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The relationship between ditch water level and peat subsidence: 50 years of measurements with levelling and subsidence plates in the Netherlands

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Abstract

One of the consequences of deeper drainage of peat soils is the increase in surface level subsidence. Over a period of 50 years, soil surface subsidence and subsidence at different depths in the soil profile were measured using levelling and subsidence plates at 29 sites in seven locations in the Netherlands. Over those 50 years, the surface level for these sites has dropped by an average of 0.7 cm/year. A significant relationship between the measured ditch water level and the soil surface level subsidence rate was found. The subsidence plates, which were installed at different depths, allowed us to compare the contribution of the various soil layers to the subsidence of the surface. This showed that about 2/3 of the subsidence took place in the layers, where oxygen can penetrate (<0.8 m below soil surface). In those layers, oxidation and shrinkage are the most important subsidence processes. In the layers that are always saturated, 1/3 of the ground level subsidence still occurred, which is mainly caused by consolidation and creep but with a contribution of anaerobic decomposition. Finally, the results showed that subsidence rates during the period 1970–1990 were on average higher than during the period 1990–2024. Variability over sites was large, illustrating that site-specific conditions have a large impact on soil subsidence rates. The implications of our research are that peat subsidence monitoring, in the Netherlands and elsewhere, has to (1) be long-term, (2) monitor at different depths and (3) include multiple sites.

Introduction

When peat soils are drained, they start emitting CO_2 (e.g. Darusman et al., 2023; Erkens et al., 2016; Evans et al., 2021; Freeman et al., 2022; Wösten et al., 1997), and they also start subsiding (Bakema et al., 2025; Evans et al., 2019; Freeman et al., 2022). This subsidence is partly caused by oxidation, but additional processes, which are all influenced by drainage too, are shrinkage, consolidation and creep (e.g. Schothorst, 1977).

In parts of the Netherlands, drainage of peat for agriculture already started around a 1,000 years ago (Bakema et al., 2025; Jansen et al., 2009; Querner et al., 2007; Van Asselen et al., 2025; Van de Ven, 2004) and has over the centuries resulted in surface subsidence of several metres (Erkens et al., 2016; Jansen et al., 2009; Schothorst, 1977). Subsidence in peat areas can result in various problems (Van Asselen et al., 2025), such as damage to buildings and infrastructure (Van Asselen et al., 2020), increasing costs and complexity of water management (Deverel & Leighton, 2010; Pronger et al., 2014; Van den Akker et al., 2007), increased flooding risk (e.g. Dawson et al., 2010; Ikkala et al., 2021; Pronger et al., 2014; Van Asselen et al., 2020; Zanello et al., 2011) and seepage (Deverel & Leighton, 2010), and increased salinity of groundwater and drying-out of nature areas (Querner et al., 2007; Van den Akker et al., 2007).

This subsidence has been estimated to have been about 0.13–0.20 cm per year on average (Erkens et al., 2016; Schothorst (1977); Van Asselen et al., 2018) until the middle of the 19th century. At that time, windmills were gradually replaced by steam engines, which allowed a lowering of the ditch water level, especially in winter, as the steam engines were more effective in draining than the windmills. This resulted in an increase of subsidence rates to around 0.6 cm/y (Schothorst, 1977). A further lowering of ditch water levels took place in the 1960s and 1970s to improve trafficability of the land and to promote efficient and highly productive dairy farming, causing a further increase in subsidence rates, at least initially (Jansen et al., 2009).

As the groundwater level is of importance for all peat subsidence processes, with oxidation and shrinkage (due to desiccation) above the water table, and consolidation (due to increased effective stress) and creep below it (Massop et al., 2024), relationships between the groundwater level and soil subsidence as well as between the groundwater level and CO_2 emissions are to be expected. For emissions, these have also been observed (e.g. Aben et al., 2024; Evans et al., 2021; Freeman et al., 2022; Tiemeyer et al., 2020), but they appear to be confounded by additional factors such as peat type, soil profile, vegetation, fertilisation and temperature (Darusman et al., 2023; Hatano, 2019), as the type of relationship is not always the same. The same could be true for soil subsidence. For example, Stephens et al. (1984) reported an influence of peat type and temperature on subsidence.

Another complicating factor for subsidence is that the different subsidence processes occur at different depths within the soil profile (e.g. Massop et al., 2024), depending on the groundwater level. Therefore, to disentangle the different processes, subsidence measurements at different depths are needed. Furthermore, measurements need to be long-term as it has been shown that yearly fluctuation in surface elevation can be around a factor 10 larger than long-term subsidence (Massop et al., 2024; Van Asselen et al., 2025). Finally, some subsidence processes are expected to have decreasing rates over time (e.g. consolidation), whilst others may proceed at a more constant rate, provided that water table depth below the soil surface remains more or less the same (e.g. oxidation, see e.g. Stephens et al., 1984).

For the Netherlands, Van den Akker et al. (2007, 2008) developed relationships between the soil subsidence rate and the average ditch water level for peat soils with and without clay cover. It should be noted that the groundwater level rather than the ditch water level is expected to be the main controlling factor, but data on the ditch water level are more readily available and should theoretically be well correlated with the groundwater level, though this relationship can be influenced by factors such as peat type, hydraulic conductivity and distance between ditches.

Van den Akker et al. (2007, 2008) also found lower subsidence rates for peat soils with clay cover. The main reason why peat with a clay cover has lower CO_2 emissions and surface subsidence is that the top-layer of clay is mainly mineral and therefore does not break down. With a thin clay cover (25–40 cm), the surface level subsidence, thus the emissions, can be reduced by up to about 50% compared with a complete peat layer (Van den Akker et al., 2018). A lot of peat oxidation is often observed directly below the clay layer because the clay cover quickly cracks under dry conditions, and the underlying peat is richly supplied with oxygen through the cracks (Van den Akker et al., 2018). A clay cover is therefore only able to prevent peat oxidation of the underlying peat to a limited extent and is most effective if the groundwater level always remains in the clay layer (Paul et al., 2024).

The subsidence measurements examined in this article started in the late 1960s. At the time, researchers were concerned about the consequences of the large-scale lowering of the ditch water level that was being implemented everywhere in the peat meadow area (Schothorst, 1977). To follow the process of subsidence, subsidence plates (Massop et al., 2024; Schothorst, 1977) were installed at various locations in the 1960–1980's. To this day, Wageningen University and Research is carrying out measurements of soil subsidence at a number of these locations.

We used the same data that Van de Akker et al. (2007, 2008) also used, but including longer time series (>50 years in several cases), more research sites and we used a somewhat different method of analysis. Our aims were: (1) To determine whether a relationship between the ditch water level and soil subsidence can also be found for our more extensive dataset, (2) To assess the contribution of different subsidence processes to total subsidence and (3) To assess changes in subsidence rate over time.

