

Functional properties of soils formed from biochemical ripening of dredged sediments—subsidence mitigation in delta areas

Bruna R. F. Oliveira¹ · Martijn P. J. Smit¹ · Leon A. van Paassen² · Tim C. Grotenhuis¹ · Huub H. M. Rijnaarts¹

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Abstract

Purpose In delta areas, dense networks of canals have been developed through time and have to be periodically dredged. Lowering the groundwater level in delta areas deepens the aerobic zone, leading to the oxidation of organic matter and possibly to land subsidence. The use of the dredged sediments on land can be a solution to mitigate land subsidence in delta areas.

Materials and methods Five types of dredged sediments with different organic matter content and particle size distribution were dewatered for 7 days and then submitted to biochemical ripening during 141 days on a laboratorial scale with constant temperature and relative humidity. The functional properties analysed were the type and content of organic matter, pH, total C, N, P and S, dry bulk density, water retention capacity, aggregate stability and load-bearing capacity.

Results and discussion After biochemical ripening, there was no significant loss in the mass of organic matter but there was an increase in the fraction of stable organic compounds, observed by an increase in oxygen-bearing compounds and a decrease in hydrocarbons during biochemical ripening. The

pH was not affected by biochemical ripening, and the total C, N, P and S concentrations are high and therefore the dredged sediments can improve the quality of the land. Most volume lost during dewatering and biochemical ripening can be attributed to the loss of water. The water retention capacity of the dredged sediments changed with biochemical ripening. The soils formed from biochemical ripening have very stable aggregates, and its load-bearing capacity is enough to sustain cattle and tractors.

Conclusions Most volume lost during dewatering and biochemical ripening can be attributed to the loss of water and not organic matter. Therefore, the studied dredged sediments have potential to mitigate land subsidence in delta areas when spread on land.

Keywords Beneficial use · Biochemical ripening · Dredged sediments · Land subsidence

1 Introduction

In many delta areas, dense networks of ditches and canals have been developed through time to regulate the water level, to avoid flooding and to facilitate navigation, transport, agriculture and infra-structure construction. Lowering the groundwater level in these areas deepens the aerobic zone of the soil, leading (especially in peatlands) to the oxidation of organic matter and further land subsidence (Querner et al. 2012).

Some studies report that the high subsidence rates observed in the layer above the groundwater level in low moor peat soils are 15 % ascribed to shrinkage and 85 % to oxidation of organic matter (Schothorst 1977), whereas others relate land subsidence mainly with consolidation (Teatini et al. 2011). Other authors concluded that the contribution of oxidation of organic matter and compaction to land subsidence is variable

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✉ Bruna R. F. Oliveira
Bruna.Oliveira@wur.nl

¹ Environmental Technology, Wageningen University and Research Centre, Bornse Weiland 9, 6709 WG Wageningen, The Netherlands

² Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

in time (van Asselen 2011). Land subsidence as a result of water discharging is occurring in many low-lying areas and delta areas worldwide (Kolker et al. 2011; Teatini et al. 2011; van Asselen 2011; Wöppelmann et al. 2013), and many attempts are made to attenuate or reverse this process (Querner et al. 2012).

Periodical dredging of ditches and canals is generally performed to maintain their nautical and hydrological functions and improve water quality. Spreading the dredged sediments on land might be a solution to reverse land subsidence by rising the land surface level (Bramley and Rimmer 1988). The practice of spreading dredged sediments on land has been carried out for many years, and all reported studies about this practice refer to the behaviour of contaminants (Vandecasteele et al. 2002; Bedell et al. 2003; Ohimain et al. 2004; Perrodin et al. 2006), without detailed characterization of the properties and behaviour of the sediments.

