variations are clearly visible. Every year shows a steep decline around the summer months in which significant subsidence occurs. The winter months show hardly any subsidence.

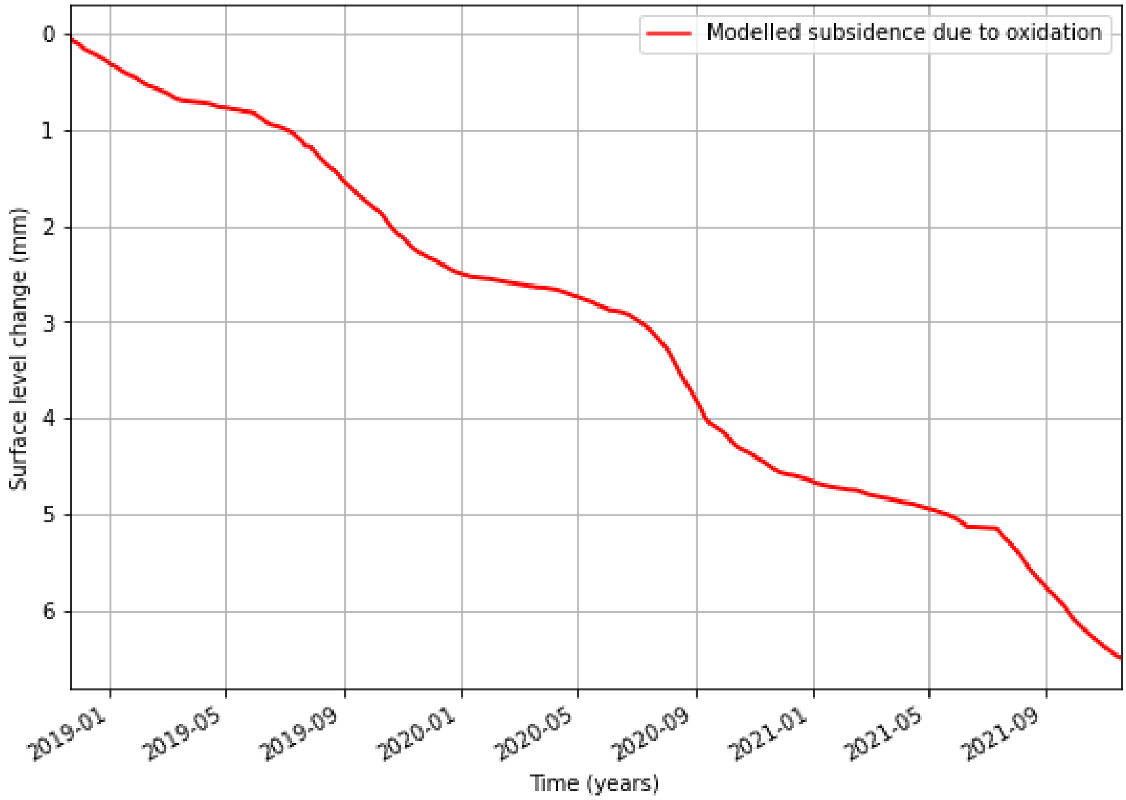

Figure 14. Cumulative modeled land subsidence due to oxidation (red) at parcel 05B (Rouveen). This parcel is remarkable for the relatively weak season variations. Most subsidence due to oxidation still occurs in the summer months, but the winter also contributes, especially the winters of 2019 and 2021.

3.3 Model comparison and sensitivity analysis results

In this section, the results of the sensitivity analysis are shown in the form of an uncertainty bandwidth around the modelled land subsidence due to oxidation. These are compared with oxidation values reported in the literature and subsidence due to oxidation analyzed from measurements, which both are also shown with an uncertainty bandwidth.

3.3.1 Zegveld

The calculated bandwidth of the basal respiration model parameter shows subsidence due to oxidation rates in the same order of magnitude as the uncertainty bandwidth of oxidation values from literature and oxidation values analyzed from measurements (Figure 15 and 16). For both parcels, the basal respiration bandwidth forms about 33% of the total modeled subsidence due to oxidation. The oxidation caused subsidence values from literature correspond well to the modeled values on parcel 13, whereas the measured values show less surface level change. The overlap is not present at parcel 16 (Fig. 16) where the modeled values are clearly largest. They are, however, still in the same order of magnitude.

The oxidation trends (1994-2020 and 1973-2020) at parcel 13 are both supported by high correlation coefficients (Table 1; Figure 15). The long-term trend has a higher contribution to total subsidence and slightly higher correlation coefficients. It is possible that measurement errors lead to a less reliable R-value on the shorter term (1994-2020). For example, the measurements of subsidence at parcel 13 shows a strangely large subsidence for 2020 (see Figure 8). At parcel 16, the 1994-2020 trend line may be less reliable due to the very low correlation coefficient of 0.07 for the division line that separates the part where oxidation occurs from the part without oxidation. This may be caused by gaps in the subsidence measurements and measurement errors. In addition, the 1970-2020 trend line has good correlation coefficients and estimates the contribution of oxidation to total subsidence at a more realistic value (57% compared to 93%). This is consistent with the 44% oxidation to total subsidence that is found at parcel 13. At parcel 16, the difference between modeled oxidation and deduced oxidation from measurements remains large, especially because the 1970-2020 (upper black line) is deemed significantly more likely than the 1994-2020 trend line.