Methods

Methodology

Several techniques can be used to measure land subsidence in peat areas (Van Asselen et al., 2020), but most methods only provide information about subsidence of the soil surface (e.g. levelling, exposure of structures (Zanello et al., 2011) and wells (Campbell et al., 2021), repeated measurements of peat thickness (Oleszczuk et al., 2020, 2022; Pronger et al., 2014), InSAR (Interferometric Synthetic Aperture Radar) and LiDAR (Light Detection and Ranging)). Methods that do provide information for different depths often do not have long time series (e.g. extensometers, Van Asselen et al., 2020, 2025).

One method that can be used to measure soil subsidence at different depths in the peat profile is by using subsidence plates (Massop et al., 2024; Schothorst, 1977). Subsidence plates (see Figure 1) consist of two connected metal plates with a diameter of 8 cm (Beuving & Van den Akker, 1996) that can be installed

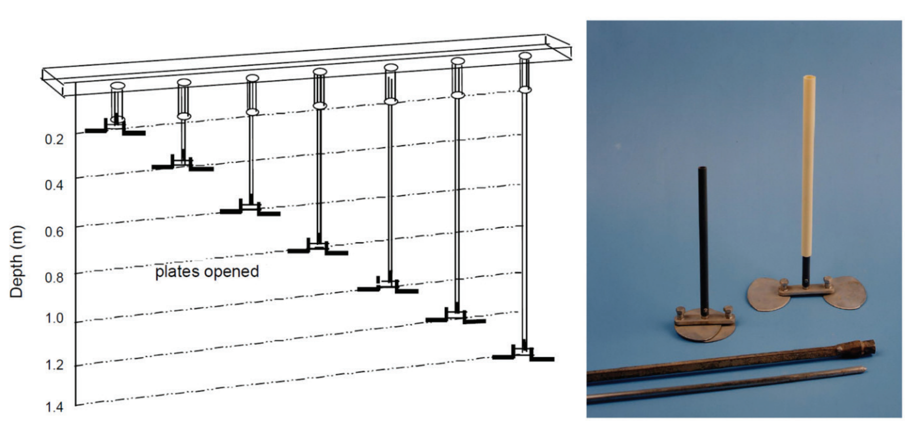

Figure 1. Subsidence plates (Massop et al., 2024). At the soil surface, there is a wooden box (open at the bottom) to protect the top of the subsidence plates. For further description, see Massop et al. (2024).

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via an auger hole. When the plates are at the desired depth, the plates can be rotated to cut into the surrounding undisturbed peat and thus become fixed (meaning that they follow the vertical movement of the peat at that depth). Details on the set-up can be found in Massop et al. (2024). By installing a series of subsidence plates at different depths, it is possible to determine vertical soil movement at different depths, which makes it possible to determine where in the soil profile subsidence occurs. Every year in early spring when the soil is soaked and swollen, the altitude of the soil surface and the plates was measured using levelling. The average of 10 measurements around the box with subsidence plates was taken as measured value to avoid undue influence of very local variations in elevation. For levelling, a subsidence reference point is used. This is a metal pipe that is driven in the sand below the peat layer, which was assumed to be stable (hence not subsiding). The elevation of the surface level and subsidence plates has been measured relative to the reference point. However, Massop et al. (2024) showed that not all subsidence reference points were actually stable; some did subside. Massop et al. (2024) were able to correct for this in their study in one location, but the data to do that lack for most of the locations included in the current study. This precludes a detailed analysis of results for each separate location, so that our analysis had to focus more on general trends, without attempting to correct uncertain data. Therefore, if visual inspection suggested that data were uncertain, we did not use these data. A Pearson correlation was performed to investigate correlations between surface subsidence in the sites; the expectation being that most sites would be correlated positively as they are all subsiding, so that negative correlations might indicate that data are less reliable. Furthermore, we focused our analysis on soil layers with an initial thickness of 0.4 m, namely, 0.0–0.4, 0.4–0.8, 0.8–1.2 and >1.2 (where the >1.2 m layer is often more than 0.4 m thick) and only used data when measurements for all relevant depths (0, 0.4, 0.8 and 1.2 m) were available. Finally, we looked at changes in the subsidence rate over time by averaging data over 10-year periods.

The subsidence of the soil surface and the subsidence plates were analysed by looking at year-on-year changes in the surface level and the heights of the subsidence plates. For both the surface level and the subsidence plates, measurements conducted in spring were used, to minimise the effect of fluctuations in elevation that occur within the years. Spring measurements are assumed to represent the situation where the peat is maximally swollen. Figure 2 shows a graphical representation for the calculation of the rate of subsidence of the surface level.

Because the spring measurement is not taken on the same day every year, the difference is standardised to a decrease of 1 year according to the following formula:

$$\Delta surface_t = \frac{surface_t - surface_{t-1}}{\frac{number\ of\ days\ between\ t\ and\ t-1}{365}} \tag{1}$$

By taking the change in the surface level as response variable (instead of the surface level, as done in earlier studies, e.g. Massop et al., 2024; Van den Akker et al., 2007, 2008), autocorrelation between residuals when performing a regression is avoided. The regression that is performed therefore takes on the simple form

$$\Delta surface_t = \alpha + \varepsilon_t \tag{2}$$

where ε_t is a random component and with:

$$\alpha = \frac{\sum_{i=0}^{n} \Delta surface_i}{n} \tag{3}$$

where n is the number of annual observations.
The standard error of α is given by:

$$\Delta SE_\alpha = \frac{\sqrt{\frac{1}{n-1}\sum_{i=0}^{n}\left(\Delta surface_i - \alpha\right)^2}}{\sqrt{n}} \tag{4}$$

Study sites

Subsidence plate measurements have been conducted at 29 sites in 7 locations. Figure 3 shows that all locations are located within the Dutch peat meadow area, and that they are distributed throughout the western and northern peat areas.

All sites are fen peats, which started to develop in the Holocene due to rising sea levels. They are underlain by usually sandy Pleistocene deposits. Full descriptions of the study sites can be found in Bakema et al. (2025). A summary with main characteristics of the study site and determined subsidence rates per site is given in Table 1, whilst data on OM content are provided in Table 2.