Dredged sediments are frequently stored in upland deposits and when the clay content is higher than 8 % and/or the organic matter content is higher than 3 %, sedimentation, consolidation and ripening occur (Pons and Zonneveld 1965). Sedimentation refers to the settling and rearrangement of the smaller fractions of the particles into multi-particle conglomerates. Sedimentation is a relatively fast process that takes place within hours or days. Coarse or high-density particles have higher sedimentation rates than small- or low-density particles. Sedimentation is followed by consolidation during which the weight of overlying sediment forces out the pore water. The volume occupied by the sediments will only be reduced if the water is able to drain. Therefore, the consolidation rate depends on the permeability of the sediments, the permeability of the boundaries of the deposit and on the height of the sediment layer (Terzaghi et al. 1996). The ripening process is a soil-forming process that converts waterlogged sediments into soils. Ripening of dredged sediments can be subdivided into physical, chemical and biological ripening, even though the three ripening processes proceed simultaneously and interact with each other (Vermeulen et al. 2003).

Previous studies have shown that multiple processes affect the ripening of dredged sediments and subsequent soil formation (Vermeulen 2007; Sheehan et al. 2010; Lafrenz et al. 2013). Some of the functional properties that play an important role in the nature of ripening and affect the properties of the soil are the type of organic matter (Akker et al. 2008; Berglund and Berglund 2011; Schmidt et al. 2011; Urbanek et al. 2011; Guenet et al. 2012; Aich et al. 2013), pH and nutrient content (Ayuke et al. 2011; Knicker 2011; Leue and Lang 2012), water retention capacity (Berglund and Berglund 2011; Bolte et al. 2011; Querner et al. 2012), dry bulk density (van Asselen 2011), aggregate stability (Amézketa 1999; Six et al. 2004; Elmholt et al. 2008; Munkholm 2011; Deviren Saygin et al. 2012) and load-bearing capacity (Gui et al. 2011). The objective of this study is to relate these functional

properties of soils formed from different types of dredged sediments after dewatering and biochemical ripening at laboratory scale. In separate studies, the behaviour of sediments was characterised on meso and field scales and the results will be reported elsewhere.

Soil organic matter is associated with soil fertility for plant growth, soil and water quality, soil resistance to erosion and it stores at least three times more carbon than the atmosphere or in living plants (Schmidt et al. 2011; Aich et al. 2013; Kirkels et al. 2014). When dredged sediments are transferred to upland deposits, the oxidation of organic matter begins. Due to oxidation, the type of organic matter will change with time to form stable organic matter compounds. Determination of the type of soil organic matter before and after biochemical ripening will lead to quantification of the stable soil organic matter (Sanei et al. 2005). Furthermore, the total mass of organic matter before and after ripening will lead to insight in the role of organic matter oxidation in land subsidence (Schothorst 1977).

Soil pH is affected by the soil air, liquid and solid components. The solid components buffer soils to pH changes caused by natural and anthropic processes. Soil pH affects a wide range of soil biochemical properties, such as the surface charge of organic matter, clay and mineral particles; the solubility, mobility and toxicity of contaminants; the relative binding of positively charged ions to the cation exchange sites; calcium carbonate equivalents; ion mobility; precipitation and dissolution equilibria and kinetics; oxidation-reduction equilibria; and nutrient availability (Winfield and Lee, 1999; Sumner 2000). Soil pH also affects the decomposition of organic matter by determining the microbial activity and growth (Delaune et al. 1981; Madigan et al. 2010).

Soil organic matter is a source of energy and nutrients for soil biota and plants. The more stable fraction of soil organic matter has a near constant carbon (C), nitrogen (N), phosphorus (P) and sulphur (S) ratio and has higher N, P and S content per unit of C than less stable organic matter (Kramer et al. 2003; Kirkby et al. 2013). Some authors hypothesised that the availability of N, P and S may limit the stabilization of organic matter (Lal 2008; Knicker 2011; Kirkby et al. 2013). In addition, changes in the structure of the organic matter significantly alter the soil texture and structure, and the nutrient dynamics leads to organic matter with varying C/N/P/S ratios (Sumner 2000). Dredged sediments are a source of nutrients that can decrease the decomposition of organic matter and increase the fertility of the receiving soil (Fontaine et al. 2011; Leue and Lang 2012).

