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Monitoring long-term peat subsidence with subsidence platens in Zegveld, The Netherlands

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ABSTRACT

Peat oxidation in peat meadow areas is causing greenhouse gas emissions as well as land subsidence. Due to yearly fluctuations in soil surface level, long-term monitoring is needed to determine long-term net subsidence rates. In the experimental peat-meadow farm at Zegveld (NL) subsidence platens were installed in 1970 in a field with low ditchwater level, and in 1973 in a field with high ditchwater level. Platens were installed at 7 different depths, allowing to investigate where in the peat profile subsidence occurs. Elevation of platens as well as soil surface has been measured with surveyor's levelling each year at the end of winter, so that a long timeseries up to 2023 is available. Analysis showed that surface level in the field with high ditchwater level subsided by 24 cm in 50 years (4.8 mm/yr), while in the field with low ditchwater level this was 31 cm in 53 years (5.8 mm/yr). Results also indicated that in the field with low ditchwater level, most subsidence due to permanent shrinkage and peat oxidation occurred between 40 and 100 cm depth, while for the other field this was between 0 and 20 and between 40 and 60 cm depth. Finally, in 2023 subsidence was still observed under continuously saturated conditions at 140 cm depth. Presumably, in the aerated part of the profile peat oxidation and the associated earthification process is the main cause of subsidence, while the observed subsidence in the saturated soil at 140 cm depth must be due to other processes, such as consolidation and creep.

1. Introduction

Emissions of greenhouse gasses from peat areas are currently the subject of much research in Europe, as these emissions need to be reduced to achieve climate targets that have been formulated for 2030 and 2050 (EC, 2020). It is well-known that when peat soils (Histosols) are drained, they will start emitting CO_2 due to oxidation of peat (e.g., Wösten, 1997; Erkens et al., 2016; Leifeld and Menichetti, 2018; Evans et al., 2021; Freeman et al., 2022). This causes loss of soil volume, resulting in subsidence of the peat soil surface. In the western part of the Netherlands, drainage of peat to enable agricultural use already started around the 11th – 12th century (Van de Ven, 2004, Querner et al., 2007), and has over the centuries resulted in subsidence of several metres (Schothorst, 1977; Erkens et al., 2016), which in combination with geologic processes (tectonic, isostatic and compaction movements, Kooi et al, 1998) and sea level rise (mainly during the last century) has resulted in surface elevations that are currently more than 2 m below mean sea level. Around 1965, subsidence rates increased because a modernization of dairy farming started, including lowering of ditch-water levels to improve the bearing capacity of peat meadow parcels (Van den Akker et al, 2021). Subsidence has severe consequences, because it causes damage to buildings and infrastructure (Van Asselen et al., 2020), and it makes water management ever more complex and costly (Van den Akker et al., 2007; Pronger et al., 2014), while risk of flooding increases (e.g. Van Asselen et al., 2009, 2020; Dawson et al., 2010; Zanello et al., 2011; Pronger et al., 2014; Ikkala et al., 2021). The groundwater pumping that causes subsidence may also cause an increase in salinity and a drying-out of nature areas (Querner et al., 2007, Van den Akker et al., 2007).

Land subsidence in peat areas is caused by several processes (Schothorst, 1977), namely oxidation, shrinkage and compression (see Table 1 for definitions). Schothorst (1977) estimated that in the long term (and assuming that compression has stopped) 85 % of subsidence in agricultural areas is caused by oxidation. Although other authors have

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Table 1
Definitions of land subsidence processes considered in this paper, and where in the soil profile they occur.

Process	Definition	Where
Oxidation	A biogeochemical process of soil organic matter decomposition and earthifying of peat by micro-organisms (Schothorst, 1977). This causes a volume reduction (Van Asselen et al., 2018) as well as GHG emissions.	Only above groundwater table
Shrinkage	Volume reduction of peat above the groundwater level due to desiccation (Wösten et al, 1997), resulting in contraction of plant fibers (Erkens et al, 2016) and an increase in bulk density (Wösten et al, 1997).	Only above groundwater table
Compression	The sum of consolidation and creep. Defined by Paul and Barras (1998) as the reduction in equilibrium volume due to an increase in effective stress.	Mainly below groundwater table
Consolidation	Hydrodynamic compression with dissipation of excess pore pressure, increasing effective stress, also called primary compression (Den Haan, 1994).	Mainly below groundwater table
Creep	Deformation at constant effective stress, also called secondary compression (Den Haan, 1994).	Mainly below groundwater table

provided different estimates (see Van den Akker et al., 2008), the general consensus is that long-term subsidence in peat meadow areas is mainly the result of peat oxidation (e.g., Hendriks et al., 2008). In build-up areas, consolidation and creep are often of larger importance due to loading of the underlying peat by anthropogenic brought-up soils prior to construction (e.g., Koster et al., 2018; Van Asselen et al., 2018). Nevertheless, Beuving and Van den Akker (1996) reported that for high ditchwater level meadows in Zegveld, consolidation and creep also made up as much as 38 % of total subsidence over a period of 25 years. The relative contribution of the different subsidence processes is likely to change over time (e.g., Pronger et al., 2014), and may also vary in dependence of peat thickness. For example, most consolidation takes place in the first years after drainage (Van den Akker et al, 2007; Ikkala et al, 2021; Oleszczuk et al, 2022; Pronger et al., 2014) and in thicker peat layers processes that operate in the saturated zone (i.e., consolidation and creep) may have a larger contribution (e.g. Grønlund et al., 2008). To reduce subsidence of peat meadow areas it is important to know which part of the subsidence is caused by which process, in the local context and at appropriate time scale, as this allows to take appropriate measures. Besides, land subsidence has been used as proxy for CO_2 emissions (e.g., Van den Akker et al., 2008) based on the assumption that oxidation can be assumed to be the main cause for land subsidence in the long term. Information on the relative contribution of the different processes is needed to verify that assumption.

Several techniques have been used to measure land subsidence in peat areas, including levelling, extensometers (Van Asselen et al, 2020), exposure of structures (Zanello et al, 2011), repeated measurements of peat thickness (Oleszczuk et al, 2020, 2022; Pronger et al., 2014) and recently radar satellite-based and laser scanning-based methods (InSAR and LiDAR respectively; Van Asselen et al, 2020). Most of these methods only provide data on subsidence of the peat surface, and not on the contribution of different peat layers to subsidence. An exception are extensometers, and also the subsidence platen method described in this paper, and already applied by Schothorst (1977).

Measurement of land subsidence in Dutch peat areas is complicated by the fact that surface level also fluctuates during the course of the year, mainly as a result of changing phreatic groundwater levels which cause shrinkage and swell as well as elastic deformation of the saturated peat soil (Van Asselen et al., 2020). Groundwater levels are often close to the soil surface during winter, due to rainfall and low evaporation, but may in the western peat meadow area of the Netherlands drop to around 1 m below the surface during the growing season, causing yearly fluctuations in surface level, amongst others due to shrink and swell of the peat. These fluctuations can amount to 10 cm per year (Van Asselen et al, 2024). As long-term net subsidence rates in the Dutch peat meadow areas are more in the order of 5–10 mm per year (e.g., Schothorst 1977, 1982; Beuving and Van den Akker, 1996; Hoogland et al. 2012; Van Asselen et al, 2024), long-term monitoring is needed to detect land subsidence. Our dataset is exceptional in that it consists of almost yearly subsidence measurements at different depths in the soil, and covering a period of 50 years. Such a dataset allows to extract long-term subsidence rates as well as information on where in the profile subsidence takes place, which in turn provides information on the different subsidence processes.

The aims of this paper are to 1) describe the subsidence platens method, 2) present results of measurements conducted since 1970, 3) derive long-term subsidence rates from the data, and 4) investigate the relative contribution of the different subsidence processes.

2. Study area and methods

2.1. Experimental site

The experimental farm near the village Zegveld and the small Oude Meije river was founded in 1966, amongst others to monitor the expected increase of land subsidence due to lowered ditchwater levels (Van den Akker et al., 2007). The experimental farm is located in the western part of the Netherlands, within a typical peat meadow landscape (Fig. 1). The soil profile in Zegveld consists predominantly of eutrophic wood-sedge peat (Carex and Alnus) (Schothorst, 1977) (Histosol) and is underlain by Pleistocene sand at a depth of around 6 m below the soil surface (Hoving et al., 2021). The organic matter content in the 0–30 cm surface layer roughly ranges from 50 to 70 % by weight. The organic matter content gradually increases to 80–85 % at a depth of 80 cm below the surface as the degree of decomposition decreases (Schothorst, 1977). Remains of wood are most common in the upper 3 m of the profile, while below that depth peat derived from sedge and reed dominates. Land use is permanent grassland, used for grazing and mowing.