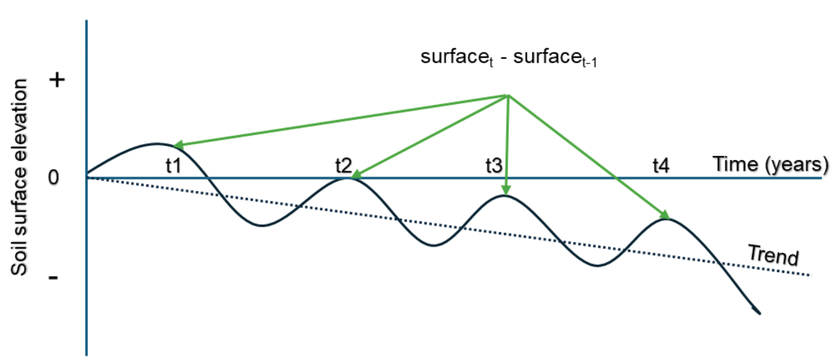

Figure 2. Representation of the soil surface subsidence process, with large yearly fluctuation superimposed on a declining trend (based on Van Asselen et al., 2024). Green arrows indicate timing of soil surface measurements in spring.

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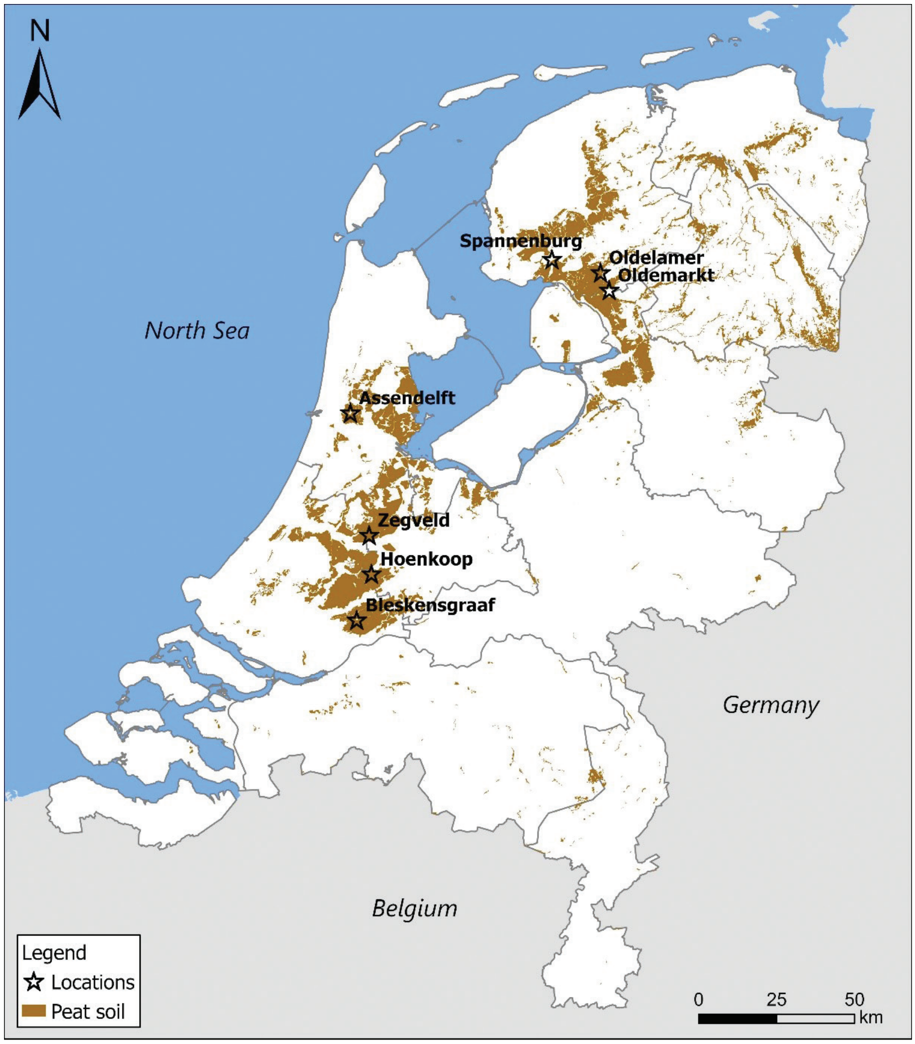

Figure 3. Research locations. Map of peat soils based on Brouwer et al. (2021).

As can be seen from Table 1, some of the sites have a clay cover and some do not. In the Dutch soil classification, a clay cover is defined as a clay layer of 0.15–0.40 m thickness. This means that the thickness can vary, and therefore, the effect of the clay cover on subsidence would be likely to vary too. Besides, there is a continuum between peaty clay and clayey peat, but the first is classified as clay cover, whilst the second is not.

Results

Results per site are presented in Bakema et al. (2025) and are summarised here. Figure 4 provides results of one of the 29 sites, to illustrate what results look like. The highest average surface level subsidence rates were measured at locations Spannenburg B and Assendelft 1 with a subsidence of 1.8 and 1.7 cm per year, respectively (Table 1). The lowest average subsidence was measured for Hoenkoop E with 0.2 cm/y and in Zegveld 11Z with 0.07 cm/y. The average soil surface subsidence rate over the entire period of 50 years and across all measurement locations was 0.7 cm/year.

From the relative size of the standard error of the measurement compared to the average subsidence (Table 1), it can be concluded that there is a high degree of uncertainty about the measured soil surface subsidence rate. This is probably caused by the fact that the moisture conditions in winter/spring differ greatly between the measurement years, as a result of which, the peat has swollen to a greater or lesser degree in spring. The accuracy with which ground level subsidence is measured can be increased by measuring at several points in time in spring, averaging these measurements annually and performing trend analysis on these annual figures.

Figure 5 shows pairwise Pearson correlation coefficients between the soil surface data series from the different sites. The figure shows that there is a positive correlation between most sites. This was to be expected as almost all sites are subsiding (Bakema et al., 2025), and subsidence processes in all sites are similar (all peat meadow areas with controlled ditch water levels). However, there are also some sites that are negatively correlated with several other sites, examples being Zegveld 2N, Zegveld 2Z, Zegveld 3N and Zegveld 11Z.