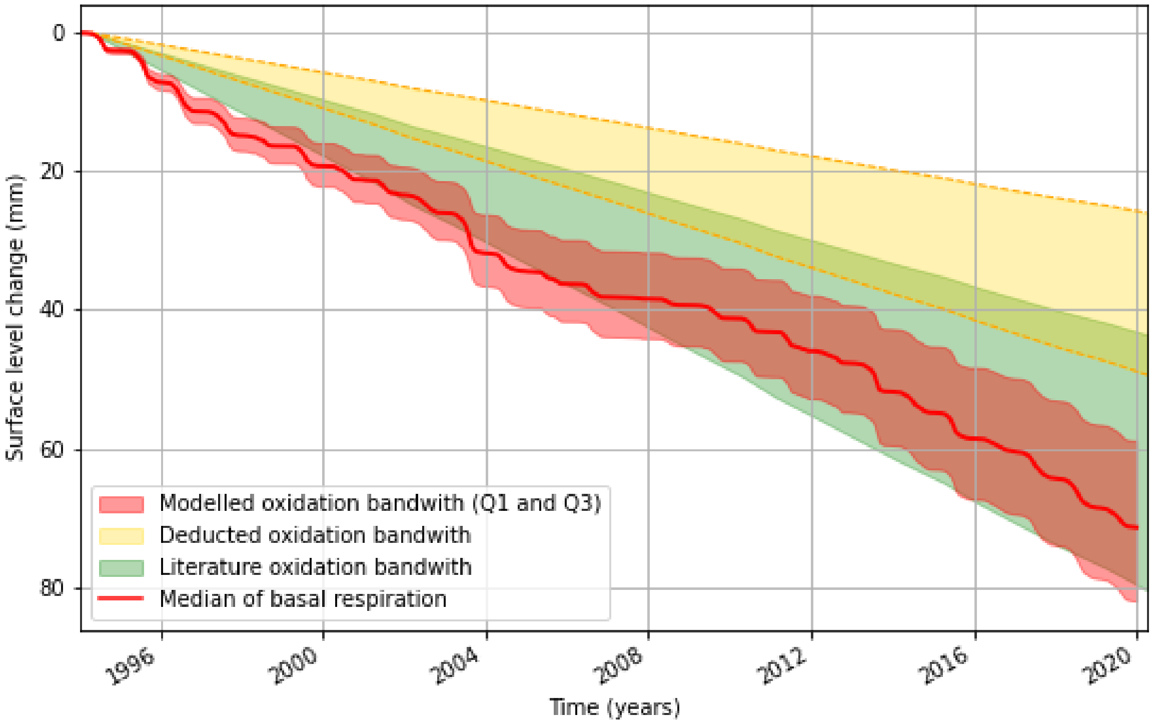

Figure 15. Modeled land subsidence due to oxidation (red) at parcel 13 (Zegveld) compared to deduced oxidation from measurements and oxidation values from literature. The indicated bandwidth around modeled subsidence due to oxidation are the Q1 (first quartile) and Q3 (third quartile) values of basal respiration measurements. The striped orange lines indicate the range of the deduced oxidation bandwidth from measurements. The upper and lower line are represented by respectively the 1994-2020 and 1973-2020 analyses. The bandwidths show oxidation caused subsidence rates in the same order of magnitude.

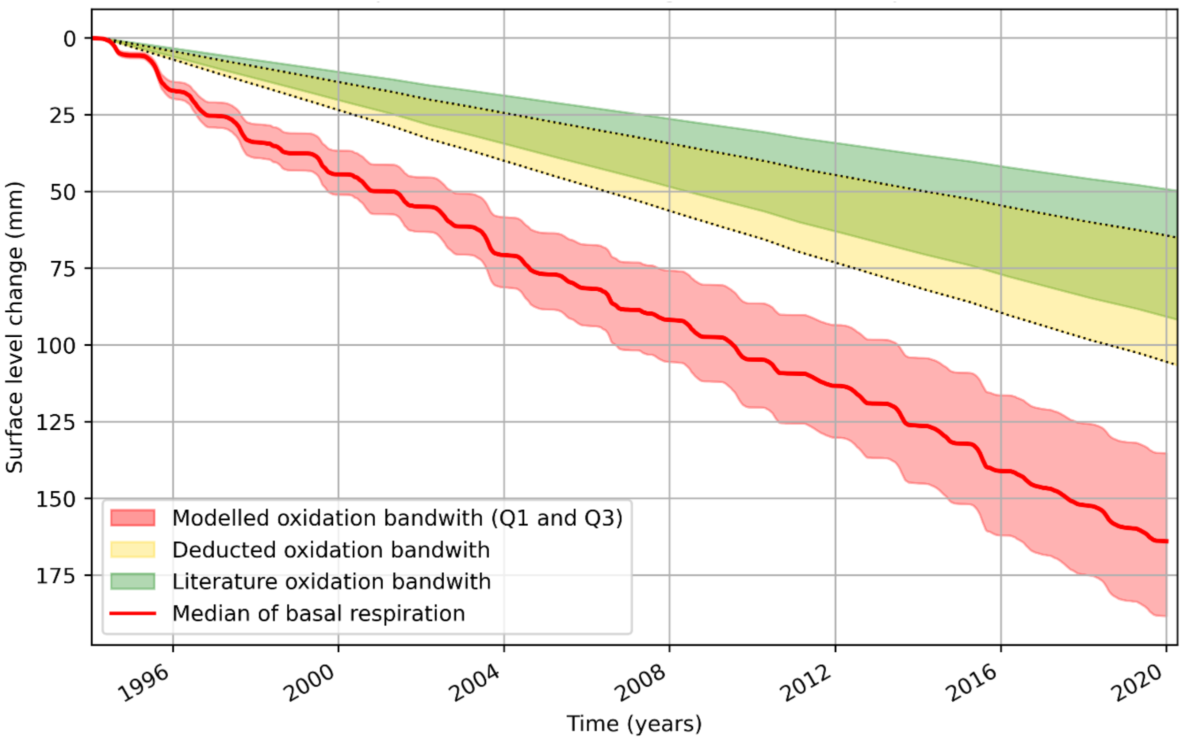

Figure 16. Modeled land subsidence due to oxidation (red) at parcel 16 (Zegveld) compared to deduced oxidation and oxidation from literature. The indicated bandwidth around modeled oxidation are the Q1 (first quartile) and Q3 (third quartile) values of basal respiration measurement. The black striped lines indicate the range of the deduced oxidation bandwidth. The upper and lower line are represented by respectively the 1970-2020 and 1994-2020 analyses.