In 1969, the ditchwater system of part of the farm (green parcels in Fig. 1) was disconnected from the water system of the polder Zegveld and the ditchwater level in this part was managed with a pump ever since. In this part of the farm, the ditchwater levels were lowered to 70 cm below surface level in 1969. During the period 1970–1996 the ditchwater level in general was between 60 and 70 cm, although the target ditchwater level was 60 cm below soil surface. From 1996 on the ditchwater level varied between 55–60 cm below the soil surface. For the remaining part of the farm, the ditches remained connected to the water system of the polder Zegveld, with ditchwater levels of 35 cm below the soil surface in 1969. Although the water authority partly adapted the ditchwater level to ongoing subsidence from time to time, the ditchwater level gradually rose to about 15 cm below soil surface in the period 1995– 2012. After 2012 the ditchwater level in the polder Zegveld was adapted in steps of 5 cm per year to arrive at a ditchwater level of about 25 cm below soil surface. Thus, in 2023 the ditchwater levels were about 55 cm below surface level in the part of the farm with low water levels, and 25 cm below surface level in the high water level part of the farm (see Fig. 1). In 2016, water infiltration systems (WIS) were installed in four fields of the farm (fields 13–16), by inserting drainage pipes (6 m spacing) below ditchwater level (Hoving et al., 2021). These pipes allow drainage from the field to the ditch during wet periods as well as infiltration of ditchwater into the soil during dry periods. Each of the fields contains a part with no active drains (reference),

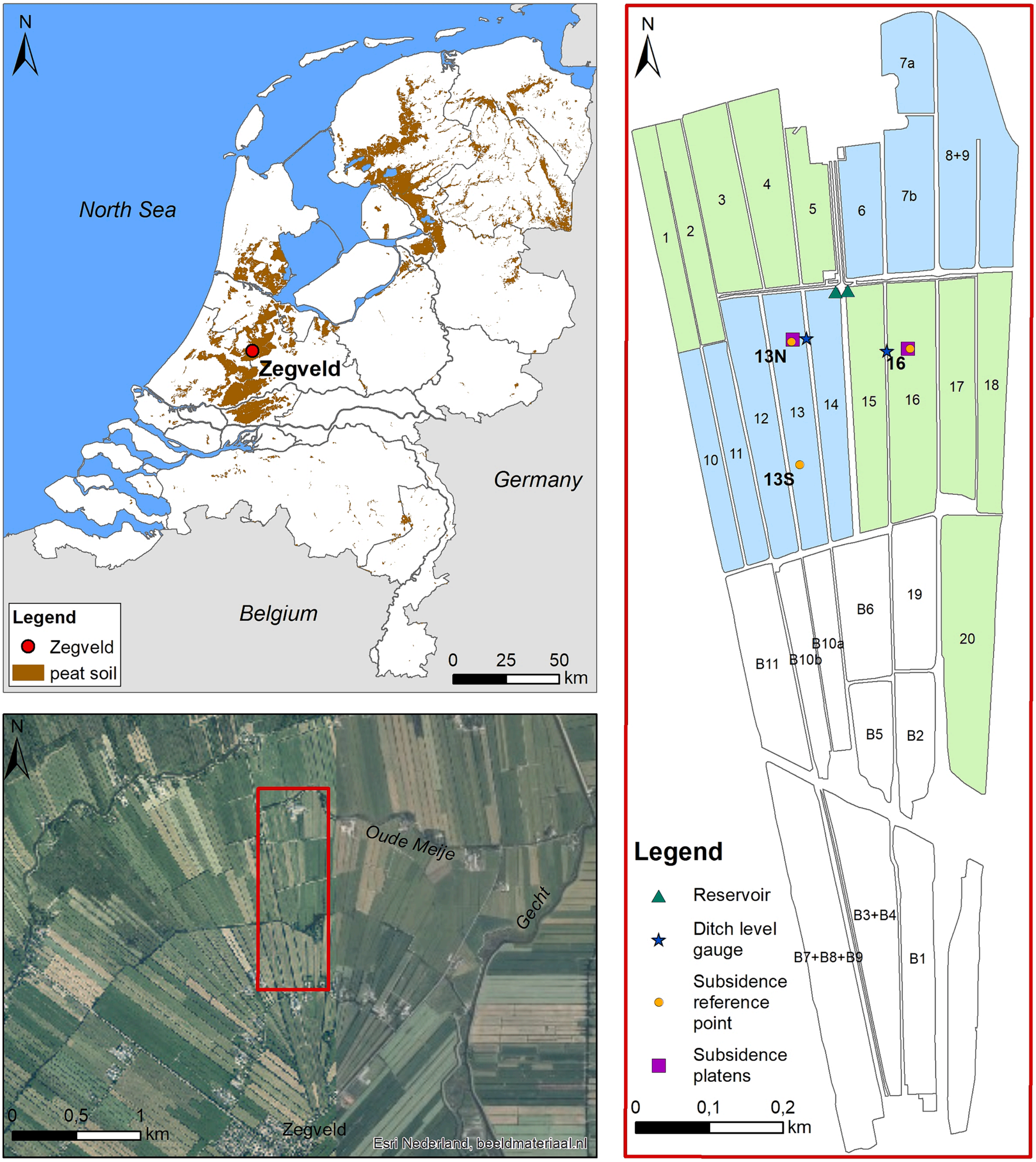


Fig. 1. Location of Zegveld study site. Map on the right shows parcels with parcel numbers that are part of the experimental farm. Blue indicates current high ditchwater level (25 cm below surface level) and green indicates low ditchwater level (55 cm below surface level). In white fields that were not part of the experiment with different ditchwater levels. Location of groundwater level measurements is not shown in the map; these are described in the text. Map in top left based on Brouwer et al, 2021. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

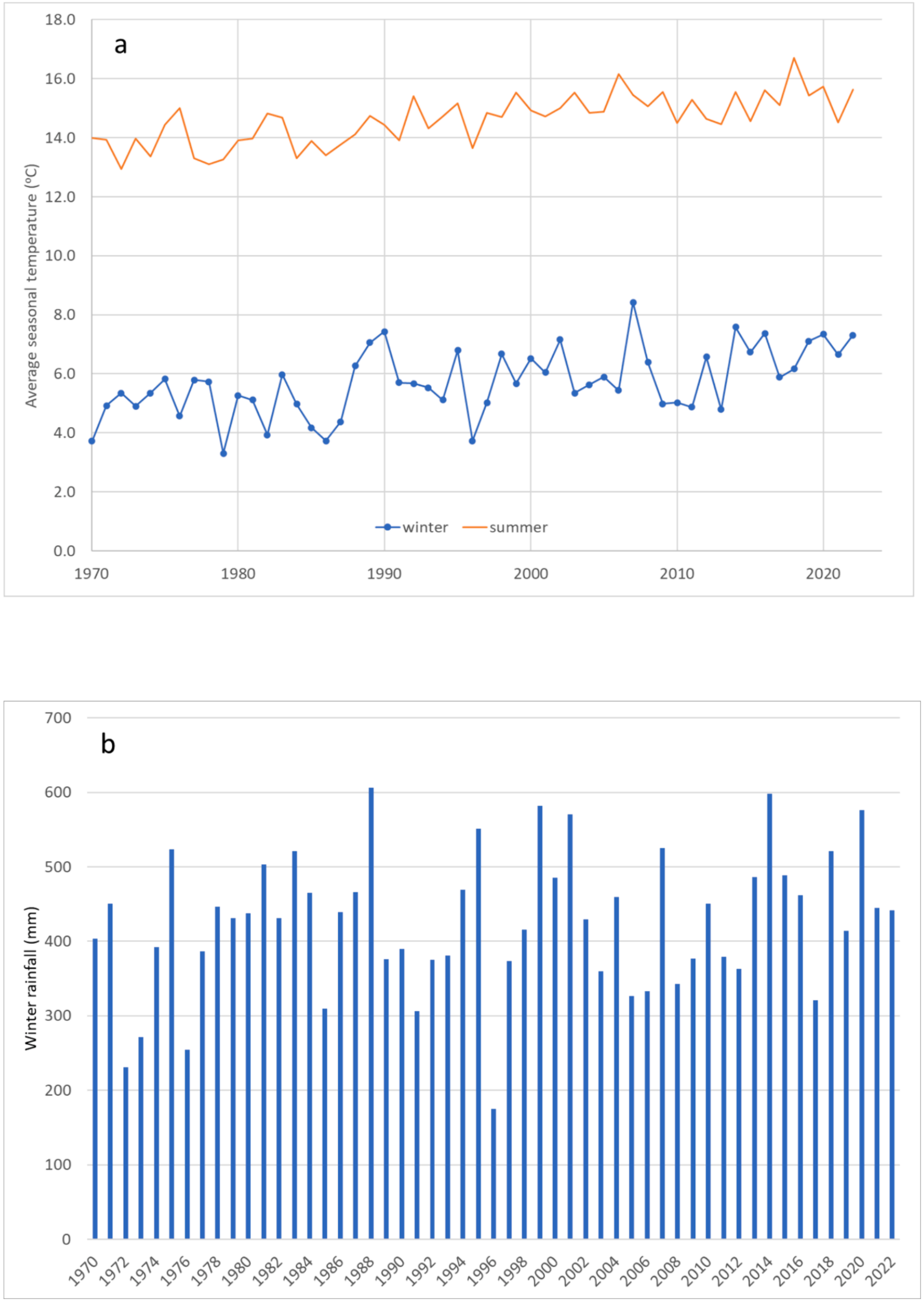


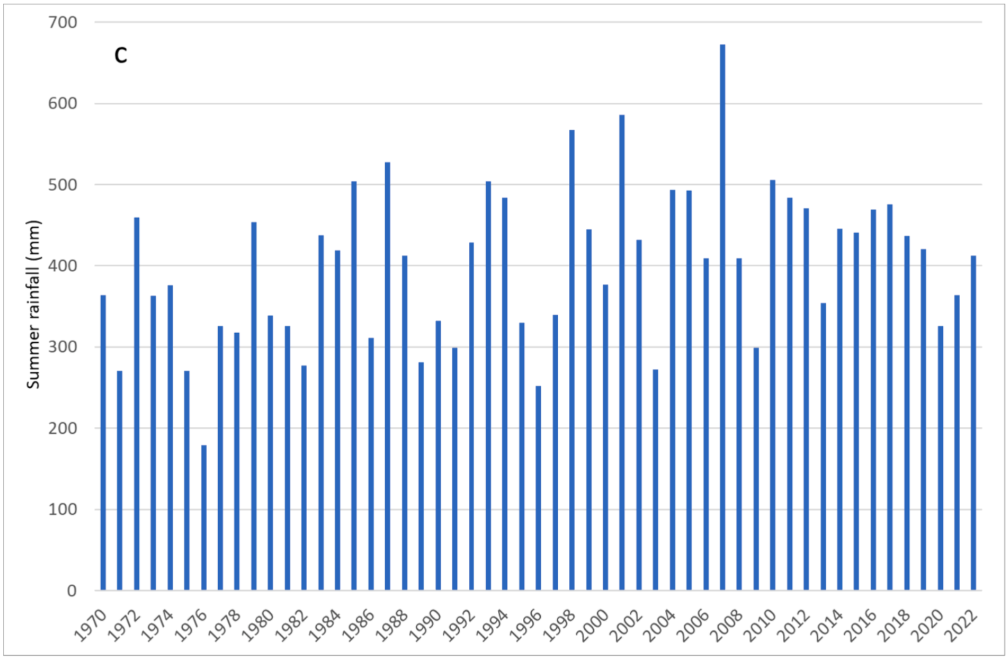
Fig. 2. A) average seasonal temperature, b) winter precipitation, c) summer precipitation and d) summer precipitation surplus for the period 1970–2022.

passive WIS (PWIS), in which pressure in the drains is controlled by ditchwater level, and active WIS (AWIS) in which pressure is controlled by water level in a reservoir (Hoving et al., 2021). The groundwater level target of the AWIS in field 13 was 40 cm below soil surface and in field 16 40–50 cm below soil surface.