In some places, dredged sediments can be a significant source of sulphur compounds, and when sulphur compounds that were stable under anaerobic conditions are transferred to an aerobic layer, these can be oxidized and cause acidification which increases the vulnerability of soil to erosion (Bramley and Rimmer 1988; Vermaat et al. 2012). Also, the sulphate

released can cause soil organic matter degradation with the formation of CO₂ (Tichý 1998).

The water content of dredged sediments decreases with time when these are transferred to upland deposits. The removal of water gradually allows oxygen to penetrate through the dredged sediments, changing the conditions from anaerobic to aerobic. The more water removed from the matrix, the more void spaces are available for oxygen penetration which increases organic matter oxidation. The water content affects the properties and behaviour of soils, as the water causes soil particles to swell or shrink, to adhere to each other and to form structural aggregates (Brady and Weil 2008).

Dewatering begins when the dredged sediments are deposited on land or in ripening basins. Soil-water potential can be divided in three components: matric or hydrostatic potential, depending if it refers to the saturated or unsaturated zone, osmotic potential and gravitational potential. All of these components act simultaneously and affect water behaviour in soils (Brady and Weil 2008). In this study, the gravitational potential and osmotic potential are considered constant. Only the matric potential is operational in unsaturated samples and results from adhesive forces and capillarity (Brady and Weil 2008). A matric potential of -100 hPa, or water potential (pF) 2, corresponds to field capacity, i.e. the matric potential at which the plants are regarded to have their optimal water intake and a pF 4.2 corresponds to wilting point after which plants can no longer extract water from the soil and microbial activity is inhibited by 80 % (Koorevaar et al. 1983; Vermeulen 2007).

In this study, the term biochemical ripening refers to the combination of biological and chemical processes that take place after dewatering, when the amount of air-filled pores increases. The major biochemical ripening process is the aerobic mineralization of organic matter (Vermeulen et al. 2007).

Soil aggregate stability is an indicator of soil degradation which can be defined as the resistance of the soil against external mechanical and physicochemical destructive forces, including the effects of rainfall, runoff, tillage, heavy machinery, treading by animals, slaking, swelling and shrinkage (Kemper and Rosenau 1986; Amézketa 1999; Munkholm 2011; Deviren Saygin et al. 2012). A soil aggregate is a naturally formed assemblage of mineral particles and organic matter that cohere to each other more strongly than to other surrounding particles, usually by natural forces and substances derived from root exudates and microbial activity. Furthermore, stable soil aggregates can protect occluded soil organic matter (SOM) against decomposition, leading to a possible long-term stabilisation of soil carbon (Baldock and Skjemstad 2000; Bossuyt et al. 2005; Pulleman et al. 2005; van Lütow et al. 2006; Wei et al. 2014; Chaplot and Cooper 2015).

The undrained shear strength is a mechanical characteristic that, given a certain texture, depends on changing parameters

such as degree of humidity, density and the strength of the connection between mineral particles (Hamza and Anderson 2005). Soil compaction increases soil load-bearing capacity and decreases soil physical fertility through decreasing storage and supply of water and nutrients (Hamza and Anderson 2005). Soil compaction refers to the rearrangement of the soil particles, decreasing the void space and increasing the soil bulk density (European Soil Portal 2012). Soil compaction also alters the spatial arrangement, size and shape of the soil aggregates (Comoss et al. 2002). When sediments are dredged, the water content is high and behaves as a liquid since there is no structure. During ripening, the waterlogged sediments gradually develop a structure, increasing the permeability and shear strength (Bramley and Rimmer 1988). The soil undrained shear strength can be used to calculate the soil load-bearing capacity and therefore to determine which forces it can sustain without failure. Therefore, to define what use can be given to the newly formed soil, it is necessary to determine its load-bearing capacity.