3.3.2 Rouveen

The model comparison at the Rouveen study site is shown (Figure 17 and 18). At parcel 05B, the deduced oxidation from measurements is small, and the oxidation caused subsidence values from the literature overlap with modeled values. The correlation (Table 2) between the 35- and 115 cm depth levels is weak due to different measurement intervals (hourly instead of yearly) and a short dataset of only 3 years. The contribution to total subsidence was estimated at only 17%, which is much lower than values reported in the literature (39-72%). The clay layer on top of the peat may explain part of this low value. Clay contains little organic matter and is present in the topsoil where normally most oxidation takes place. The land subsidence due to oxidation on parcel 09 is larger than on parcel 05B, which is as expected based on the lower groundwater levels at parcel 09. The modeled subsidence due to oxidation is 4 times as large as the literature subsidence.

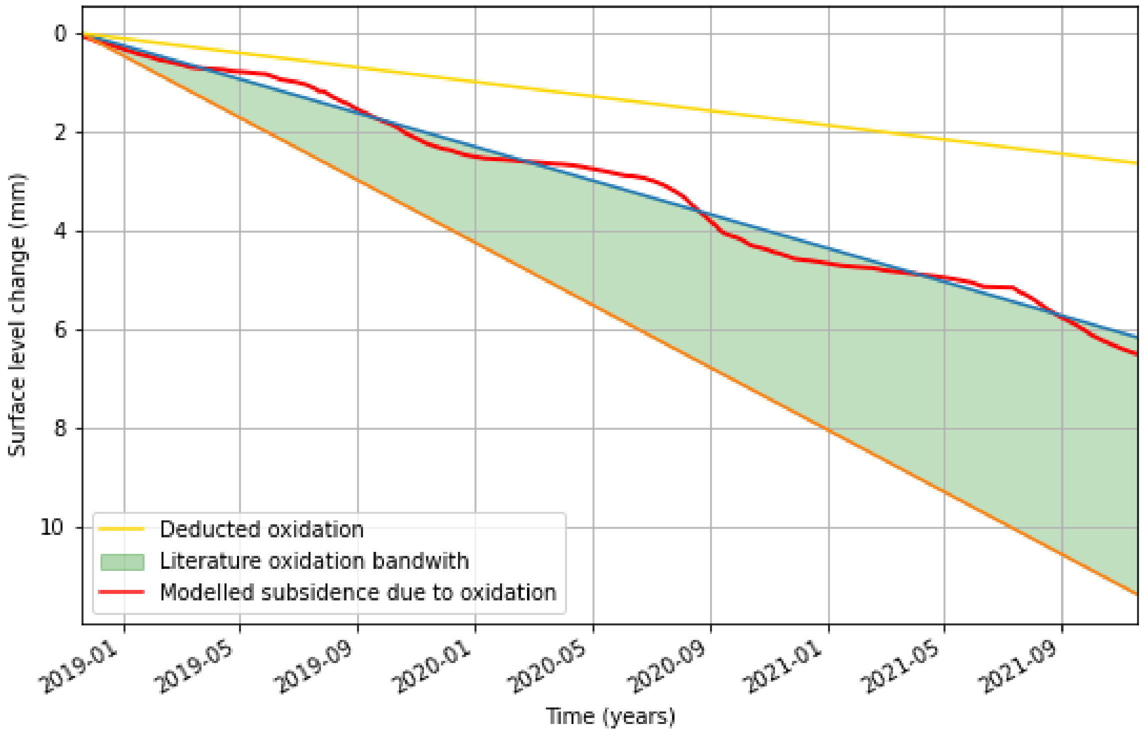

Figure 17. Modeled land subsidence due to oxidation (red) at parcel 05B (Rouveen) compared to deduced oxidation (yellow) and oxidation from literature (green bandwidth). The blue and orange line represent the upper and lower boundary of literature oxidation, respectively 39% (Van Asselen (2018) and 72% (Erkens et al., 2016).