Precipitation data are available for Zegveld (KNMI station 470,[1] see also Hoving et al., 2021), while for air temperature and evapotranspiration data (calculated with Makkink equation) from De Bilt (KNMI station 260) have been used (Hoving et al., 2021). Fig. 2 shows the change of temperature, precipitation and precipitation surplus (precipitation – evapotranspiration) over time. A distinction has been made between winter (October-March) and summer (April-September). To calculate yearly data the year is taken as October previous year until September.

Fig. 2 shows that both winter and summer temperature have increased since 1970, with similar trend, but with more variability in winter than in summer. Precipitation shows significant variability between years. Though average rainfall seems to increase too, especially in summer, this may also be due to variability over time. For example, without the dry summers around 1976 no clear trend would be visible.

[1] See daily values precipation stations KNMI (Koninklijk Nederlands Meteorologisch Instituut – Royal Netherlands Meteorolical Institute) at: Dagwaarden neerslagstations (knmi.nl) and meteorological data KNMI at: KNMI – Klimatologie.



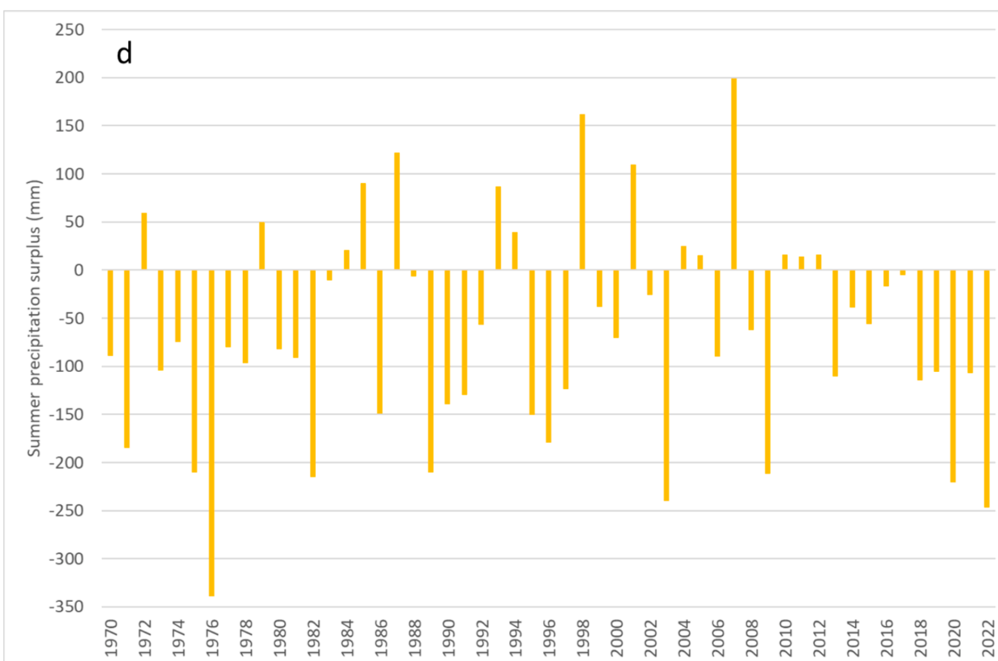


Fig. 2. (*continued*).

Mean precipitation in the area is 826 mm/yr (rainfall data Zegveld 1970–2022). Potential evapotranspiration has been estimated to be around 545 mm/yr (Trambauer et al 2011), so that on yearly basis there is a precipitation surplus. However, as Fig. 2 shows there is a rainfall deficit in most summers, resulting in a drop of phreatic groundwater levels. No clear trend in rainfall surplus/deficit can be seen in Fig. 2 for the summer period. The average rainfall deficit in summer (1970–2022) was 65 mm, but it exceeded 200 mm in eight years during this period, including in 2020 and 2022.

2.2. Methods

Subsidence platens have been installed in several fields of the farm (see Schothorst 1977, who used the term 'metal discs' for the subsidence platens). Subsidence platens consist of two connected metal plates (Fig. 3) with a diameter of 8 cm (Beuving and Van den Akker, 1996). The platens can be installed via an auger hole. When the platens are at the desired depth the platens can be rotated so that they cut into the peat and thus become fixed (meaning that they follow the vertical movement of the peat at installation depth). A PVC tube is connected to the platens and reaches to about 15 cm below the soil surface level. The upper part

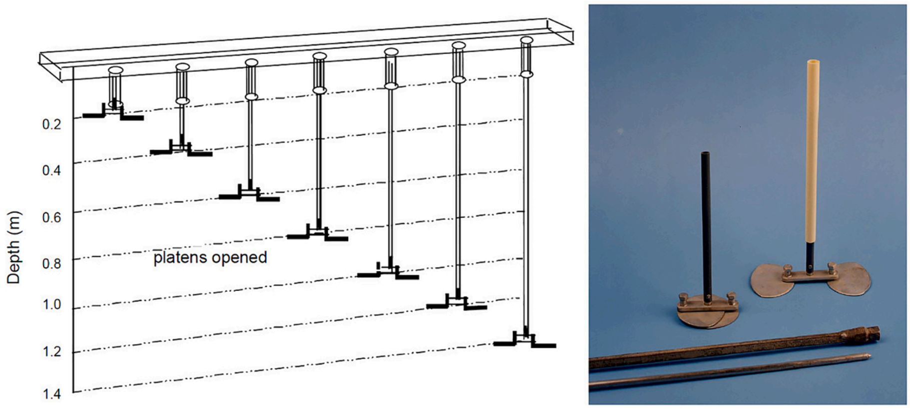


Fig. 3. Subsidence platens. The horizontal distance between the different platens is about 20 cm.

of the PVC tube is protected by a wider extra tube which ends a few centimeters below surface level. Further protection is provided by a wooden box that encloses the tops of the tubes. The box is open at the bottom and closed at the top and is designed in such a way that livestock and tractors can pass over the box without causing damage to the platens. The box can be removed for periodic measurement of the elevation of the platens using levelling. For measuring elevation, a metal rod of known length can be inserted in the PVC tube, and when it rests on the subsidence platen the top of the rod can be measured with a surveyor's level. By installing a series of subsidence platens at different depths (see Fig. 3) it is possible to determine vertical soil movement at different depths, which also allows to determine where in the soil profile subsidence occurs.

In this paper we focus on subsidence platens in two fields; one in the part of the farm where the ditchwater levels were lowered in 1969 (field 16) and one in the part of the farm where this was not done (field 13) (positions indicated in Fig. 1). The peat profile at both fields is similar, though in historic times a thin layer of organic waste material was applied on field 16 to improve fertility and trafficability. This material was high in mineral parts and is now mixed in the upper 20–30 cm of the profile. In both fields, the platens were installed in the part of the field where in 2016 AWIS was installed. In both field 13 and field 16 subsidence platens were installed at 7 depths, namely approximately every 20 cm up to 140 cm (Fig. 3). In field 13 measurements started in 1973, while in field 16 they started in 1970. Every year in early spring when the soil is soaked and swollen, the altitude of the soil surface and the platens was measured using surveyor levelling. As the time of measurement was based on field conditions it varied between years, but was almost always in March or April. In this way, the effects of yearly fluctuations were minimized as much as possible. Measuring was each year done for all the subsidence platens that could be found. However, it can occur that when the measurement rod is inserted in the pipe of the subsidence platen, the subsidence platen is not encountered. This is probably due to deterioration/displacement of subsidence platens over time. For this reason, some subsidence platens have been replaced during the measurement period. When this was done the difference in elevation between the original platen and the replaced one was measured, and this difference was added to measured elevations from then on to allow continuation of the data series. For levelling, a subsidence reference point is used. This is a metal pipe that is driven in the sand below the peat layer, and was considered to be stable (i.e., not subsiding). The elevation of the surface level and subsidence platens has been measured relative to the reference point. In field 13, two reference points are located (13 N and 13S), while in field 16 one reference point is present (see Fig. 1 for locations). To verify the stability of the elevation of the subsidence reference points, they have been levelled a few times since installation, with increasing frequency towards the end of the monitoring period as some subsidence reference points appeared to be not stable but subsiding. For levelling of the reference points, fixed points on a bridge (Dutch Ordnance Datum benchmark 31D0218) and nearby house have been used (see Beuving and Van den Akker, 1996). Data from the Department of Waterways and Public Works indicates that benchmark 31D0218 subsided around 3 mm in the period 1989–2017, and hence is almost stable. Levelling data of the reference points has been used to correct the subsidence platen measurements.

Given the uncertainty in levelling data that exists due to reference points that may not have been stable, we analysed the subsidence platen data in two complimentary ways:

1. We analysed the changes in thickness of specific soil layers (e.g., 0–20 cm, 20–40 cm etc) over time. The thickness of each soil layer in any particular year is independent of the reference point, as for any particular year the measurements at all depts are affected equally by uncertainty about the level of the reference point. The development of thickness of layers over time is also independent of the reference point. However, this method has some potential issues:
   a. Whenever there are missing data for a certain depth, thickness cannot be calculated for the layer above this depth as well as the layer below this depth.
   b. When there are measurement errors at a certain depth this affects the thickness calculation of the layer above and the layer below in opposite ways.
   c. To arrive at an estimate of soil subsidence the analyses of thickness of layers always has to be combined with levelling data for a particular depth. For example, if the thickness of the layer 0–120 cm is analysed, measured subsidence at 120 cm has to be added to arrive at total soil surface subsidence. These levelling data do remain dependent on the reference points.
2. We analysed the elevation of the different subsidence platens as well as the soil surface over time. These data are affected by uncertainty about stability of reference points, but as explained above, without them total soil surface subsidence cannot be assessed. Elevation measurements of subsidence platens may have additional uncertainty compared to elevation measurements at the surface, e.g., because of (undocumented) changes in rod length or because the rod does not properly rest on the subsidence platen during measurement.