Figure 6 shows the relationship between the average ditchwater level below the soil surface and measured average soil surface subsidence rate for all sites combined. Thus, each site is represented by a single point in the figure; this point

Table 1. Summary table of study sites

Site	ADWL (m below surface)	Period	Peat type	Thickness holocene (m)	Peat in holocene (m)	Cover (thickness in cm)[1]	Av. surface subs. (cm/y)	St. error subs. (cm/y)
Assendelft 1	0.99	1975–1997	Sedge	15	2	Clay (30)	1.65	0.47
Assendelft 2	0.41	1975–1997	Sedge	15	2	Clay (30)	0.92	0.32
Bleskensgraaf 1	0.72	1970–2011	Wood	8.5	5.5	Clay (30)	0.69	0.26
Bleskensgraaf 3	0.49	1970–2014	Wood	8.5	5.5	Clay (30)	0.31	0.28
Bleskensgraaf 5	0.46	1973–2015	Wood	8.5	5.5	Clay (30)	0.40	0.27
Hoenkoop B	0.76	1969–2015	Wood	6	3	Clay (40)	0.50	0.23
Hoenkoop D	0.71	1969–2015	Wood	6	3	Clay (40)	0.37	0.30
Hoenkoop E	0.50	1973–2008	Wood	6	3	Clay (40)	0.19	0.23
Oldelamer 1	0.98	1992–2004	Peat moss	4	4	No clay	1.39	1.08
Oldelamer 3	0.88	1992–2004	Peat moss	4	4	No clay	0.90	0.73
Oldemarkt B	0.80	1978–1984	Peat moss	1.5	1.5	Clay (20)	0.84	0.40
Oldemarkt C	0.80	1978–1984	Peat moss	1.5	1.5	Clay (20)	0.68	0.44
Oldemarkt E	0.80	1978–1984	Peat moss	1.5	1.5	Clay (20)	1.20	0.68
Spannenburg B	1.03	1978–1998	Peat moss	1.5	1	Clay (15)	1.80	0.37
Spannenburg D	1.08	1978–1998	Peat moss	1.5	1	Clay (15)	1.26	0.37
Zegveld 2N	0.56	2004–2024	Wood	6	6	No clay	0.40	0.47
Zegveld 2Z	0.63	2004–2015	Wood	6	6	No clay	0.44	0.81
Zegveld 3M	0.57	1971–2010	Wood	6	6	No clay	1.05	0.41
Zegveld 3N	0.56	2010–2015	Wood	6	6	No clay	0.53	0.55
Zegveld 3Z	0.55	2007–2024	Wood	6	6	No clay	0.89	0.57
Zegveld 8M	0.29	1976–2024	Wood	6	6	No clay	0.40	0.28
Zegveld 11N	0.24	2004–2018	Wood	6	6	No clay	0.51	0.72
Zegveld 11 Z	0.33	2004–2024	Wood	6	6	No clay	0.07	0.81
Zegveld 13N	0.18	1973–2024	Wood	6	6	No clay	0.47	0.23
Zegveld 13Z	0.25	2004–2024	Wood	6	6	No clay	0.42	0.49
Zegveld 16M	0.62	1970–2024	Wood	6	6	No clay	0.57	0.35
Zegveld 20O	0.40	1970–2024	Wood	6	6	No clay	0.47	0.36
Zegveld 20W	0.39	1970–2024	Wood	6	6	No clay	0.26	0.39
Zegveld bos10	0.58	1974–2002	Wood	6	6	No clay	0.56	0.55
Average							0.69	0.46

Based on Bakema et al. (2025). ADWL = average ditch water level over measurement period.
[1]Data on thickness of clay layer from Bakema et al. (2025).

indicates the average ditch water level and the average soil surface subsidence over the entire measurement period of the site. The figure shows that a linear relationship fits the data well. This relationship has an R^2 of 0.56; details of the regression model are provided in Table 3. The equation is

$$S = 1.2954 \times L - 0.0813 \tag{5}$$

where S is the average yearly soil surface subsidence (cm/y) and L is the average ditchwater level below soil surface in spring (m).

Table 3 shows that a positive linear relationship exists, at the level of significance of 0.05. Equation 5 shows that if the average ditchwater level is raised by 10 cm (0.1 m), soil surface subsidence decreases by 0.13 cm per year. These results confirm the findings by Van den Akker et al. (2007, 2008), though they found a slightly larger effect of ditch water level on soil subsidence, since, in their study, the decrease in subsidence for a 10 cm rise in ditch water level was 0.155 cm per year. Contrary to Van den Akker et al. (2007, 2008), we did not find evidence for a difference in subsidence between peat with and without a clay cover.

Our work and that of Van den Akker et al. (2007, 2008) show that rewetting of peat is an effective way to slow down soil subsidence. All the more so because the depth of groundwater table has been found to be the best predictor for the soil subsidence rate (Evans et al., 2019; Freeman et al., 2022), and the ditch water level is basically used as a proxy for the groundwater level due to lack of data on the groundwater level. As the relationship between the ditch water level and the groundwater level can be influenced by factors such as peat characteristics (i.e. hydraulic conductivity) and distance between ditches, a spread of data points around the regression line is to be expected. Despite this variation, a clear relationship between the ditch water level and soil subsidence is found across sites.

The subsidence plates allowed us to also investigate where in the soil profile most subsidence occurs. Table 4 shows results for those sites, for which data were available for all depths that were considered.

Table 4 shows that there is a lot of variation between sites, but nevertheless, the average of all locations together presents a clear picture. For example, 67% of soil subsidence is found to take place in the upper 0.8 m of the soil, with the upper layer contributing 39% and the 0.4–0.8 m layer 28%. The upper part of the soil is most often exposed to oxygen. However, the soil layer below 1.2 m, which is expected to be saturated year round, also contributes 27% of total subsidence. The layer 0.8–1.2 m contributes little.

Table 5 provides information on the change of average subsidence rate over time. It shows average soil surface subsidence for 10-year periods. To avoid undue influence of individual years, results are only shown for decades, for which at least 5 years of data are available. Generally speaking, the subsidence rate has decreased over the measurement period of 50 years. In the seventies and eighties, the average rate was 0.9 cm/year, whilst afterwards, it varied around 0.5 cm/year.

Table 2. Organic matter content (weight %)

Site	0–0.4 m	0.4–0.8 m	0.8–1.2 m	>1.2 m
Assendelft 1	37	85	59	72
Assendelft 2	29	43	26	77
Bleskensgraaf 3	39	83	71	66
Bleskensgraaf 5	38	85	76	85
Hoenkoop B	28	75	75	71
Hoenkoop D	24	64	67	78
Hoenkoop E	19	46	77	75
Oldelamer 1	84	96	96	75
Oldemarkt B	36	92	90	90
Oldemarkt C	49	94	92	90
Oldemarkt E	32	95	90	90
Spannenburg B	41	52	80	Sand at 1.1 m
Spannenburg D	40	95	80	Sand at 1.1 m
Zegveld 3	56	82	85	85
Zegveld 8	46	73	70	75
Zegveld 13	61	83	80	77
Zegveld 16	49	83	70	70
Zegveld 20W	31	67	75	70
Average	41	77	75	78

Partly based on Beuving and Van den Akker (1996) and bodemdata.nl (last consulted 15/7/2025). Further info and full data are provided in underlying material, see data availability.

Discussion

Data quality

As already noted by Massop et al. (2024), 50 years of yearly measurements of soil subsidence at different depths in the soil constitutes a unique time series. However, it is also a challenge. In these 50 years, many different researchers have worked on measurement, recording and interpretation of data. Although the measurement method has not changed, there have been various changes in conditions in the different sites. For example, ditch water levels have changed; in some sites, ground works occurred, and the climate has changed. Some of these changes have been documented, but not all of them, so that interpretation is not always easy.