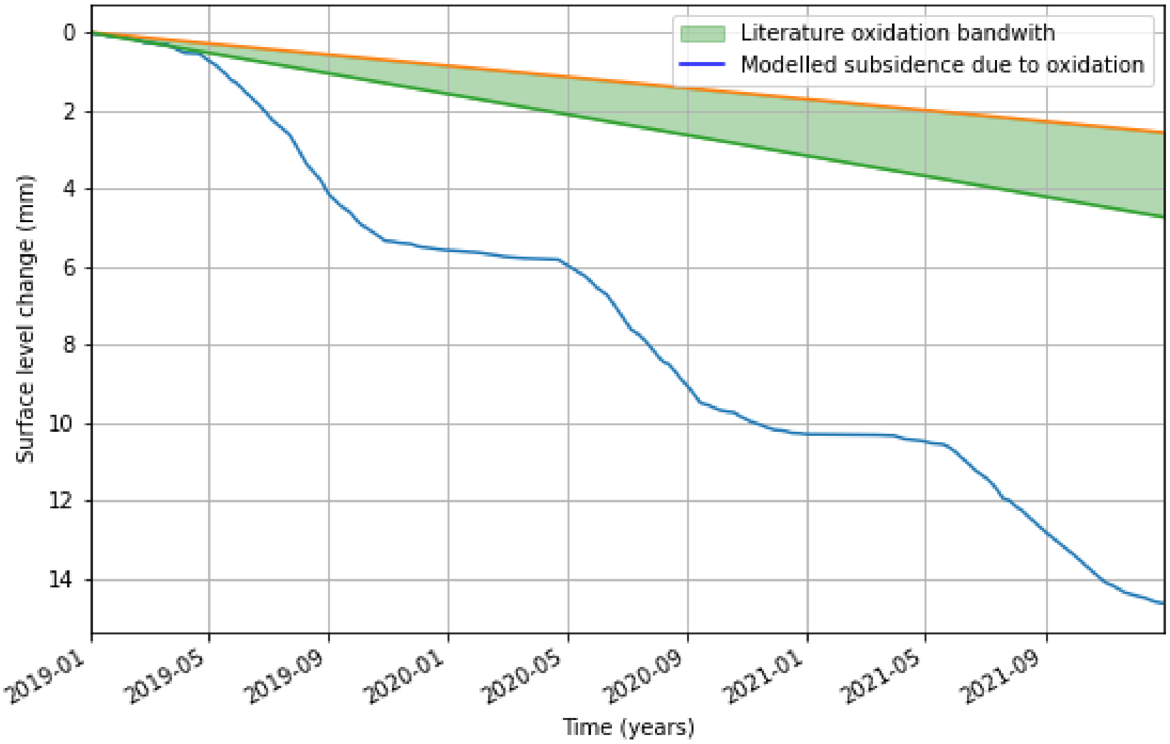

Figure 18. Modeled land subsidence due to oxidation (blue line) at parcel 09 (Rouveen) compared to oxidation from the literature. The analysis of oxidation from subsidence measurements could not be performed reliably at this site and is therefore absent. The orange and green line represent the upper and lower boundary of literature oxidation, respectively 39% (Van Asselen et al., 2018) and 72% (Erkens et al., 2016)

3.4 Relation between density and organic matter mass percentage

As mentioned in the methods section, peat density in SSOM does not play a role in the calculation of subsidence due to oxidation. The relation between organic matter percentage and volume loss is strongly influenced by peat density (Figure 4 and 5). Figure 19-21 show the relation between organic matter density and relative organic matter content. Note that the organic matter density (OMD) is the organic matter content (F_{org}) multiplied by the soil bulk density. As noted by Erkens et al. (2016) the organic matter density is largely independent of the organic matter content for values greater than 20%. However, the plots show a wide variation of peat densities between 75 and nearly 250 kg/m^3. The same plot is made for measurements taken specifically at NOBV measurement sites from the top 120 cm of the soil (Figure 20).

Remarkable are two things: (1) the average density is significantly higher (150 kg/m^3 for NOBV data compared to 124 kg/m^3 for the overall dataset of Fig. 19) and (2) the plot is less complete in the sense that not all combinations of OMD and F_{org} are present. Between OMD of 75 kg/m^3 and 100 kg/m3, there are many data points present in Figure 19, whereas they are not in Figure 20. Apparently, the peats with low densities are not present abundantly in the top 120 cm of the soil between OMD 20-70%. In addition, there are two clusters of peat type present: (1) fresh peat with high organic matter content of 70-90% and a relatively low density and (2) compacted peat with low F_{org} values of 20-50% and high densities of roughly 150-250 kg/m^3. This finding is supported by the figure that shows the same relationship, but specifically for the Zegveld model location (Figure 21). At the upper-left and lower-right-hand side, two clusters of peat are visible.

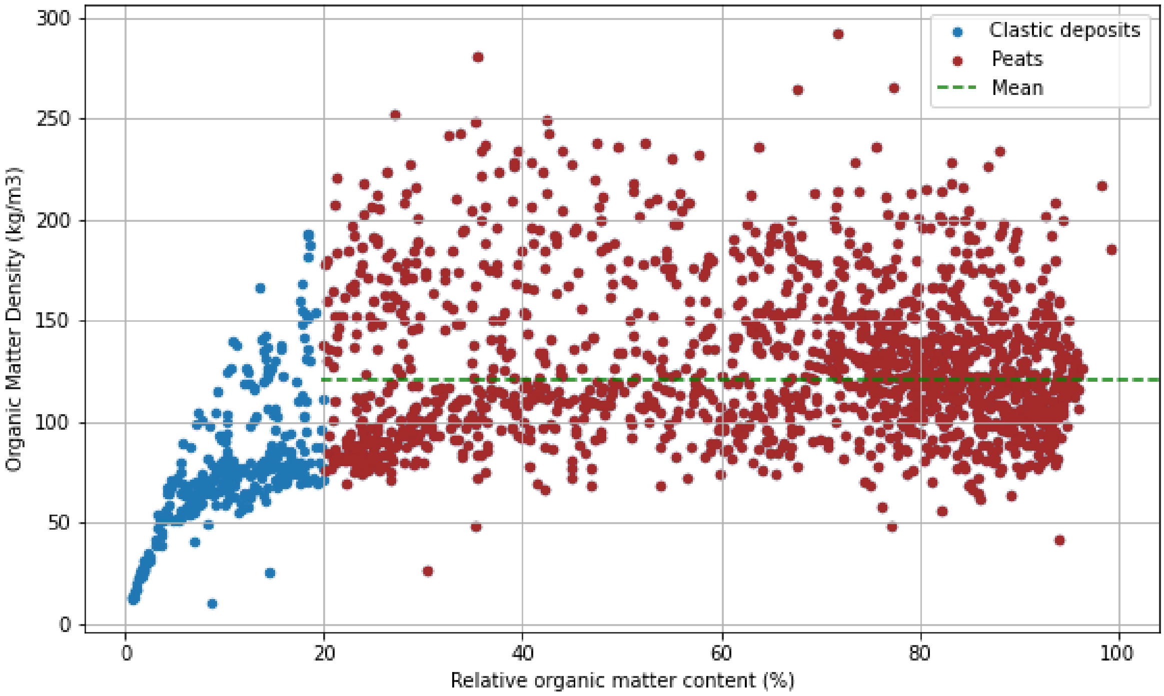

Figure 19. The relation between organic matter density and organic matter percentage. The plot includes data from the entire dataset (NOBV values and the dataset of the coastal plain by Erkens et al., (2016) regardless of depth. The green line depicts the average organic matter density.