Several studies regarding the use of dredged sediments characterised only part of the parameters described above, leading to a risk of non-optimal performance of ripened sediments in its beneficial use (Giulio Bernstein et al. 2002; Torres et al. 2009; Zentar et al. 2009; Malasavage et al. 2012; Perrodin et al. 2012; Dang et al. 2013). The objective of this study is to characterise the functional properties of five types of dredged sediments before and after dewatering and biochemical ripening in order to assess their suitability to mitigate land subsidence in agricultural-delta areas. In addition, the contribution of shrinkage and organic matter oxidation to the overall volume lost by the sediments when transferred from water to upland conditions is determined.

2 Materials and methods

2.1 Collection of samples

Sampling points S1 to S4 were selected within the Green Heart area, province Zuid-Holland, the Netherlands. According to the World Reference Base for soil resource classification, this area is very heterogeneous and mainly composed by fluvisols and histosols (WRB 2014); <http://eusoils.jrc.ec.europa.eu/>). Using monitoring data from the water board Hoogheemraadschap van Schieland en de Krimpenerwaard (HHSK), the sampling points S1 to S4 were selected with the objective of having distinct particle size distribution and organic matter content, preferably extremes in clay and/or organic matter content. Approximately, 60 l of each sample was dredged from small ditches using a bucket.

Sample S5 was dredged in the Wormer- en Jisperveld nature area in the province Noord-Holland. According to the World

Reference Base for soil resource classification, the area surrounding S5 is classified as histosols (WRB 2014); <http://eusoils.jrc.ec.europa.eu/>). Currently, the area is a protected wetland and is mostly used for animal husbandry and various recreational activities (Natuurmonumenten2015). Sample S5 was dredged by the water board Hoogheemraadschap Hollands Noorderkwartier (HHNK) from one of these small ditches using a crane, placed in a 1-m³ container and sent to the laboratory.

In the laboratory, all dredged sediment samples were manually wet-sieved and the fraction smaller than 2 mm was stored in airtight containers under anaerobic conditions (under water) at 4 °C until used in the experiments. The fractions larger than 2 mm were discarded since soil classification systems only consider fractions smaller than 2 mm to be soil (Sumner 2000). The fractions larger than 2 mm were estimated to be less than 15 % of the total mass by observation.

2.2 Organic matter content, particle size distribution and fibre content of the dredged sediments

The organic matter content (Table 1) was calculated following the loss on ignition (4 h at 550 °C) method (ISO/TS 17892-1:2014). To facilitate the interpretation of the results, the samples will be presented from S5 to S1 which is from higher to lower organic matter content.

The fibre content (Table 1) was determined following the standard test method for laboratory determination of the fibre content of peat samples by dry mass ASTM D1997-91 (2008).

For determination of the particle size distribution of the mineral fraction (Table 1), the samples were first air-dried and then the organic matter was removed with H₂O₂ and the CaCO₃ with HCl. The particle size distribution was determined following the ISO standard ISO/TS 17892-4:2014. Fractions <2, 2–16 and 16–50 µm were determined by the pipet method, and fraction 50–63 µm was determined by wet sieving at the Soil Chemical Biological Soil Laboratory

(CBLB) of Wageningen UR. The fractions 63–150, 150–420 and 420–2000 µm were determined by dry sieving by the Soil Physics Laboratory of Wageningen UR.

2.3 Experimental procedure

2.3.1 Dewatering

To dewater the dredged sediment samples, suction chambers were used where a suction pressure of –100 hPa was applied below the sample to achieve the matric potential corresponding to field capacity. To retain the fine particles in the suction chambers, a nylon filter with pore size of 0.45 µm was used. It was assumed that equilibrium between the matric potential of the sample and the applied suction is reached when the water outflows from the sample ceases (Klute and Dirksen 1986). This was generally observed within 7 days.