In addition, the raw measured data have been processed in several ways, which could, in some cases, have introduced errors. For example, the elevation of subsidence plates has been measured in relation to reference points that were assumed to be stable but may actually not have been stable (Massop et al., 2024). Raw data are in several cases not available anymore, only the data that have already been corrected. These have been recorded first on paper and later in spreadsheets. Errors could have occurred, but data to verify whether this was the

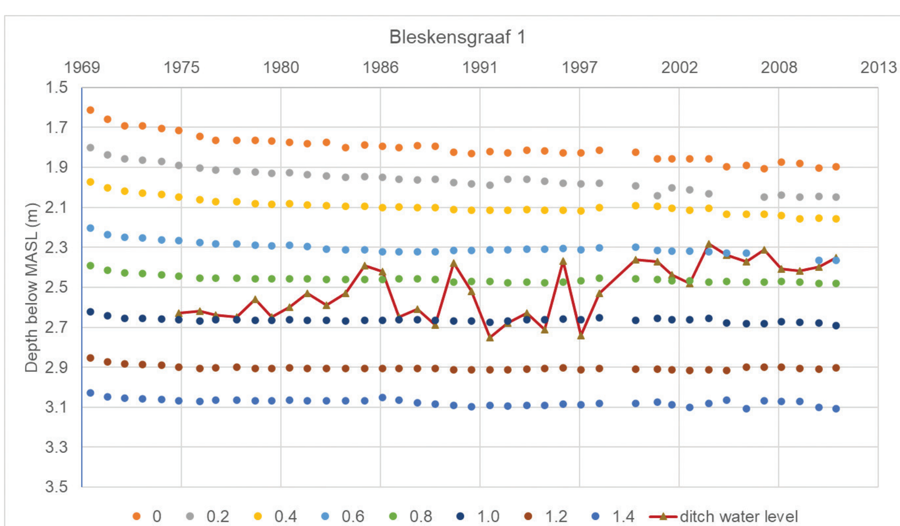

Figure 4. Subsidence plate results from site Bleskensgraaf 1. Colours indicate depth (m) of subsidence plates below the soil surface. MASL = Mean Annual Sea Level.

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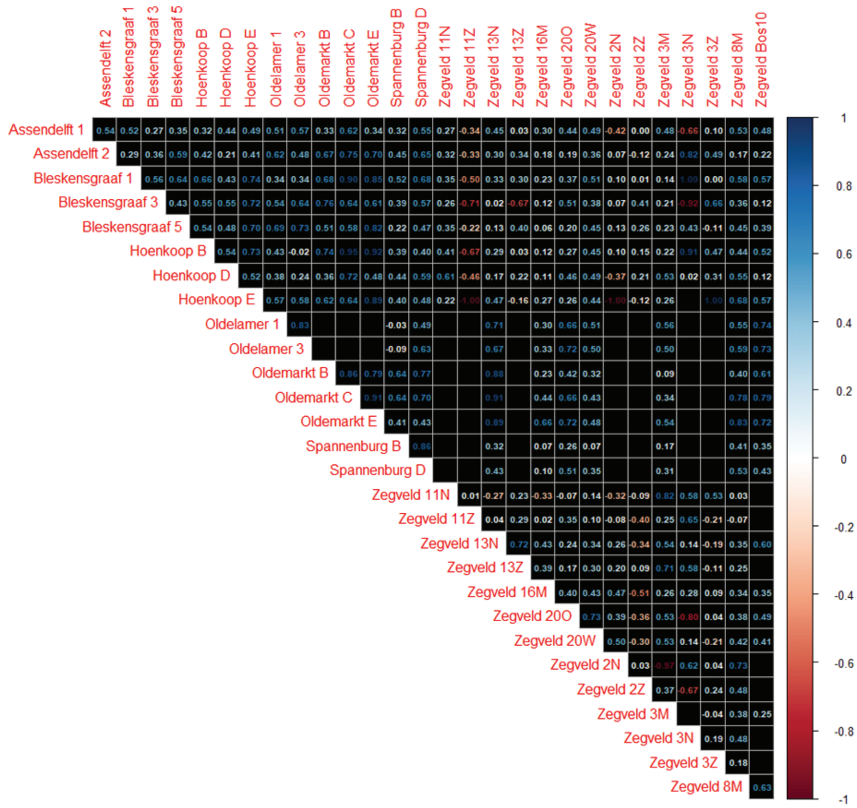

Figure 5. Pairwise Pearson correlation coefficients between data series from different locations. Blue indicates positive correlation and red negative.

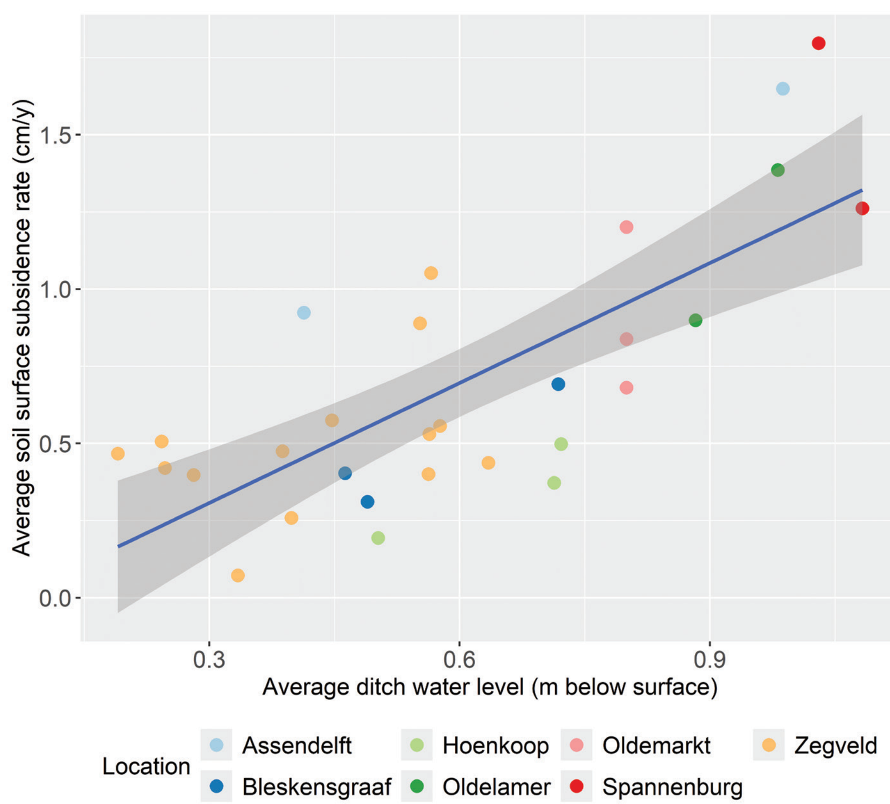

Figure 6. Relationship between the average soil surface subsidence rate and average ditch water level in spring.