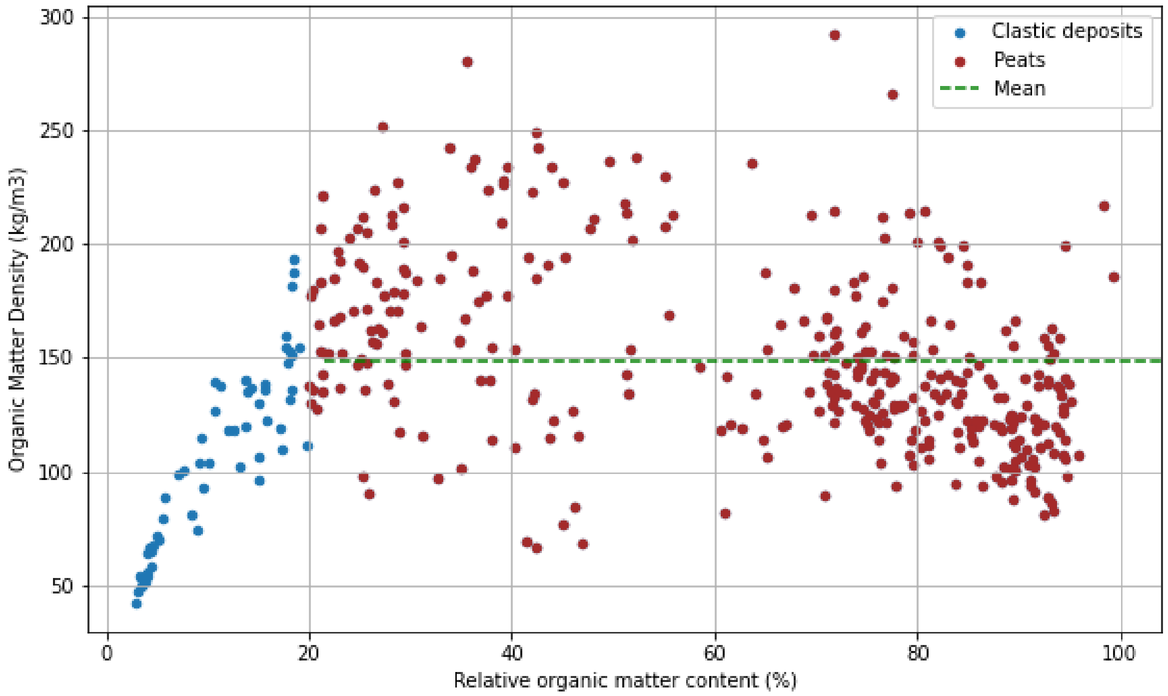

Figure 20. The relation between organic matter density and organic matter percentage. The plot includes data from the NOBV dataset with depths of 120 cm and less.

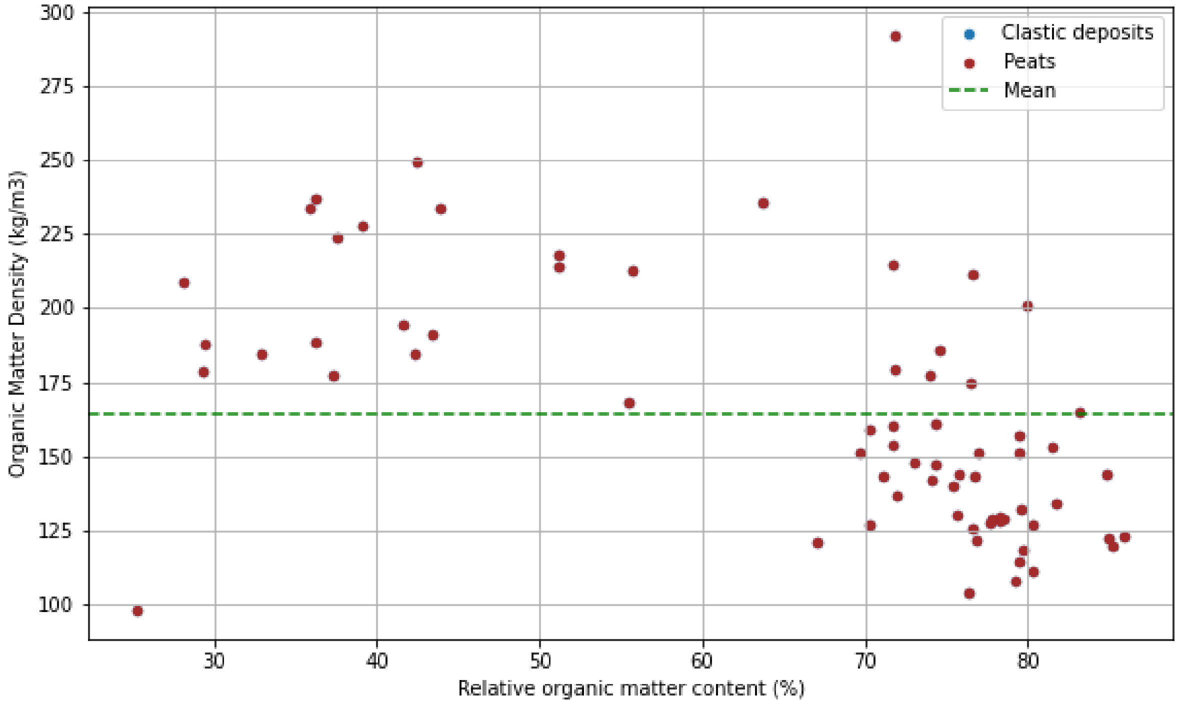

Figure 21. The relation between organic matter density and organic matter percentage. The plot includes data from the NOBV dataset with depths of 120 cm and less for Zegveld.