Dewatering was done at 20 ± 1 °C, and the suction chambers were completely closed to the atmosphere, i.e. evaporation was avoided using a lid on the setup. The water removed from the sample was collected in a tube for quantification by weighing. Periodically, a plug on top of the suction chamber was open to release the pressure due to the decrease of the volume by removed water from the sample.

The internal diameter of the suction chambers was 5 cm, and the amount of sample poured in the suction chambers was calculated for each sample individually with the objective of achieving a final height of 1.5 cm, i.e. after dewatering, all samples had 1.5 cm in height and 5 cm in diameter. The volume of sample lost during dewatering was calculated from the initial and final mass of the sample, density of water and dry bulk density of the sample.

After dewatering, some samples were sacrificed in order to determine the water and organic matter content. This was done to determine the homogeneity in water content in samples of the same type of dredged sediments.

Table 1 Organic matter content, fibre content and particle size distribution and classification according to the USDA classification system (USDA 1987) and according to the ISO/TS 17892-4:2014

Sample	S5	S4	S3	S2	S1
Organic matter (% g _{OM} g ⁻¹ dry matter)	45.6	16.1	11.8	11.8	6.0
Fibres (% g _{fibres} g ⁻¹ dry matter)	25.9	19.6	56.5	4.1	8.2
Particle size distribution					
<2 mm	47.9	10.2	9.8	25.1	13.9
2–16 mm	17.6	3.4	3.5	16.1	4.6
16–63 mm	2.8	5.2	5.1	21.4	10.8
63–150 mm	9.3	20.2	17.4	33.1	58.5
150–420 mm	15.1	58.1	62.6	4.1	11.6
420–2000 mm	7.2	3.0	1.7	0.2	0.6
USDA classification	Clay	Loamy sand	Loamy sand	Loam	Sandy loam
ISO/TS 17892-4:2014	Fine grained	Mixed grained	Mixed grained	Fine grained	Mixed grained

2.3.2 Biochemical ripening

After dewatering, nine samples of each type of dredged sediments were submitted to biochemical ripening in specifically designed batch bottles (BBs) (Electronic Fig. S1). Each sample was placed in one of these BBs which allowed monitoring of individual variations. The BBs were closed to the atmosphere, and the gas phase was periodically monitored to assure that there was biological activity and that there was no oxygen limitation, i.e. oxygen concentration in the headspace was always above 10 % (v/v). To avoid condensation and keep the relative humidity constant in the BBs, a saturated solution of potassium nitrate (KNO₃) with a concentration of 360 g l⁻¹ was kept inside the BBs. The KNO₃ has neutral pH, absorbs about 0.03 % water in 80 % relative humidity over 50 days and in a closed environment at 20 °C keeps the relative humidity constant at 94.5 %. The BBs were operated for 141 days at 20 ± 1 °C.

To obtain a better insight on the aerobic degradation of organic matter and O₂ transport through the samples during biochemical ripening, a PreSens imaging system was used as a non-invasive method (PreSens 2013). This system combines an imaging technology by a digital camera with fluorescent chemical optical sensor foils to visualize 2D distributions of O₂ at a specific surface of heterogeneous samples. The sensor foils were calibrated in the BBs without sample and with and without the saturated salt solution of KNO₃, following the multipoint calibration described in the manual (PreSens 2013). From the results of the calibration, the O₂ sensor foils did not prove to be suitable for measurement of O₂ diffusion rate through the samples under the described experimental conditions.

2.3.3 Analytical methods

The geotechnical water content was calculated from the oven dry weight of the samples (24 h at 105 °C) (ISO/TS 17892-1:2014).

O₂ and CO₂ in the BB headspace were measured with gas chromatography (Shimadzu GC-2010) with a thermal conductivity detector (TCD).