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Table 3. Linear regression model for the relationship between soil subsidence per year (cm/y) and ditch water level in spring (m), $y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$

Coefficient	Estimate	Standard error	*t*	*P*(>|*t*|)
β_0	-0.0813	0.1418	-0.573	0.571
β_1	1.2954	0.2191	5.913	$2.66 * 10^{-6}$

Table 4. Contribution (%) of different soil layers to total soil surface subsidence

Site	0–0.40	0.40–0.80	0.80–1.20	Below 1.20
Assendelft 1	40%	10%	7%	43%
Assendelft 2	43%	33%	2%	22%
Bleskensgraaf 1	29%	39%	13%	19%
Bleskensgraaf 3	29%	49%	-6%	28%
Bleskensgraaf 5	49%	8%	24%	18%
Hoenkoop B	25%	36%	22%	17%
Hoenkoop D	11%	41%	24%	24%
Hoenkoop E	-11%	64%	-8%	54%
Oldelamer 1	85%	-15%	3%	27%
Oldelamer 3	56%	-8%	1%	52%
Oldemarkt B	65%	29%	3%	4%
Oldemarkt C	65%	39%	-1%	-4%
Oldemarkt E	69%	18%	-4%	16%
Spannenburg B	64%	8%	14%	14%
Spannenburg D	21%	12%	29%	38%
Zegveld 2N	23%	68%	-46%	55%
Zegveld 3M	42%	26%	6%	25%
Zegveld 8M	29%	75%	-38%	35%
Zegveld 13N	56%	18%	-3%	28%
Zegveld 16M	7%	46%	12%	36%
Zegveld 20O	25%	-20%	89%	6%
Zegveld 20W	37%	28%	-2%	36%
Average	39%	28%	6%	27%

Layers are expressed in m below the soil surface.

case or not are lacking. Massop et al. (2024) were able to correct their data for two plots in Zegveld, as for that site, data were available to do this, but nevertheless, some uncertainties in their data remained. In the current study, we looked at 29 sites in seven locations. We did look at the consistency of measured time series (see Bakema et al., 2025) to identify uncertain data or unexpected trends but could not correct the data. A visual assessment and statistic comparison of the measurement series (Pearson analysis) indicated that there are no strange jumps in the measurement series, and that the data processing appears reliable despite the very long measurement period.

Surface subsidence rates

The subsidence rates we found are comparable to rates reported by other studies in the Dutch peat meadow area, which, in general, reported rates between 0.5 and 1.0 cm/y (Beuving & Van den Akker, 1996; Hoogland et al., 2012; Schothorst, 1977, 1982; Van Asselen et al., 2025). They are also similar to rates reported from other parts of Europe, such as those reported by Dawson et al. (2010), Zanello et al. (2011), Ikkala et al. (2021) and Oleszczuk et al. (2020, 2022). Though these studies looked at very different locations, different peat types, different periods and used different methods, they all reported subsidence rates ranging between 0.6 and 1.5 cm/y.

Though the average rates we found are in correspondence with literature, we did find fairly high soil subsidence rates if ditch water levels were close to the surface. It should be noted though that these data are all for the location Zegveld, so that the cause might be site-specific. For Zegveld, Massop et al. (2024) also reported subsidence rates of 0.48 cm/y for their field with high groundwater level (around 20 cm below surface).

Finally, we also observed that the average rate we found (0.7 cm/y for all sites, 0.5 cm/y for Zegveld sites) is close to the 0.6 cm/y reported by Schothorst for Zegveld over the period mid-19th century to mid-20th century. This could indicate that the effects of deeper drainage in the 1960's and 1970's have now ended.

Causes for differences in surface subsidence rate

Clear relationships between the ditch water level and soil subsidence (Van den Akker et al., 2007, 2008; this study) as well as between the groundwater level and CO_2 emissions (e.g. Aben et al., 2024; Evans et al., 2021; Tiemeyer et al., 2020) have been found. However, usually, a large spread of data points around the regression line is observed, both in emission studies and in subsidence studies. This suggests that there are other factors that also have a large effect on emissions or subsidence. Here, we discuss some of the additional factors that could result in variation of the soil subsidence rate.

Presence or absence of clay cover

As shown in Table 1, the locations Zegveld and Oldelamer do not have a clay cover, whilst the other sites do. However, the data presented in Figure 6 do not indicate a difference in subsidence between sites with and without clay cover. This is contrary to the results obtained by Van den Akker et al. (2007, 2008). A possible explanation for this is the data we used. Though we partially used the same data as Van den Akker et al. (2007, 2008), our time series are longer, and the number of sites was larger. In addition, Van den Akker et al. included data from Janssen (1986), which have not been used in our study. Another reason might be that the uppermost peat layers in sites without clay cover have become earthified over time, which has likely reduced their oxidation rate, bringing it closer to the oxidation rate in sites with clay cover.

Peat thickness

Several studies have indicated that thicker peat layers show more soil subsidence (e.g. Grzywna, 2017; Ikkala et al., 2021), which can be attributed to a larger contribution of consolidation/creep (Massop et al., 2024) or to a different SOM content (Deverel & Leighton, 2010). Van Asselen et al. (2025) found that for several peat sites in the Netherlands, the site with the thickest peat layer showed the largest yearly fluctuation in soil surface level, which is probably due to larger poro-elastic deformation. In this study, we looked at the thickness of the Holocene sequence, which includes peats but also soft clays. The thickness of the Holocene sequence ranges from about 1.5 m in the northern sites to more than 15 m in Assendelft (Table 1). We plotted the average subsidence

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Table 5. Average soil surface subsidence rate (cm/y)

Site	1970–1980	1980–1990	1990–2000	2000–2010	2010–2020
Assendelft 1	2.77	1.35	0.99		
Assendelft 2	1.83	0.75	0.41		
Bleskensgraaf 1	1.57	0.59	-0.06	0.74	
Bleskensgraaf 3	0.65	0.38	0.1	0.38	
Bleskensgraaf 5	0.48	0.53	0.28	0.57	
Hoenkoop B	0.98	0.57	0.1	0.33	
Hoenkoop D	0.18	0.71	0.08	0.77	
Hoenkoop E	0.52	0.31	0.01	-0.06	
Oldelamer 1			1.8	0.66	
Oldelamer 3			1.05	0.64	
Spannenburg B		2.03	1.16		
Spannenburg D		1.36	0.84		
Zegveld 2N				0.46	0.59
Zegveld 2Z				0.79	0.18
Zegveld 3M	1.33	1.35	0.69	0.8	
Zegveld 3N				0.46	0.53
Zegveld 3Z				1.21	0.92
Zegveld 8M	-0.67	1.25	0.07	0.54	0.66
Zegveld 11N				0.71	0.36
Zegveld 11Z				-1.2	0.59
Zegveld 13N	0.73	0.55	0.34	0.35	0.94
Zegveld 13Z				0.47	0.86
Zegveld 16M	0.74	0.31	1.35	0.03	1.11
Zegveld 20O	0.53	1.13	0.33	0.03	0.53
Zegveld 20W	1.05	0.86	0.64	-0.13	-0.14
Zegveld Bos10	0.56	0.94	-0.14	1.74	
Average	0.88	0.88	0.53	0.43	0.59