4. Discussion

SSOM is capable to reproduce subsidence due to oxidation in the same order of magnitude compared to the oxidation values based on subsidence measurements and oxidation related subsidence values in the literature. The oxidation related subsidence values are comparable to values found by subsidence model Atlantis (Bootsma et al., 2020) Moreover, in contrast to the existing empirical relationship (Van Den Akker, 2008; Figure 2), SSOM has simulated distinct seasonal variations with high subsidence rates in summer months and low rates in winter. Furthermore, variations between years are clearly shown by the model results, specifically at the Zegveld study site.

However, the subsidence due to oxidation simulated by SSOM is presently consistently larger than the oxidation based on measurements, especially at parcel 16 (Zegveld). The modeled oxidation compares well to oxidation related subsidence values from the literature at parcel 13 and 05B and differ significantly at parcel 16 and 09. The difference between modeled and measured subsidence due to oxidation implies either an overestimation of the model or an underestimation of the oxidation based on measurements. The measurements at Zegveld introduce uncertainty, because of several factors:

- The measurement period at Zegveld is long but has a very low temporal resolution of one measurement per year.
- The measurements are taken at varying periods of the year, ranging from early February to the end of May.
- There are gaps in the measurement period where data was not collected at parcel 16, especially between 1982-1988 and, at the 60-120 depth level between 2015 and 2020.
- There are some outliers in the dataset, which can have a large influence on the linear trend line.

The measurements at Rouveen are also paired with uncertainty. The automatic hourly measurements are more reliable, but the limited timespan prevents accurate determination of permanent land subsidence. These factors lead to an uncertainty in the computed oxidation component. Also, the method of dividing the soil in a zone of oxidation and a zone of consolidation has uncertainties. Above the division line, compaction due to strength loss and shrinkage may take place apart from oxidation. The contribution of these processes is not exactly known.

Generally, the deduced oxidation from subsidence measurements at Zegveld is considered more reliable than the result from Rouveen due to the significantly longer measurement period. The measurements at Rouveen could not be analyzed as reliably with this method because of the large variation in reversible land movements and the short measurement period. It, however, still shows lower oxidation rates for peat with clay on top, compared to only peat, as found by Van Den Akker (2008).

Furthermore, the extent to which the oxidation related subsidence values from the literature are applicable to this area is not exactly known. Erkens et al., (2016) and Van Asselen et al., (2018) determined their value over a 1000-year period, whereas we model a period of 26 and 3 years. However, as we have seen, the order of magnitude is correct, and it gives an idea of the proportion of oxidation to total subsidence. Hereafter, it is evaluated which components of SSOM may introduce an uncertainty or error.

4.1 Evaluation of conceptual model

4.1.1 Basal respiration

The basal respiration component can lead to an overestimation of the modeled subsidence due to oxidation. It is assumed to be a material property (unit [kg OM kg OM^{-1} d^{-1}]). Figure 15 and 16 show a large sensitivity to changes in basal respiration, in the order of up to 25-30% variation, between the first and third quartile, of the total subsidence. It is thus an important parameter to estimate correctly. Furthermore, it is assumed that the peat density has no influence on the decomposition rate, and thus that the population size of bacteria scales with the availability of organic matter. For example, when considering two peat samples with the same volume but OM densities of 100 kg/m^3 and 200 kg/m^3 the mass in the same volume is twice as large and therefore the amount of available organic matter too. The bacteria population may scale with the greater available mass of organic matter, but other conditions changes such as permeability and porosity due to e.g. compaction of macro pores also change (Van Paassen et al., 2020). This leads to decreases in oxygen influx and water and thus bacteria transport (Duiker, 2004). Inhibition of either bacteria transport or oxygen influx will lead to a decrease or even stop in oxidation and thus land subsidence as a result of oxidation. Pore water is taken into account by the AAP, but oxygen influx and bacteria availability are not. The basal respiration under optimal conditions will remain the same, but a scaling of the basal respiration may be required to be applicable in the field under highly compressed conditions.

In addition, the measurements are currently based on a timescale of days, whereas it would be more accurate to incorporate long-term respiration data to obtain only long-cyclic carbon (peat cycling) rather than the short-term cycle of carbon (plants decomposition). It is expected that the basal respiration reduces on longer timescales.

Furthermore, Berg (2000) reported that there is a finite pool of labile carbon that oxidizes quickly, leaving only the most resistant peat parts less prone to decomposition. Initially this would lead to rapid carbon loss before stabilizing. The most resistant peat parts are also the densest, leading to a decrease in subsidence due to oxidation according to the processing described above. In addition, the available surface area where bacteria can attach to in order to decompose does not scale linearly with density. It was found that the specific surface area (surface area per unit mass) diminished during compaction (Gregg and Langford, 1977). In SSOM a doubled density leads to a doubled decomposition rate, but the available surface area for bacteria will diminish with increasing density and therefore may too be a limiting factor to double the rate in reality. Due to this and the aforementioned factors, the basal respiration is likely to lead to an overestimation of peat decomposition rate.

4.1.2 Specific volume scaling

The specific volume scaling relates the organic matter mass loss to volume loss. The presented approach (section 2.2.2) is based on a model developed by Deltares (2021). However, the analysis of organic matter density and organic matter content measurements (section 3.4) demonstrates the need to adjust this model.