The pH of the dredged sediments was determined directly by immersing the electrode in the wet sediments since the water content was above 70 % for all samples. The pH of the biochemically ripened sediments was determined on a 1:1 soil-water suspension using a glass electrode (Soil and Plant Analysis Council Inc. 1999).

The total C, N, P and S were determined at the Chemical Biological Soil Laboratory of Wageningen UR, The Netherlands. The dredged sediment samples were centrifuged to separate the solid fraction from the supernatant. The supernatant was then filtrated and the colloid fraction collected in the filter was added to the solid fraction. One sub-sample

of the solid fraction was digested with the DigiPrep (aquaregia method, according to NEN-69610) and analysed with a Thermo (type iCAP) ICP-AES. Another sub-sample of the solid fraction was used to analyse total organic C and total N with a Leco C/N analyser. The total P and total S of the liquid fraction were analysed with a Varian ICP-AES, and the total organic carbon and total nitrogen were analysed with a Skalar Segmented Flow Analyser (SFA).

The type of organic matter was characterised with the Rock-Eval 6@ method. The samples of 20 mg of sediments are heated in pyrolysis and oxidation ovens at a heating rate of 25 °C min⁻¹ of the Rock-Eval 6@ apparatus. The pyrolysis occurs between 100 and 650 °C under an inert atmosphere of N₂. During the pyrolysis, the free hydrocarbons present in the sample and the hydrocarbons released by the thermal cracking of organic matter are detected by the flame ionization detector. Simultaneously, the CO and CO₂ released during thermal cracking of oxygen-bearing organic compounds are measured by infrared detectors. The measurement of CO is conducted up to 570 °C to avoid interference from the release of inorganic CO at higher temperatures. The measurement of CO₂ is conducted up to 400 °C to avoid interference from the release of inorganic CO₂ at higher temperatures. Following the pyrolysis stage, the sample is transferred to the oxidation oven and heated from 400 to 850 °C in air, incinerating all the residual organic carbon. The CO and CO₂ released during combustion of residual organic carbon are measured by online infrared detectors. The hydrogen index (HI) is an indicative value for the amount of hydrocarbons released by thermal cracking of organic matter per gramme of total organic carbon (TOC), and the oxygen index (OI_{RE6}) is an indicative value for the amount of CO₂ and CO by thermal cracking of oxygen-bearing organic compounds per gramme of TOC (Electronic Supplementary Material, Table S2). Changes in the HI and OI_{RE6} are analysed to evaluate a transition in the type of organic matter. Rock-Eval 6@ analyses were performed at Deltares, the Netherlands.

The water retention curve determination was performed by the Soil Physics Laboratory of Wageningen UR, the Netherlands. The water retention curve determination was performed in a climatized room, at 16 ± 1 °C and a relative humidity of 60 ± 5 %, using pressure plates, according to the ISO 11274:1998. The non-treated samples were filtered and further dried in a 100-cm³ sample ring at height of 2.5 cm of suction. The water retention curve is presented in terms of pF vs volumetric moisture ratio (cm³ cm⁻³). The volumetric moisture ratio, θ , is:

$$\theta = \frac{V_l}{V_t} \quad (1)$$

in which V_l is the volume of liquid and V_t the volume of saturated sample.

Since the starting pF for the biochemically ripened samples was pF 2 (previously dewatered to this pF), the volumetric moisture ratio was normalized to the volume of the sample at pF 2, θ_{pF2} normalized:

$$\theta_{pF2 \text{ normalized}} = \frac{V_1}{V_{Vt,pF2}} \tag{2}$$

This normalization was chosen because ripening is an irreversible process (Vermeulen et al. 2003), and re-wetting the samples would lead to unrealistic results. Hence, to compare the water retention curve of the dredged sediments samples (a) with the biochemically ripened samples (c), also the water retention curve of the dredged sediments samples was referenced to the volume of the sample at pF 2.

The volume of the biochemically ripened samples was calculated from the measured dimensions using a marking gauge. The water retention was determined until pF 4.2 since this corresponds to the conditions when plants can no longer extract water from the soil (Vermeulen 2007).