Given the limitations mentioned above we have used the soil surface elevation data to assess total subsidence. To assess where in the soil profile subsidence occurs, we have used both methods that have been explained above. To avoid some of the problems mentioned above for thickness calculation, we have analysed our data for grouped soil layers of 0–40 cm, 40–80 cm and 80–120 cm depth.

Another source of uncertainty are measured values that appear to deviate from the other measurements. We have only corrected these if there was firm evidence that measured values were incorrect, and we have assumed that the most reliable long term subsidence rates are obtained by using the longest possible time series.

Phreatic groundwater levels and ditchwater levels have also been monitored. Ditchwater level monitoring was for field 13 done in the ditch east of the field and for field 16 in the ditch west of the field, using permanent staff gauges. Until 2003 groundwater levels were measured manually in wells on the same day as the subsidence platens, at a distance of about 2 m from the subsidence platens. From 2003 till 2019/2020 groundwater level was also measured in these two wells, but the date of the measurements of the groundwater level and subsidence platens differed by some days. These measurements have been replaced by measurements on a regular grid of wells, which exists throughout the parcels, since 2016. After 2020, the 3 closest groundwater measurement points on that grid were used. These measurement points were all located midway between two drains, at distances of 5.8, 7.9 and 14.0 m of the subsidence platens in field 13, and at distances of 6.9, 14.1 and 22.1 m in field 16. The date of the measurements of the subsidence platens and groundwater level also differed by up to a few days during this last period.

Groundwater level data were used to calculate the mean lowest groundwater level (LG3, Van den Akker et al, 2007). LG3 is calculated as the average of the three lowest groundwater levels measured bi-weekly during a full hydrological year (1 April – 31 March) (Van den Akker et al., 2007) nearby the subsidence platens.

3. Results

3.1. Groundwater level and ditchwater level

Fig. 4a shows the ditchwater level at the moments of the subsidence measurements and the yearly mean lowest groundwater level (LG3, Van den Akker et al., 2007) in the periods 1970–1976 and 1992–2022.

The LG3 in Fig. 4a indicates to which depth air has entered the soil. In the period 1970–1976 the mean deepest groundwater levels LG3 were lower than in the period 1992–2022. This can be at least partly explained by the lower ditchwater levels and drier summers in the first period. As mentioned before, AWIS was installed in 2016. The installation of AWIS meant that fluctuations in phreatic groundwater level decreased, with groundwater levels in summer being higher than before, resulting in a higher LG3. In winter, groundwater levels were somewhat lower than before and periods with high groundwater level lasted shorter.

Fig. 4b shows the phreatic groundwater levels that have been measured at or around the moment of the elevation measurements at the end of the winter, near the location of the subsidence platens. On average, the phreatic groundwater level at the end of the winter is 0.35 and 0.22 m below surface in field 16 and 13 respectively. However, there is large variation between years, presumably due to varying weather conditions, which results in standard deviations of 0.16 m for field 16 and 0.14 m for field 13. Still, the difference in average groundwater levels illustrates that ditchwater level management did impact groundwater level at the location of the subsidence platens. In some cases, groundwater levels were higher in field 16 compared to field 13. This may be due to different moments of measuring in the two parcels; measurements in field 13 were sometimes done several days later than in field 16.

Table 2 indicates how often certain water table depths occur in the two fields. The table is based on groundwater level measurements in the two wells next to the subsidence platens, over the period 1994–2019. This shows that deeper water tables occur more often in field 16 than in field 13, and that the maximum water table depth in field 16 is larger than in field 13. As the data in Table 2 do not cover the full period of study, water tables may have been lower occasionally (as can be seen for field 16 in Fig. 4). Therefore, we consider that the water table in field 13 is never lower than 80–100 cm, while for F16 this is 100–120 cm.

3.2. Subsidence reference points

Results of measurements of the elevation of the subsidence reference points are shown in Fig. 5.

For reference point 13 N (which is closest to the subsidence platens in field 13, see Fig. 1), the chart shows some subsidence, with an average rate of 1.4 mm/y. However, a new measurement in 2023 showed a deviating, much lower, elevation value (see Fig. 5). This is presumably due to (undocumented) shortening of the reference point (pipes/tubes). Such shortening is necessary from time to time as ongoing subsidence causes the reference point to protrude above the soil surface, making it susceptible to disturbance by farm operations. As no firm evidence on shortening the reference point was found, the measured elevations of the reference point were not corrected.

The subsidence reference point in field 16 shows a large subsidence rate. As this reference point was replaced in 2004, separate equations have been used from 1970 to 2003 and from 2004 to 2023. In addition, data of 1970–1988 had already been corrected in 1992, which is why the period 1970–2003 was subdivided in 1970–1988 and 1989–2003. The equations indicate that the average subsidence of the old reference point was 10.7 mm/y from 1970 to 1988 and 7.2 mm/y from 1992 to 2003, while for the new one this was 5.9 mm/y on average. The reason for this is most likely that the sand layer in which the reference point was founded is relatively soft, with a firmer sand layer at around 9 m depth, as was shown by a cone penetration test in field 15 (Erkens et al., 2020). As the reference point was founded in the upper sand layer it may be subsiding under its own weight, and/or it is being pulled down during summer when the surface level subsides under dry conditions but is not pulled back up when the soil surface level rebounds in winter under wet conditions. In field 13, the subsidence reference points (both 13 N and 13S) were probably founded in a deeper sand layer, as Beuving and Van den Akker (1996) reported that 10 m long steel pipes were used in field 13.

The observed subsidence of the subsidence reference points means that subsidence platen measurements should be corrected for subsidence of the reference points. Table 3 shows which corrections have been applied. These corrections are based on measurements of subsidence reference points until 2023. 13 N was not measured in 2019–2022, and the value for 2023 is clearly lower than for earlier measurements (Fig. 5 which is why for field 13 we used 13 N to correct for the period until 2018, and 13S (which is found to be stable; data not shown) for the period from 2019.

3.3. Levelling of subsidence platens

Fig. 6 shows the corrected results of the subsidence platen measurements obtained for field 13, while Fig. 7 shows the results for field 16. For both fields, trendlines have been fitted using a linear regression as the measured data did not suggest that another curve shape is needed, and e.g. an exponential fit hardly improved R^2. In view of parsimony we therefore used the simplest equation, which was the linear one. Total subsidence at different depths was calculated by applying the regression equation to the start year (1973 for field 13, 1970 for field 16) and to the end year (2023), after which the difference in elevation between these two years, i.e. subsidence, was calculated (Table 4). Also, the contribution of each soil layer to total subsidence was calculated (Table 5).

For field 16, two regression equations have been used for the surface and for the subsidence platen at 20 cm depth. The reason for this is that Beuving and Van den Akker (1996) indicated that ground works have been done in September 1988, and that the subsidence platen at 20 cm depth was reinstalled after these works. In these ground works, the top 20 to 30 cm was loosened and soil was moved from the sides to the middle of the parcel. In this way the surface level of the middle part of the field (where the subsidence platens are located) was artificially raised to compensate for long-term subsidence. Surface elevation measurements in spring 1988 and spring 1989 (Fig. 7) indicate that the