In the current specific volume model, the scaling factor is 1 for organic matter fractions above 0.4 and decreases as the organic mass fraction goes below 0.4 (Figure 4). At this point, the clay structure gradually takes over the bearing role of the soil and organic matter has been decomposed extensively or has never been present in large amounts. Above the 40% threshold, organic matter mass loss leads to a proportional volume loss, i.e. the organic matter density does not change during the oxidation process until the threshold is reached (Deltares, 2021).

An alternative specific volume model suggests an increase in organic matter density during the initial oxidation of new highly organic peat soils. During this initial phase, easily decomposable peat is broken down. This mass loss leads to more volume loss than is proportionally expected (1:1 in the current model), thereby increasing the organic matter density. The mechanisms are oxidation combined with strength loss of the soil (compaction). This conceptual model is supported by observations of organic matter densities and organic matter percentages in the peat meadow areas top 120 cm of the soil (Figure 22). In the initial phase, the highly organic peat will move from the right-hand bottom to regions of higher organic matter density and lower organic matter percentage. Generally, at low depths the density is higher, and the OM content is lower. The highly organic low-density peats occur at 60-120 cm depths in the zone that is almost always saturated in many Dutch peat areas. When the groundwater table is lowered, these highly organic peats become available for oxidation as well as compaction due to strength loss. They may decompose rapidly to end up in the peat group of low OM content and high OMD. The most recalcitrant peat parts remain, which are also more tightly compacted resulting in slower oxidation rates due to the aforementioned processes, e.g. lower oxygen influx and effective surface area.

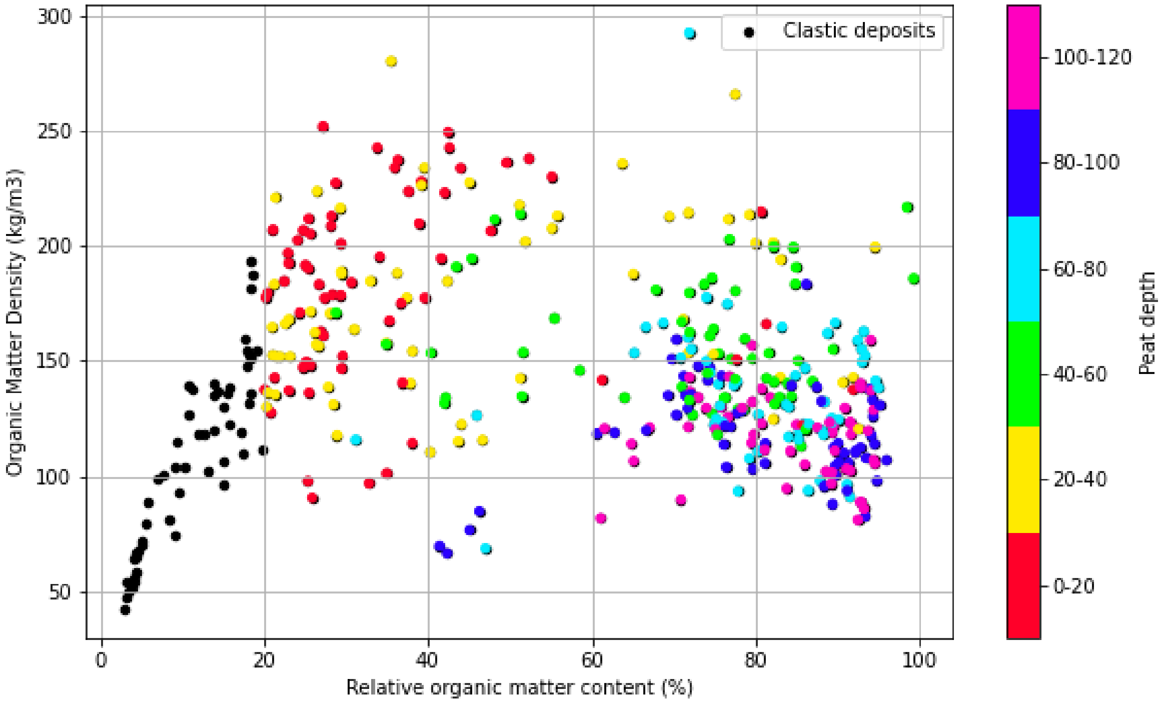

Figure 22. The relation between organic matter density and organic matter percentage. The plot includes data from the NOBV dataset with depths of 120 cm and less. At the right-hand side peat depths are depicted. A trend in peat depth is visible from the lower right-hand side to the upper left-hand side, ranging from low density (80-140 kg/m^3) highly organic peats (70-95%) to a wider group of high density (150-250 kg/m^3) moderate organic peats (20-55%).

It is clear that the different subsidence processes influence each other significantly. Oxidation leads to strength loss and thus compaction, whereas compaction in turn may reduce the oxidation rate. This model only computed subsidence due to oxidation, i.e. the actual volume lost and its contribution to subsidence. The analyses of measured subsidence data assumed that compaction as a result of oxidation are part of the oxidation process, because it is not possible to separate this. It would therefore be better to use the new conceptual model and include the oxidation caused strength loss into the model. This leads to a better representation of the process that occur in the field. The current model may have led to an underestimation of subsidence due to oxidation, because for fresh peat the volume reduction during oxidation is larger than currently is predicted. The alternative model for specific volume scaling is based on data researched during this study and needs more research to incorporate in the model accurately.

4.1.3 Aerobic respiration potential (AAP)

The SSOM results strongly rely on assumptions made in SOMERS 1.0. The aerobic microbial activity is affected by the oxygen concentration apart from already implemented soil moisture and soil temperature (NOBV, 2022). The oxygen availability is currently not part of SSOM. Implicitly, it is assumed that oxygen uptake into the soil and CO_2 transport out of the soil is not limited. This is, however, not always the case, mainly at higher densities. High densities of peat (150 kg/m^3 >) lead to decreased porosity and permeability, which may inhibit oxygen transport and thus subsidence by oxidation (Van Paassen, 2020). The SSOM results will likely be slightly too high as a result of this assumption.