The dry bulk density was determined after air drying a sample and following the linear measurement method described in the standard ISO 17892-2:2014.

Aggregate stability was determined according to the method described by Kemper and Rosenau for wet aggregate stability determination. The calculated aggregate stability varies from 0—unstable—to 1—very stable (Kemper and Rosenau 1986). This method measures the breakdown of aggregates upon rapid wetting (slaking) and the subsequent breakdown of aggregates due to the mechanical sieving action. The wet sieving apparatus from Eijkelkamp was used for the mechanical sieving.

The undrained shear strength was determined with the fall cone method of the biochemically ripened samples, following the procedure described in the ISO/TS 17892-6:2004. The measured undrained shear strengths were used to calculate the bearing capacity in order to evaluate whether the soil is accessible for cattle and tractors. The bearing capacity of the soil is calculated according to the method described, e.g. in Terzaghi et al. (1996).

$$q = s_c d_c c_u N_c + s_q d_q \gamma D N_q + s_\gamma 0.5 \gamma B N_\gamma \tag{3}$$

in which q is the bearing capacity in [kPa], c_u is the undrained shear strength in [kPa], γ is the bulk unit weight of the soil in [kN m^{-3}], D is the depth at which the load is applied below surface level in [m], B is the width of the load surface in [m] assuming an infinitely long strip footing, N_c , N_q and N_γ are so-called bearing capacity factors, which are related the friction angle of the soil, s_c , s_q and s_γ are shape factors which are used to correct for the shape of the surface on which the load is applied and d_c and d_q are depth factors which need to be taken into account when the load is applied below surface level. Considering that the load of cattle or tractors is applied

at surface level and only for a short period of time at the same location, $D = 0$ m, $N_\gamma = 0$, $N_q = 1$ and $N_c = 5.14$ (Barnes 2000), the equation above can be simplified to:

$$q = \left(1 + \frac{N_q}{N_c} \right) c_u N_c = 6.14 c_u \tag{4}$$

In this empirical approach, the soil is presumed to be infinitely stiff and homogeneous in both horizontal and vertical directions, which are considered to be valid presumptions when the load is applied in the open field. In case a tractor or cow is standing close to a ditch, the bearing capacity may be significantly lower and that scenario was not considered in this study.

The load applied by cattle on the soil was calculated considering an average weight of 600 kg and considering that the weight is evenly distributed by the four paws with a surface area of 0.01 m² each. For tractors, it was considered an average weight of 2900 kg per front wheel and an average weight of 6000 kg per rear wheel. The values on Table 2 correspond to cattle and tractors operating at the Wormer- en Jisperveld nature area and may vary from place to place.

3 Results

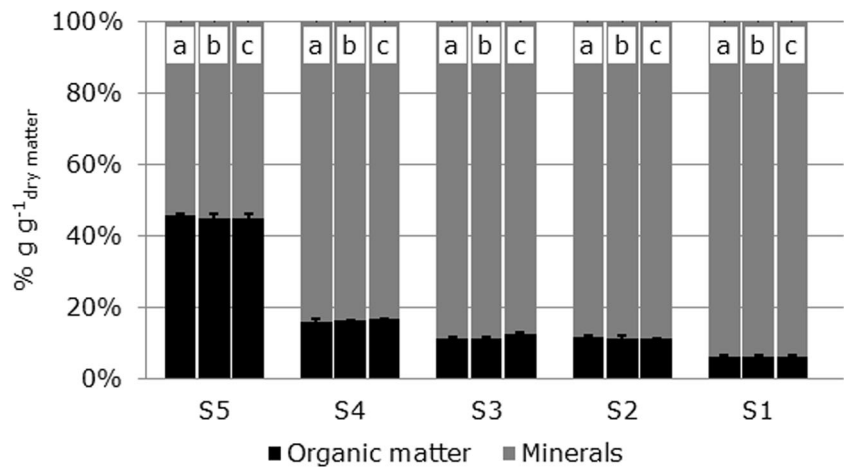
The mass of organic matter content determined following the loss on ignition method did not change significantly for any of the five samples during the 7 days of dewatering and during the 141 days of biochemical ripening (Fig. 1). Even though, there was oxygen (O₂) consumption and carbon dioxide (CO₂) production (Fig. 2) evidencing that there was microbial activity in the BBs.