Decades with less than 5 years of data have been omitted. Due to its short time series location, Oldemarkt is not included. Negative values indicate a rise of the soil surface.

rate against the thickness of the Holocene sequence (data not shown) but did not find a significant relationship between the two (R^2 was 0.044). One possible explanation for a lack of a relationship may be geohydrological, as it may depend on how the hydraulic head at the base of the peat layer changes as a result of falling the groundwater level. If it drops, one would expect increased subsidence throughout the peat profile, but if it remains constant (e.g. because it is controlled by the head in the underlying Pleistocene deposits), the change in subsidence might be small. It is also possible that peat and clay layers behave differently, so that results might be different if only peat layers are considered. However, it does seem likely that clay layers would also be subjected to consolidation/creep.

Peat type

The peat type in the different locations is different (Table 1). In Zegveld, Bleskensgraaf and Hoenkoop, the peat is eutrophic (wood peat), in Assendelft, it is mesotrophic (sedge peat) and in Spannenburg, Oldemarkt and Oldelamer, it is oligotrophic (peat moss (sphagnum) peat). Our data provide some indication that the soil subsidence rate might increase with the eutrophication level. Urbanová and Hájek (2021) reported different respiration rates for bog peat and fen peat. Tolunay et al. (2024) investigated variation in peat decay rates for different types of peat from the Netherlands and found that reed and sedge peat exhibited larger decay rates in anaerobic conditions in comparison to forest and peat moss peat. They stressed the importance of botanical composition of peat for the prediction of peat decay rates and soil subsidence rates. The subsidence rate also depends on organic matter content of the peat (Deverel & Leighton, 2010).

Ground works

In the locations Spannenburg and Oldelamer, the soil has been deep-plowed prior to installation of the subsidence plates. This has probably resulted in a looser upper part of the profile, and/or peat has been brought to the soil surface. It is possible that this has resulted in larger than average subsidence rates in the years that followed the ploughing, as also reported by Stephens et al. (1984). This effect is best visible for Spannenburg B (Bakema et al., 2025), where the thickness of the upper 20 cm layer has sharply decreased. Massop et al. (2024) also observed a much larger subsidence rate in the first years after ground works had been done in one of the fields they studied.

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To summarise our findings on causes of differences in the subsidence rate between sites that could play a role in addition to differences in the ditch water level; a comparison between locations with and without clay cover did not show a clear difference in the relationship between the ditch level and surface level subsidence, so that a new (old is Van den Akker et al., 2007) relation between the surface level subsidence and the groundwater level (or ditch level) had to be developed. This paper provides such a new equation, but as several other factors might affect subsidence too, it may be necessary to include different types of layers covering the peat (e.g. clayey peat, peaty clay, more sandy layers), peat type and degree of earthification in the future.

Different subsidence processes

Our data showed that 27% of subsidence occurred below 1.2 m depth, thus in the permanently saturated part of the profile. It should be noted that this is a conservative estimate as groundwater levels below 1.2 m occur very rarely, and there are sites in which the lowest observed groundwater level is considerably higher than 1.2 m. Consolidation/creep can also occur in parts of the profile that are periodically saturated. These results confirm the results of earlier studies in the Dutch peat meadow area, which showed that around 1/3 of total subsidence is caused by consolidation and/or creep (with contribution of anaerobic decomposition) and 2/3 by oxidation and shrinkage (Beuving & Van den Akker, 1996; Erkens et al., 2016; Massop et al., 2024; Van Asselen et al., 2018). Though their Californian study site was very different from our sites, Deverel and Leighton (2010) reported a similar contribution of consolidation. In our study, the layer 0.8–1.2 m contributed least, which can be explained from the fact that it is not often exposed to oxygen, whilst the layer is usually thin compared to the layer below 1.2 m, so that consolidation and creep are small compared to the deeper layer.

The largest part of subsidence below the groundwater table is probably caused by consolidation/creep, though Fairbairn et al. (2023) and Tolunay et al. (2024) showed that anaerobic decomposition of peat can also play a role. An indication of anaerobic decomposition can be found at the Spannenburg location, where, despite a very thin peat layer, considerable subsidence below 1.2 m is found. Hoogland et al. (2019) reported that anaerobic decomposition of peat may occur at a rate that is 2–10 times lower than that of aerobic decomposition. In a laboratory experiment, Vermeulen and Hendriks (1996) found that under anaerobic conditions, CO_2 production was between one fifth and one third of that under aerobic conditions. In another laboratory experiment, Tolunay et al. (2024) reported that long-term availability of oxygen increases CO_2 emissions 3.9 fold compared to initial anoxic conditions. Finally, Urbanová and Hájek (2021) reported that peat respiration rates were four times higher under oxic than under anoxic conditions. These literature results show that although the rate of aerobic decomposition is higher than that of anaerobic decomposition, anaerobic decomposition is not negligible. However, it is questionable to what extent laboratory studies will yield results that are representative for field conditions. Vermeulen and Hendriks (1996), for example, stated that rates in field conditions would be considerably lower than found by them in the laboratory, as the conditions in the laboratory might not be representative for the long-term anaerobic conditions that exist in the field. Furthermore, Hoogland et al. (2019) also mentioned that anaerobic decomposition could also take place above the groundwater table as water contents above the groundwater table can still be very high (Boonman et al., 2022; Campbell et al., 2021; Tolunay et al., 2024). This makes it more difficult to clearly distinguish the contributions of aerobic and anaerobic decomposition. Therefore, although it is clear that anaerobic decomposition can play a role, further research is needed to better determine how much it could contribute to peat decomposition and soil subsidence.