4.2 Recommendations

To further improve model quality and to enable better comparison, calibration and validation of SSOM by measurements, several recommendations for further research are presented:

- Measure basal respiration with organic matter density from the field. With this information, the basal respiration from different compacted peat samples can be determined and incorporated in the model to account for the changes that occur when density has changed. This way, SSOM can account for decreases in permeability and changes in the surface area of peat that bacteria need to attach to for decomposition.
- Measure basal respiration on a longer timescale in the order of months to years in order to obtain a more accurate value of peat decomposition. This way the short-term carbon cycling can be excluded from the measurements and basal respiration solely based on peat decomposition (and not plant respiration) can be obtained.
- Include the oxygen availability in the AAP. Oxygen is a requirement for decomposition and should be in the AAP as such. It is necessary to know at which depth and at which (organic matter) density oxygen becomes a limiting factor for peat oxidation.
- Consolidation could be modeled using e.g. the isotache (Den Haan, 1996; Deltares, 2018) model to compare deduce oxidation values differently. Finding similar results could gain more insight in the reliability of the method that is used to extract the oxidation component from total subsidence measurements.
- Implement different bulk density calculations in the SOMERS 1.0 model, which is directly density dependent. The bulk density can be calculated based on the averages found in the density analysis (see Fig. 19-21). The average density currently in the SOMERS 1.0 model is 100 kg/m3, whereas the outcome of this study indicates an average density of nearly 150 kg/m^3 at shallow depths in peat-meadow areas (Fig. 20). Note that there is a large variety in density (100-250 kg/m^3). It would be most accurate to calculate a density per soil horizon to take into account these differences. The CO_2 calculations would be improved, which would also lead to more accurate SSOM results.
- Incorporate the new specific volume scaling model presented in section 4.1.2. More research is needed on how mass loss leads to volume loss in the initial stages of peat decomposition after groundwater level lowering.
- Measure land subsidence on a long timescale with a high temporal resolution. This way seasonal, yearly, and possibly climatic variations can be observed and compared to modeled

subsidence. Calibration of SSOM could take place with large scale measurements to improve the model.

- Compute the land subsidence due to oxidation on a national scale. The groundwater model in SOMERS is available on a national scale with relatively short run times. This can be used to improve national land subsidence prediction maps. Incorporation into other land subsidence models, such as Atlantis (Bootsma et al., 2020) is suggested.

4.3 Research impact

The negative societal consequences of land subsidence due to oxidation are numerous (PBL, 2016; Van Asselen et al., 2018; Brouns et al., 2015). This research provides a big step towards process-based modeling of land subsidence due to oxidation, which is essential to counter the negative consequences of subsidence in peatlands. The effects of soil temperature, soil composition and soil moisture are assessed, leading to significantly more detail than previously possible. In this study, measured groundwater levels are used, but it is also possible to use dynamically modeled groundwater levels as input. Consequently, groundwater measures and their effects on land subsidence due to oxidation can now be computed. Moreover, the effects of droughts in terms of subsidence can be analyzed, enabling the possibility to obtain information on what climatic changes will mean for the peat meadow areas. Furthermore, variations in subsidence due to oxidation between years and within years can be computed. This might add the opportunity for operational water managers to adapt water levels seasonally.

5. Conclusions

- Land subsidence due to oxidation is computed using SSOM at study locations Zegveld and Rouveen in the Netherlands. The average modeled oxidation-induced subsidence rates are 2.8 mm/y (SD 1.3 mm/y, parcel 13) and 6.4 mm/y (SD 1.9 mm/y, parcel 16) at the Zegveld parcels, whereas at the Rouveen sites the modeled rates are 4.9 mm/y (SD 0.6 mm/y, parcel 09) and 2.2 mm/y (SD 0.2 mm/y, parcel 05B). These rates are in the same order of magnitude as oxidation related subsidence values extracted from measurements and from the literature. Furthermore, soil parameters, such as pore water and organic matter are now assessed in order to determine oxidation related subsidence, contrary to previous modeling efforts.
- Large variations between years are found, especially at the Zegveld study site. At Zegveld parcel 13, the range between smallest and largest yearly value is 0.24 mm and 5.9 mm, whereas at parcel 16 the minimum is 3.4 mm and the maximum is 11.6 mm. Changes between years are attributed to hydrologic and climatic variations, such as groundwater level and air temperature.
- Large variations within years are found. Subsidence due to oxidation predominantly occurs around the summer months and decreases strongly in winter months, according to SSOM results. This result is in contrast to previous modeling efforts of subsidence due to oxidation, where seasonal variations were not present.
- Subsidence due to oxidation by SSOM is currently larger than the oxidation based on subsidence measurements. This implies either an overestimation of the model or an underestimation of the oxidation based on measurements. Identified uncertainties in the measurements are (1) a low temporal resolution, (2) gaps in the measurement period where data is absent, (3) outliers in the dataset which seem to be from measurement errors but can influence the linear trend significantly. Long-term land subsidence measurements with a high temporal resolution are therefore recommended.
- The most important identified uncertainties in SSOM are (1) the absence of scaling for density changes, (2) oxygen availability is not accounted for in the AAP, (3) basal respiration is not yet determined with long-term measurements. To further improve model quality, research on long-term basal respiration with local densities is strongly recommended.
- Using SSOM, it is now possible to compute the effects of mitigating measures, such as groundwater level changes, on future land subsidence due to oxidation in the Netherlands.
- Despite the SSOM results and subsidence due to oxidation from measurements and literature not being exactly the same, the modeling method looks promising. It provides a strong basis for further modeling efforts and incorporation into other land subsidence models.

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