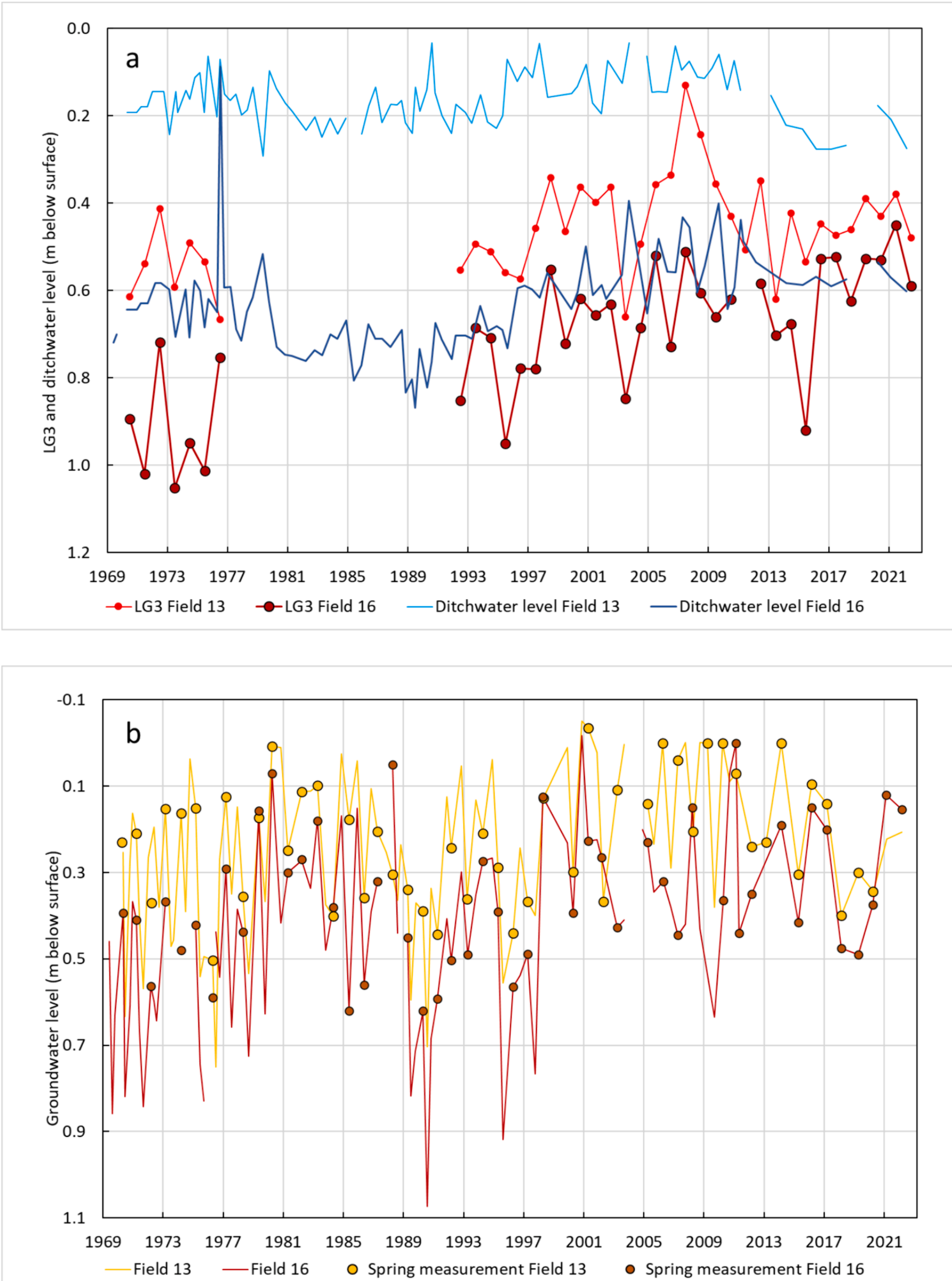


Fig. 4. A) Ditchwater level and mean lowest groundwater level LG3 in fields 13 and 16. In the extremely dry summer of 1976 the ditchwater levels were raised, and the fields were irrigated. b) Groundwater level nearby the subsidence platens in fields 13 and 16. The measurement moments in early spring are indicated.

Table 2
Percent of time for which water table was above the specified depth. Values are the average of the measured values in the two wells next to the subsidence platens. Data 1994–2019.

Depth	Field 13	Field 16
0	25 %	8.8 %
20	48 %	27 %
40	87 %	53 %
60	99 %	88 %
80	100 %	98 %
100	100 %	100 %
120	100 %	100 %
140	100 %	100 %

surface was raised about 7.5 cm in 1988. Fig. 7 indicates that the added amount disappeared within 2 years, probably due to 1) increased oxidation, 2) because the relatively loose material that was added compacted and 3) because the additional weight that was added also seems to have resulted in additional subsidence at 20 and 40 cm depth (Fig. 7).

Figs. 6 and 7 show that measurements of the subsidence platens have been done almost every year since installation. For both fields there are, however, also some missing data. In addition, some subsidence platens have been lost (meaning they could not be measured anymore) without being replaced. Examples include the subsidence platen at 140 cm depth in parcel 13 (not measured after 2009), and the subsidence platens at 20, 100 and 120 cm in parcel 16. For these depths the trendlines were extended to 2023 to allow calculation of total subsidence at this depth.

Results for field 13 (Fig. 6, Tables 4 and 5) show:

– That subsidence generally decreases with depth (Table 4), with subsidence at 0 cm being 24 cm, at 20–40 cm total subsidence was 14 cm, between 60 and 120 it was somewhat variable (8 cm on average), while at 140 cm subsidence was 5 cm. This is what would be expected as subsidence of the surface is cumulative, i.e. it is the sum of subsidence over the whole peat profile.
– That most of the subsidence (10 cm) occurred between 0 and 20 cm depth, followed by 40–60 cm depht, see Table 5.
– If 80 cm depth is taken as maximum water table depth (Table 2) total subsidence below the lowest water table was 9 cm, or 39 % of the total subsidence of 24 cm. If we assume that water table may have reached 100 cm in exceptional cases this is 7 cm, or 31 %.
– The data show that there was a sudden subsidence from 2018 to 2019 at almost all depths. This probably has to do with undocumented shortening of the reference point. As no firm evidence of shortening was available, data were not corrected. However, an analysis covering period 1973–2018 resulted in a similar yearly subsidence at the soil surface (4.6 mm/y instead of the 4.8 mm/y shown in Fig. 6).

Results for field 16 (Fig. 7, Tables 4 and 5) show:

– That for the soil surface subsidence rate in the period from 1989 was smaller than in the period until 1988.
– That, like for field 13, subsidence rates generally decrease with depth, but 140 cm clearly deviates from this trend. The subsidence at 140 cm is higher than that at 100 and 120 cm and is also almost four times higher than the subsidence of platen 140 in field 13. The higher measured subsidence at 140 cm is unexplained, but the data series itself does not indicate any irregularities in the measurements. Hence there is not sufficient reason to disregard measurements at 140 cm. Note also that due to missing data at 100 and 120 cm depth after 2015 the slope for these depths may have been underestimated, which would imply larger subsidence at these depths and a less deviating value at 140 cm depth.
– That the data for 20 cm depth are, after 1989, influenced by the strong subsidence in 1989 and 1990, especially as this data series ends in 2008. Therefore, subsidence at this depth is probably overestimated. Without 1989 and 1990, subsidence rate at 20 cm becomes 5.1 mm/y instead of the 7.7 mm/y shown in Fig. 7.
– That in the upper 40 cm of the profile there was no contribution to subsidence (Table 5), if the measured value at 20 cm depth is neglected. Depths 40–100 cm showed 5–7 cm subsidence per 20 cm layer, and subsidence at 120 cm was smallest, with the −6 cm value for 120–140 cm (Table 5) being due to the unexplained results for 140 cm, and perhaps partly to possible underestimated of subsidence at 100 and 120 cm depth (see earlier point).
– If 100 cm is taken as maximum water table depth (Table 2), 13 out of 31 cm (40 %) of total subsidence occurred below the lowest water table depth, while if 120 cm is used this is 12 cm (38 %).

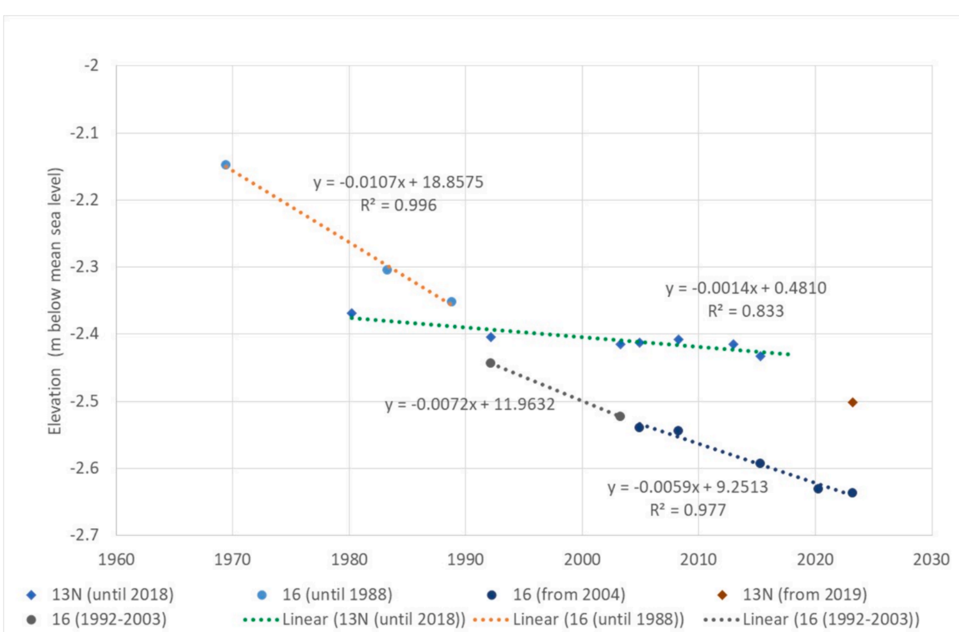


Fig. 5. Elevation (m MSL) of subsidence reference points in fields 13 and 16.

Table 3
Corrections applied to account for subsidence of the subsidence reference points. When the correction is a constant, this value has been applied for all years in the range of years that is mentioned, while if a trend is given the correction value for each year is different (the trend shows by how much the value of a certain year differs from the year before).

Location	Years	Correction	Remarks
13 N	1973–1980	No correction needed	Data retrieved from archives Schothorst (1977, 1982), who checked reference point to a stable reference point in deep founded farm house.
	1981–2018	1.44 mm/y subsidence;	Application of regression equation Fig. 5
	2019–2023	No correction needed	Because alternative stable reference point (13S in Fig. 1) was used during measurement of platens
16	1970–1988	No correction needed	Because already corrected by Schothorst (1977, 1982) and by Beuving and Van den Akker (1996) based on measurements of reference points shown in Fig. 5; this corresponds to subsidence of 10.7 mm/y
	1989–2003	Linear interpolation and extrapolation of measured values in 1992 and 2003; this corresponds to subsidence of 7.2 mm/yr	
	From 2004	5.9 mm/y subsidence	Application of regression equation from Fig. 5.

Comparison of results from both fields indicated:

- That total subsidence is higher in field 16 than in field 13 (also if corrected for the different duration of measurements), with surface subsidence being 7 cm more in field 16. Subsidence at surface level was found to be 4.8 mm/year (24 cm in 50 years) for field 13 and 5.8 mm/year (31 cm in 53 years) for field 16.
- A difference in the depths at which most subsidence occurred. For field 13 this was 0–20 and 40–60 cm, while for field 16 it is 40–100 cm. This is likely due to the lower groundwater levels that exist in field 16, especially in summer, hence oxidation can occur at greater depth in field 16 than in field 13, and the variation in effective stress will also be larger.
- That both field 13 and field 16 show subsidence throughout the entire profile, even at depths well below the groundwater table. For field 16, total subsidence below the deepest water table depth is estimated at 12–13 cm (38–40 %), while for field 13 this was 7–9 cm (31–39 %).

3.4. Thickness of soil layers

To limit the effect of missing data on calculation of thickness of soil layers, we analysed the change of thickness for layers 0–40, 40–80 and 80–120 cm for both fields. In addition, we also investigated the change of thickness of the layer 0–120 cm for field 13, and 0–140 cm for field 16. Depths differed between the two fields, because of missing data (for 140 cm in field 13, and for 120 cm in field 16).