Decreasing subsidence rates over time

Our data indicated that subsidence rates in the 1970's and 1980's were higher than afterwards. Several possible reasons for the smaller rates since 1980 can be mentioned:

Higher ditch water levels

We have investigated how ditch water levels have changed over time (data not shown here, but can be found in Bakema et al., 2025), to see whether an increase in the ditch water level since the start of the measurements could be an explanation for lower subsidence rates. This showed that for some locations, the ditch water table has risen (Assendelft, Bleskensgraaf 1 (see Figure 4) & 3 and Hoenkoop B) in comparison to the soil surface. However, for other sites, there was no clear trend or even a decrease in the ditch water level. This means that for those locations, other factors are more decisive for the reduction of the rate of subsidence over the past 50 years.

Earthification of peat and decrease of organic matter content in clay cover

When peat oxidises, the organic matter content decreases, and mineral parts present in the peat gradually accumulate (Deverel & Leighton, 2010). Moreover, the fibre structure of the peat collapses and turns into a denser structure of finer particles with smaller pores (Campbell et al., 2021). In time, this results in an earthified top-layer, which has different physical and chemical properties (Säurich et al., 2019) and significantly lower organic matter content than the underlying peat. As a result of this, subsidence also decreases over time in the top-layer.

Similarly, clay covers will also exhibit decreasing organic matter content over time until an equilibrium is reached between the organic matter that is added through e.g. plant roots or application of manure and organic matter that is lost through oxidation. It can take decades before such an equilibrium is reached. As a result of this process, the clay cover will, over time, contribute less to decay of organic matter, CO_2 emissions and soil subsidence.

Climatic change

In the Netherlands, average yearly precipitation has risen from 800 mm/y in the 1960's to 925 mm in 2024 (KNMI, 2025). The largest part of this increase occurs in winter (CLO, 2023), which is the period of the year in which peat surfaces can rise due to wet conditions. Thus, the peat might be better able to recover from seasonal decreases in the soil surface level, which are caused by shrinkage and poro-elastic deformation. Increased recovery in winter might, indeed, be a possible explanation for lower long-term subsidence rates. For example, Schothorst (1977) showed that subsidence rates increased substantially

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after ditch water levels in winter were lowered in the mid-19th century.

Another factor that is significantly affected by climate change is (soil) temperature. The soil temperature in the upper 100 cm of the soil in the Netherlands has in the past 40 years (1980–2020) increased by 1.5°C on average (Bakema et al., 2022). Soil temperature is an important factor in various processes in the soil, including mineralisation, oxidation and denitrification. Stephens et al. (1984) found that it is one of the main factors determining soil subsidence rates at the global scale. In general, a rise in soil temperature would result in acceleration of these processes. For example, Vermeulen and Hendriks (1996), reported an exponential increase of CO_2 emission with temperature, using Dutch peat soils in a laboratory experiment. However, the degree to which temperature influences these processes is variable. A reason for that may be that an interplay with the soil moisture content can be expected, and that higher temperatures would result in dryer soil due to increased evapotranspiration. When the soil becomes too dry, microbial activity decreases, and oxidation rates can decrease (Boonman et al., 2022; Darusman et al., 2023; Nijman et al., 2024; Säurich et al., 2019; Tiemeyer et al., 2016). In most models, however, an increase in the process rate is assumed, following e.g. a Q_{10}-, Arrhenius- or exponential relationship (Bakema et al., 2022). Higher temperature in summer can also result in lower ground water tables due to evapotranspiration, which increases the amount of peat exposed to oxygen.

Note that for the current climate, climate variability (in particular in temperature and rainfall) can cause variability in subsidence rates between years.

Decrease in consolidation

In general, it is assumed that consolidation and creep decrease over time if groundwater tables do not change (Massop et al., 2024; Pronger et al., 2014; Schothorst, 1977). Consolidation occurs when the decrease in pore water pressure causes an increase in effective pressure. Once the soil skeleton is adapted to the new effective pressure, consolidation will end. However, creep continues after that but at a decreasing rate. However, the subsidence plate data (Bakema et al., 2025; Massop et al., 2024) show that the subsidence plates located in the permanently saturated part of the soil profile still show a more or less constant subsidence rate, even after several decades, so that we cannot yet observe a decreasing rate of consolidation/creep (Massop et al., 2024).

Role of surface subsidence and subsidence platens in future research

Though soil subsidence in peat areas generally receives less attention than CO_2 emissions from these areas, the two processes are interlinked. Provided that it can be determined which part of soil subsidence is due to oxidation, data on soil subsidence can be used to estimate emissions (Kasimir-Klemedtsson et al., 1997; Massop et al., 2024; Van den Akker et al., 2008). As advanced (satellite) methods are being developed to determine soil subsidence rates, this approach might be a welcome addition to measurement of CO_2 emissions, as such measurements are expensive (Conroy & Hanssen, 2025). In addition, soil subsidence in peat areas is, in the Netherlands, an important problem in its own right. Thus, continued measurements of soil subsidence rates in peat areas are needed.

The advantages of the subsidence plates method are (1) that the plates at different depts provide information on where in the profile the subsidence occurs, which, in turn, provides indications for the relative importance of the different soil subsidence processes, (2) that the method is cheap and simple, (3) that the plates do not disturb normal farming operations much and (4) that the plates can remain in the soil for decades.

Conclusion

Over the past 50 years, the surface level in the peat meadow areas in the Netherlands has dropped by an average of 0.7 cm/year, if we look at all 29 measurement sites.

Our data reveal that in the Dutch peat meadow areas, a relationship exists between the average ditch water level in spring and average yearly soil subsidence, confirming earlier results. We developed a new equation, which was statistically significant. However, it also exhibits considerable spread of data around the trend line, which we ascribe to site-specific conditions, including the presence of a clay cover, the type and thickness of peat and incidence of ground works. A comparison between locations with and without clay cover did not show a clear difference in the relationship between the ditch level and the surface level subsidence. However, there are indications that the eutrophication level of the peat affects the ground level subsidence rate. We recommend that these insights be included in the development of a new relationship between surface level subsidence and the groundwater level (or ditch water level).

Considerable spread is also observed between sites, in the contribution of different soil layers to soil subsidence and in changing rates of subsidence over time. Nevertheless, data from all 29 sites in combination suggest that around 1/3 of total subsidence is due to consolidation, creep or anaerobic decomposition and 2/3 to oxidation, earthification and/or shrinkage. Averaged data also suggest that subsidence rates in the 1970's and 1980's were larger than afterwards. We could not identify a main cause for these results, but factors like changes in the ditch water level, climate change, ground works and change of soil properties due to earthification are expected to play a role. Despite the challenges associated with analysis of datasets collected over the course of more than 50 years, the subsidence plates method was found to provide relevant data on subsidence rates and the relative importance of different subsidence processes.

Competing interests. The authors declare none.

Data availability. The underlying data supporting this publication are available at DOI: 10.5281/zenodo.14960800. Underlying data include not only the data used in this paper but also the results of subsidence plates measurements (which are described in Bakema et al., 2025).

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