The results are shown in Figs. 8 and 9.

Fig. 8a indicates a clear decrease of thickness of 0–40 cm layer, which is in line with the analysis based on elevation data (section 3.3), which suggested that subsidence in this field occurred mostly in the 0–20 cm layer. Change in thickness of layers 40–80 cm and 80–120 cm was smaller, and these curves seem to show opposite trends part of the time. This suggests that there have been problems with the measurement at 80 cm depth. A measurement error at 80 cm would affect calculation of thickness of 40–80 cm and 80–120 cm layers in opposite ways. Fig. 9a shows a clear decrease of thickness of the 0–120 cm layer over time. There may be a slight decrease of the rate at which thickness decreases over time (exponential fit had R^2 of 0.97), but R^2 of the linear fit is also very high. Application of the regression equation in Fig. 9a shows that the thickness of the 0–120 cm layer decreased by 16 cm over the period 1973–2023. As the total observed subsidence at the soil surface was 24 cm (Table 4) this means that 8 cm would have occurred below 120 cm,

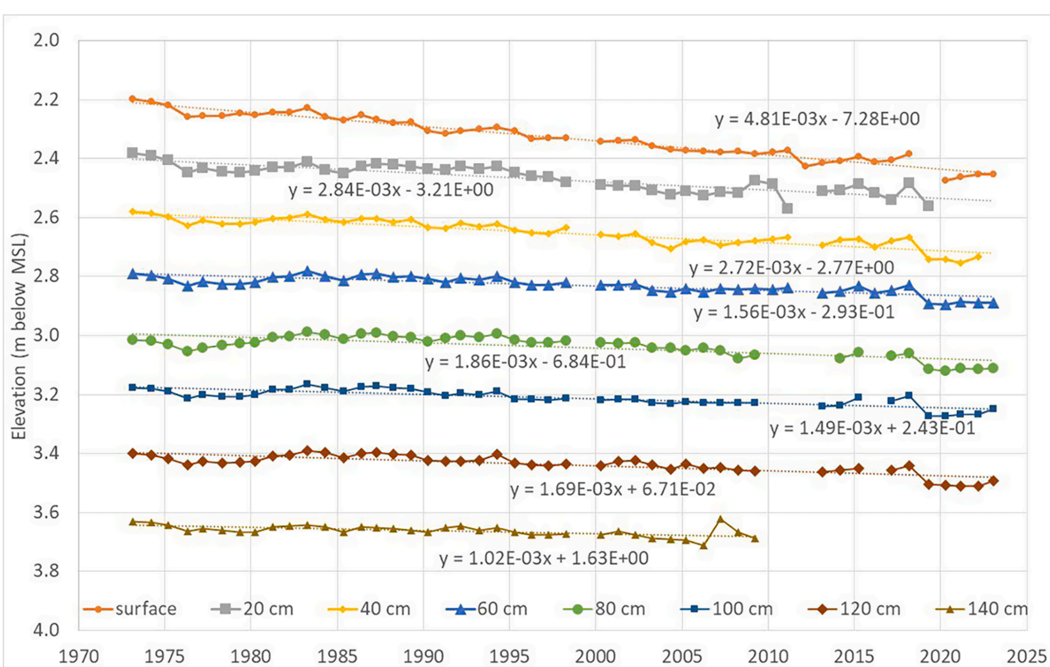


Fig. 6. Elevation of subsidence platens over time, field 13.

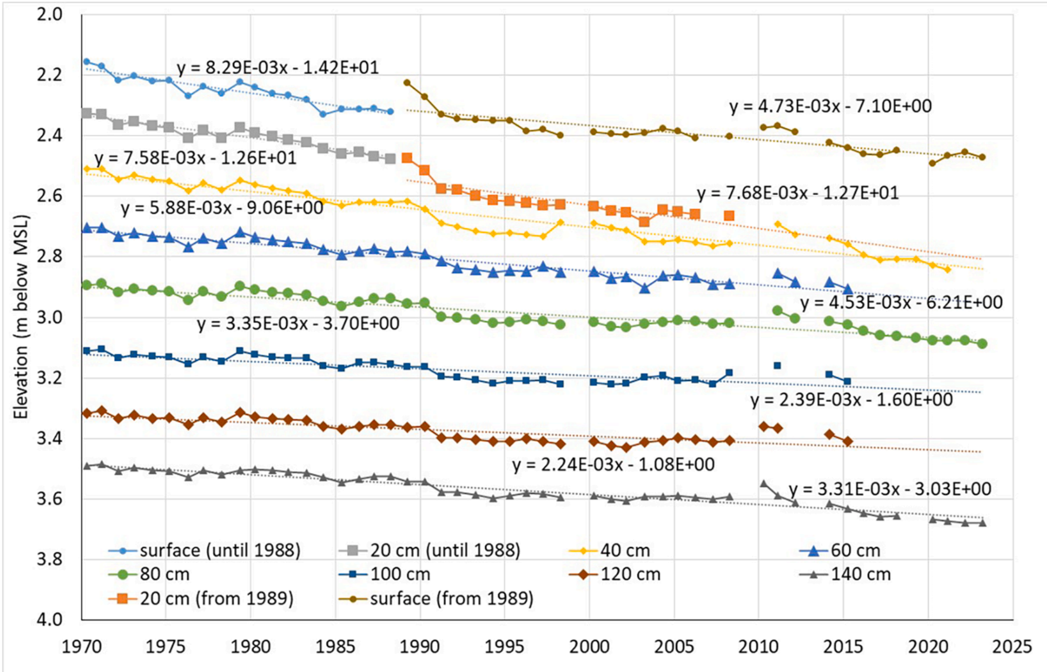


Fig. 7. Elevation of subsidence platens over time, field 16.

Table 4
Cumulative subsidence in field 13 (1973–2022) and field 16 (1970–2022) at different depths. Percentages above 100 % indicate that at that depth the measured subsidence is larger than at the soil surface.

Depth	Field 13		Field 16	
	cm	%	cm	%
0	24	100	31	100
20	14	59	40	129
40	14	56	31	99
60	8	32	24	76
80	9	39	18	56
100	7	31	13	40
120	8	35	12	38
140	5	21	18	56

Table 5
Contribution of different layers to soil subsidence (cm) in field 13 (1973–2022) and field 16 (1970–2022). Negative percentages occur when the measured subsidence at the top of the layer was smaller than at the bottom of the layer.

Depth	Field 13		Field 16	
	cm	%	cm	%
0–20	10	41	−9	−29
20–40	1	3	9	30
40–60	6	24	7	23
60–80	−2	−6	6	20
80–100	2	8	5	16
100–120	−1	−4	1	3
120–140	3	14	−6	−18
>140	5	21	18	56

which matches the number given in Table 4.

For field 16 the calculation of thickness of 0–40 cm layer was done separately for period 1970–1988 and period 1988–2023, as for the analysis based on levelling (see section 3.3). As the 0–40 cm layer is also included in the 0–140 cm layer, results for 0–140 cm are also shown separately for both periods.

Fig. 8b shows a clear decrease of thickness at all depths, with lowest rates for 80–120 cm layer and highest for 40–80 cm layer. It also shows some features that may have been due to measurement problems. For example, data for 1998–2003 indicate there was an issue with measurement at 40 cm depth during these years (as shown by the deviating values with opposite trend for the 0–40 and 40–80 cm layers). In addition, the last three values for 40–80 cm show a similar trend as the rest of the data for that layer but plot higher in the chart.

Fig. 8b also shows that the rate of thickness decrease of the 40–80 cm layer was highest (which is in agreement with the analysis based on levelling data in section 3.3), despite the possible measurement errors mentioned above. As we have no hard evidence that these data are incorrect, we have not disregarded them, but without them the slope for 40–80 cm would be steeper, and R^2 would be higher.

Finally, Fig. 8b also shows, for the 0–40 cm layer, that the rate of decrease for 1989–2023 and for 1970–1988 is almost the same. However, The trendline for the last period may have been affected by measurement error (as 0–40 and 40–80 cm layers show opposite deviations from their general trends for 1998–2003) and by the groundworks (data 1989 and 1990). Without these measurements, the slope would be smaller.

Fig. 9b shows a very rapid decrease of thickness immediately after 1989. This may be due to e.g. 1) increased oxidation rate of the layer that was added, 2) compaction of the layer that was added, 3) increased compaction of lower layers due to additional weight.

In addition, Fig. 9b indicates that the decrease in thickness of 0–140 cm layer was much slower in the second period (1989–2023). This would be even more pronounced if e.g. data from 1989 and 1990 would be disregarded (as being heavily influenced by groundworks in 1988). Application of the two equations given in Fig. 9b shows that the thickness of the 0–140 cm layer decreased by 17 cm over the period 1970–2023 (11 cm over 1970–1988 and 6 cm over 1988–2023). As the total observed subsidence was 31 cm (Table 4) this means that 14 cm would have occurred below 140 cm, which is lower than the 18 cm given in Table 4 and somewhat higher than the 12 cm subsidence that was found at 120 cm depth (Table 4).

Comparison of results from field 13 and field 16 suggests that total subsidence in the 0–120/140 cm layer was similar for both fields but occurred at different depths in the profile. In contrast, subsidence in the

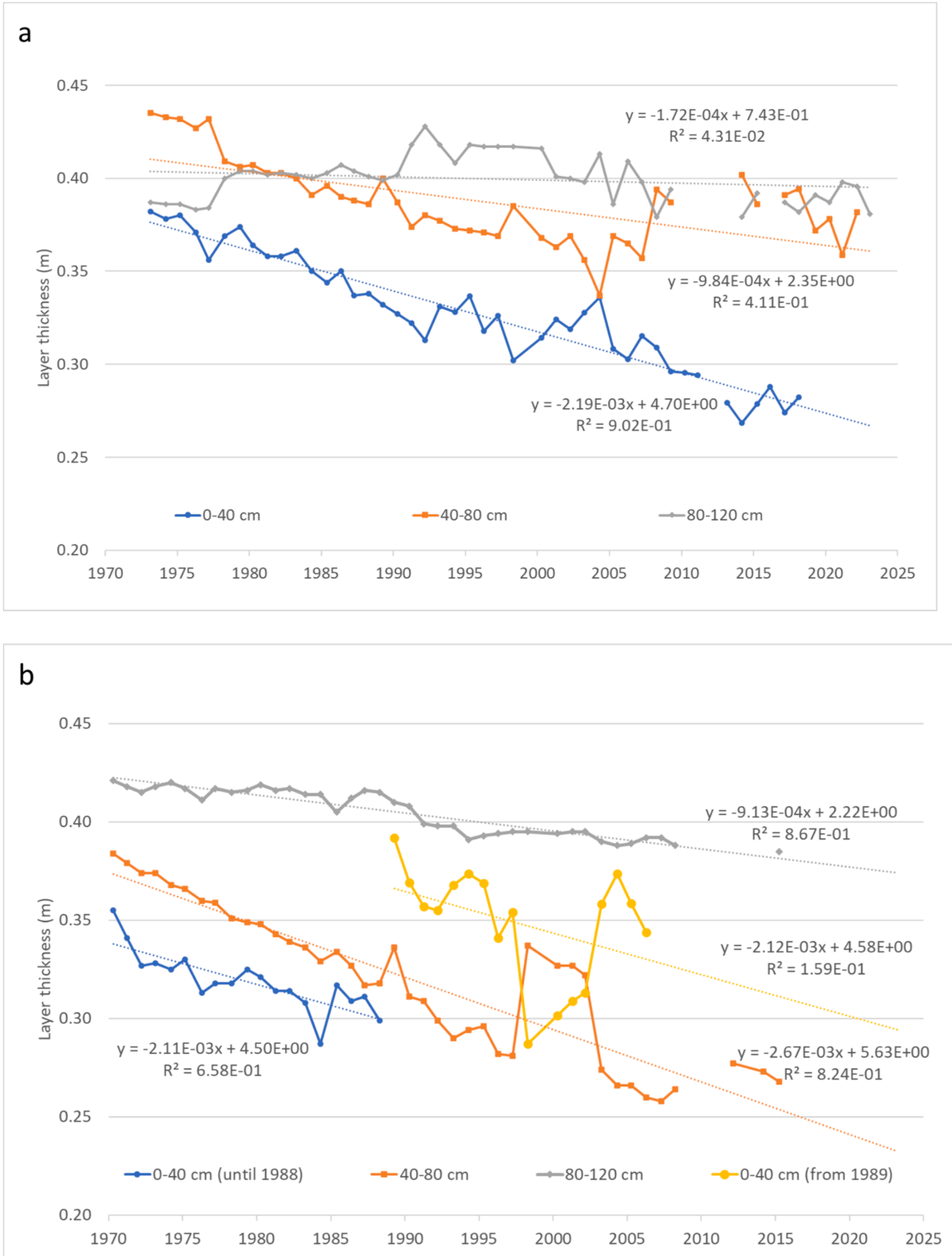


Fig. 8. Change of thickness of soil layers. a) field 13, b) field 16.

layer below 120/140 cm appeared to be much higher in field 16 than in field 13 (14 cm at 140 cm for field 16, and 8 cm at 120 cm for field 13). This does seem to indicate that in field 16 there is more subsidence below the groundwater table than in field 13, which could be ascribed to larger fluctuations in effective stress resulting from seasonally lower water tables.

4. Discussion

4.1. Data quality

The unique length of our data series is crucial to determine long-term trends in land subsidence in peat areas. On the other hand, it is also challenging to analyse these data as over the years various people did the measurements, and various interventions have taken place in the field. Reconstructing these issues proved a challenge as a central documentation was lacking. Some specific issues:

– Earth works in 1988 were initially hypothesized from measured data of elevation (showing a sudden increase in surface elevation), and later confirmed from Beuving and Van den Akker (1996), as well as by the manager of the farm. How much soil was added at the location of the subsidence platens is not exactly known. Based on the available data (surface level measurements in spring 1988 and spring

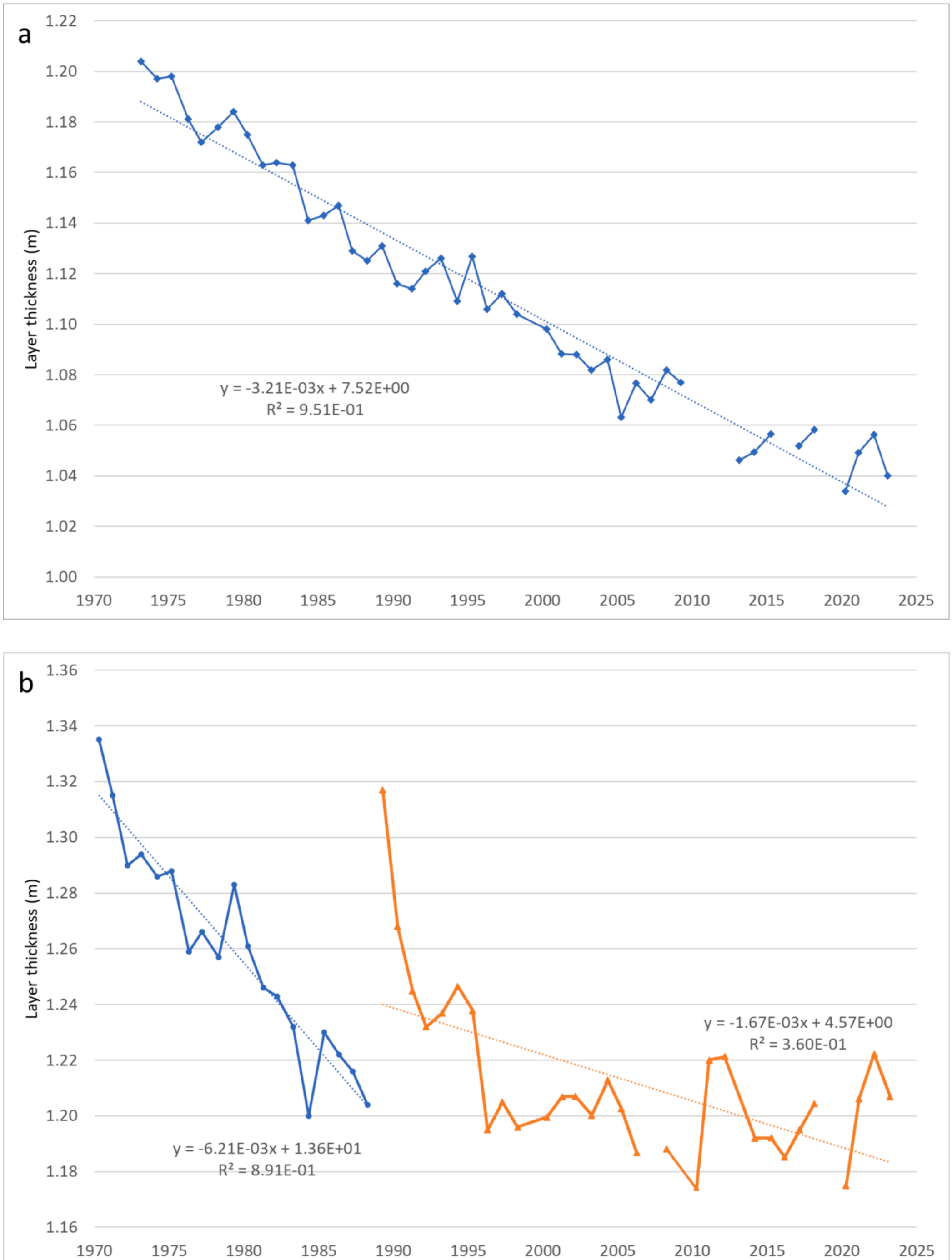


Fig. 9. Change of thickness a) 0–120 cm layer, field 13. b) 0–140 cm layer, field 16.

1989) we estimate 7.5 cm, but it may have been up to 11 cm (which is the increase in thickness of the 0–140 cm layer observed between 1988 and 1989, Fig. 9b).

– Subsidence reference points were assumed to be stable, but levelling indicated not all of them are. In the first decades of the research, the reference points were only levelled occasionally. Furthermore, one of them was replaced in 2004, some have been shortened to avoid protrusion above the soil surface, and rods of different length have been used for the levelling, which may have resulted in errors in the order of 10 cm on individual measurements (with non-quantifiable impact on the regression equations). In addition, the almost stable Dutch Ordnance Datum benchmark 31D0218 is located at a distance of about 1 km, so that levelling from this benchmark was only done a few times. Finally, we used regression equations to correct for the subsidence of reference points, which neglects that there may be variation in subsidence rate between years, while for the earlier years the equations were based on few measurements. As a consequence of these factors some uncertainly remains regarding the subsidence rates of the reference points. In 2019 an Integrated Geodetic Reference Station (Erkens et al., 2020) has been installed close to field 16 (northern end of field 15). As this station has been founded in a deeper sand layer (at 11.5 m depth) it is expected to be more stable. Hence, from 2023 onwards this station will be used as subsidence reference point.

– Due to installation of AWIS in 2016, the locations where the subsidence platens have been installed are now subjected to a different hydrological regime than before, with higher groundwater levels in summer and lower groundwater levels in winter. This would be expected to result in a decrease in subsidence rate, but our data do not yet show clear evidence of this. A longer time series would be required to see such effects.
– The upper part of the soil profile in field 16 has a higher mineral content than the upper part of the soil profile in field 13. Analysis of 9 soil samples taken in the upper 30 cm of the soil in both fields showed that average mineral content in field 16 was 0.31 g/cm^3, while in field 13 it was 0.22 g/cm^3. Van den Akker et al. (2023) postulated that this may have reduced subsidence rates in field 16 compared to other fields with similar ditchwater level. In some of these fields, subsidence platens have also been installed, but data series from these fields are less complete than those of fields 13 and 16.
– There are some issues with missing data, which make analysis of the other data more uncertain, especially if it results in time series of different length for the different subsidence platens. This is especially the case in field 16, where subsidence platens at 4 depths (20, 60, 100 and 120 cm) have now been lost. There have also been some years in which the platens were not measured due to lack of funding. On the positive side, it is remarkable that the platens have been measured almost yearly over a period of 50 years. To prevent future problems with loss of platens it is recommended to replace platens while the remaining ones can still be measured, so that measurements of old and new platens will overlap for some period of time.

4.2. Subsidence rates

Beuving and Van den Akker (1996) studied subsidence rates on the same fields in Zegveld and reported similar subsidence rates. They found 4.7 mm/y for field 13 (period 1973–1992), compared to our 4.8 mm/y. For field 16 they reported 8.9 mm/y (period 1970–1988), while we found 8.3 mm/y for that period, and 4.7 mm/y since 1988, resulting in 5.8 mm/y for the entire period 1970–2023. These subsidence rates are fairly low compared to rates reported from other parts of Europe. For example, Ikkala et al (2021) found average rates of 10.7 mm/y over 50 years for the deepest peat layers in Finland, Oleszczuk et al (2022) reported 11.7 mm/y over 50 years for extensive grassland on peat in Poland, Oleszczuk et al (2020) reported 6.2 mm/y for a 40 year period, in which the peatland was managed as grassland for about the first 20 years (and no management afterwards), Dawson et al (2010) reported 14.8 mm/y over a 13 year period for Norfolk, UK and Zanello et al (2011) reported 30 mm of subsidence in 4 years (7.5 mm/y) near Venice, Italy.

Some subsidence processes, in particular shrinkage, consolidation (Van den Akker et al., 2007; Ikkala et al., 2021; Oleszczuk et al., 2020, 2022; Pronger et al., 2014) and creep, can be expected to have decreasing rates over time, if phreatic water levels do not change (Beuving and Van den Akker, 1996). In case of fluctuations in phreatic water level this would also be the case as the deepest water level would then be the controlling factor. However, if deepest phreatic water levels fluctuate, this decrease will be less obvious and will take longer because of the occurrence of reversible processes that occur each time when the phreatic water level rises. Thus, a decrease of subsidence rates over time would be expected, but it can take considerable time before this becomes evident in cases where changes in effective stress are due to variations in phreatic water level.

For field 16, our data suggest a decrease in subsidence rate over time, as Figs. 7, 8b and 9b showed that subsidence rate was lower in 1989–2023 than in 1970–1988. However, for field 13 such a decrease is hardly evident from our data. The reason why this decrease in rate is not visible in Figs. 6 and 7 is probably that the scale of the figure implies that only a small change in slope is needed to arrive at different values of subsidence, in combination with yearly fluctuations that make it harder to judge the trend by eye. To verify this, other curve shapes than the linear one have also been tested for their goodness of fit, but their goodness of fit was similar to that of the linear curve. For example, an exponential fit of the data in Fig. 9 resulted in an R^2 of 0.956, compared to the 0.950 for the linear fit. Further work on the data set could include time series analysis such as ARIMA (autoregressive integrated moving average) modelling.

Current data suggest that the subsidence rate of field 13 is hardly decreasing over time, while subsidence rates in field 16 seem to have decreased from 8.3 mm/y (1970–1988) to 4.7 mm/y (1988–2023).This decrease could partly be due to a rise of ditchwater level, which at the start of measurements was around 70 cm below surface level in field 16, but had risen to around 55 cm in 2022. However, a rise from 35 to 25 cm in field 13 did not result in a decrease in subsidence. Another reason, as mentioned above, can be that subsidence processes decrease in magnitude over time. This might also explain why the decrease in field 16 is larger than in field 13, since the lower phreatic water tables in field 16 would initially result in higher rates for all subsidence processes (including oxidation) than in field 13. In addition, different topsoil characteristics in fields 16 and 13 can have played a role too, as the topsoil in field 16 contains more mineral parts. Finally, the ground works in field 16 may have had an influence, although our data (Figs. 7, 8b, 9b) indicate that the effect of ground works only lasted for about 2 years.

Our data also indicated that consolidation and creep do not become zero, as subsidence continues even at 120 and 140 cm depth, even after 50 years. It may be that the capacity of the 6 m thick peat layer for consolidation and especially creep is so large that these processes are still occurring at a more or less constant rate. Several authors have reported that thicker peat layers show more subsidence (e.g. Grzywna 2017; Ikkala et al., 2021), which may indicate the importance of continuing consolidation and creep even over longer time periods.

The total subsidence below the lowest water table in field 16 is about 50 % larger than in field 13. This is probably mainly caused by more compaction of the soft layers below the groundwater table because of the lower ditchwater and groundwater levels in field 16 and the extra load on the subsoil caused by the raising of the surface of field 16 with about 7.5 cm. Also the higher number of mineral parts and thus higher dry bulk density of the topsoil of field 16 compared to field 13 results in a somewhat higher load on the subsoil of field 16 than in field 13.

Another factor that could influence subsidence rates over time is climate. Meteorological data (Fig. 2) showed a clear increase of temperature over time. On the other hand, there was no trend in precipitation shortage during the summer. Nevertheless, higher soil temperatures could increase oxidation.

4.3. Subsidence processes

Beuving and Van den Akker (1996) reported, for the same fields, different proportional contributions of consolidation and creep to total subsidence for high and low ditchwater levels, namely 26 % for low ditchwater level and 38 % for high ditchwater level. Studying seasonal fluctuations in elevation, as measured with extensometers and using levelling, Van Asselen et al (2024) found that for lower water tables yearly vertical soil movement is larger, which they ascribe to a larger increase in effective stress in summer, which is due to larger yearly fluctuations in groundwater level. Data of Beuving and Van den Akker (1996) seem to indicate this may also be true for long-term subsidence, as larger variations in effective stress would cause larger consolidation and creep for lower water tables. However, through the link between ditchwater level and phreatic groundwater level, lower ditchwater levels should also result in more oxidation, so that for lower ditchwater level both consolidation & creep and oxidation & shrinkage would be higher. This would not necessarily imply a change in relative contribution of these different processes. Our results do not clearly indicate changing proportional contributions to subsidence as a function of ditchwater level, though uncertainties in data prevent drawing firm conclusions. Our data suggest that 31–39 % of total subsidence in field 13 is below the lowest water table, and 38–40 % in field 16. We hypothesize that this is due to consolidation and creep, perhaps with some contribution by anaerobic decomposition of peat. This estimate of contribution of consolidation and creep is higher than earlier estimations (e.g. Schothorst, 1977; Van den Akker et al., 2008; Hendriks et al., 2008) but similar to the results of Beuving and Van den Akker (1996) and to Erkens et al (2016) and Van Asselen et al (2018) who reported that about 2/3 of land subsidence in Dutch peatlands is due to oxidation and shrinkage, and 1/3 due to consolidation and creep.

Our data show a clear difference in subsidence at 40–80 cm depth between both fields, which suggests that oxidation is the main process at these depths, since in field 16 groundwater levels in summer regularly drop below 60 cm (and can reach 100–120 cm occasionally), while in field 13 groundwater levels remain much higher (average in summer around 50 cm, occasionally 60 cm).

It should be realized, however, that the contribution of different subsidence processes is likely to vary as a function of e.g. phreatic water levels, subsurface composition, thickness of peat deposits, peat characteristics and the timeframe that is considered.

4.4. CO_2 emissions

Subsidence rates may be used as a proxy for CO_2 emissions (e.g., Van den Akker et al., 2008), but this requires adoption of two main assumptions:

- That peat oxidation is the most important factor causing subsidence of peat. Our data, however, indicated that consolidation and creep can contribute about 30–40 % of total subsidence. Hence, when subsidence is used as a proxy for emissions it should be taken into account that a significant part of subsidence can be due to other processes than oxidation. To use subsidence data as proxy for CO_2 emissions this part needs to be quantified, which requires a site-specific understanding of peat subsidence processes.
- That during subsidence, the density and C-content of peat does not change. To verify this assumption, and to account for possible changes in density, the subsidence platens methods can be combined with C-profiling (Van den Akker et al. 2021). In this profiling, the density and C-content of peat was determined for 10 cm intervals, up to a depth of 120 cm. By comparing two C-profiles taken at different times (preferably more than 10 years in between) and taking into account that the depth below surface of subsidence platens has decreased over time, it can be determined how much C has disappeared. Applying this method over a period of about 50 years, Van den Akker et al (2021) arrived at an estimate of average yearly CO_2–emission of 10.7–14.1 t CO_2 ha^{-1} for field 13, and 14.2–15.3 t CO_2 ha^{-1} for field 16. By applying the value of 2259 kg CO_2 ha-1 yr-1 that Van den Akker et al (2008) obtained for CO_2 emission per mm land subsidence, we obtain 10.6 t CO_2 ha^{-1} yr^{-1} for field 13, and 13.1 t CO_2 ha^{-1} yr^{-1} for field 16. These values are also somewhat lower than those reported by Van den Akker et al (2021) but nevertheless suggest that a reasonable estimate of CO_2 emission can be obtained by using subsidence only, so without taking density and C-content changes into account.

5. Conclusions

Subsidence platens showed that peat soil is subsiding at all measured depths. Result clearly show that subsidence rate is lower for the parcel with ditchwater level at 25 cm below surface than for the field with ditchwater level at 55 cm below surface. Total subsidence at surface level was found to be 24 cm in 50 years for high ditchwater level, and 31 cm in 53 years for low ditchwater level. Data from different depths show that oxidation is not the only process causing peat subsidence, but also suggest that in the layers that are periodically aerated it is the main process. On the other hand, data suggest that consolidation and creep may cause a significant part of total subsidence and continue to be important even after 50 years.

CRediT authorship contribution statement

Harry T.L. Massop: Investigation, Formal analysis, Data curation. **Rudi Hessel:** Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Jan J.H. van den Akker:** Writing – review & editing, Formal analysis, Conceptualization. **Sanneke van Asselen:** Writing – review & editing. **Gilles Erkens:** Writing – review & editing, Project administration, Funding acquisition. **Paul A. Gerritsen:** Investigation. **Frank H.G.A. Gerritsen:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The underlying data supporting this publication are available at https://doi.org/10.5281/zenodo.13269433.

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