The results of O₂ consumption and CO₂ production have significant error bars which might be justified not only by the natural heterogeneity between biological systems but also by the possible leakage of some of the BBs, since no differences were observed in the organic matter content between replicates. The results in Fig. 2 reflect the total cumulative CO₂ production and O₂ consumption during 141 days of biochemical ripening. Considering that the samples had 5 cm in diameter, that biochemical ripening took 141 days and that the rate of CO₂ production was constant during biochemical ripening, the average CO₂ released from the samples ranged from

Table 2 Estimation of load applied on the soil by cattle and tractors

	Mass (kg)	Surface area (m ²)	Number of paws or wheels	Load [kPa per (paw or wheel)]
Cattle	600	0.01	4	147
Tractor front	2900	0.12	2	118
Tractor rear	6000	0.24	2	123

Fig. 1 Dry matter distribution (a) before dewatering, (b) after dewatering and (c) after biochemical ripening



6.8 $\text{g}_C \text{m}^{-2} \text{year}^{-1}$ for S3 (lowest) to 10.8 $\text{g}_C \text{m}^{-2} \text{year}^{-1}$ for S1 (highest). Assuming that the samples are not oxygen limited, these rates can be corrected for the 1.5-cm height of the samples, and therefore the average CO_2 released ranged from 456.9 $\text{g}_C \text{m}^{-3} \text{year}^{-1}$ for S3 to 716.6 $\text{g}_C \text{m}^{-3} \text{year}^{-1}$ for S1.

Regarding the type of organic matter, biochemical ripening resulted in a decrease in the HI and an increase in OI_{RE6} for all the samples, i.e. a decrease in hydrocarbons and an increase in oxygen-bearing compounds (Fig. 3). The percentage of decrease in HI and percentage of increase in OI_{RE6} seem to be dependent of the composition of each sample and are not proportional. Sample S5 had 27 % increase (highest) in the OI_{RE6} while sample S3 had 3 % increase (lowest) in the OI_{RE6} . The decrease in HI was highest for S4 with 13 % and lowest for S3 with 6 %. The smallest increase in OI_{RE6} and smallest decrease in HI were observed for sample S3 which has the highest fibre content (Table 1).

The pH (Table 3) of the samples was stable during biochemical ripening. The pH of sample S5, from North Holland, was lower than the samples from South Holland.

The dry bulk density increases with decreasing organic matter content (Table 3), except for S2 which might be caused by the high clay content (Table 1).

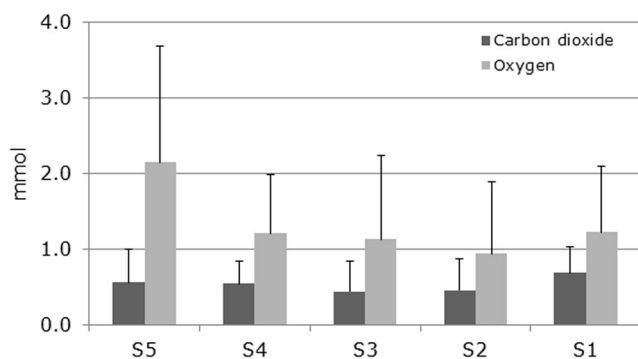


Fig. 2 Average total CO_2 produced and O_2 consumed (mmol) during the 141 h of biochemical ripening. Error bars represent standard deviation of nine replicates

Regarding the total C, N, P and S (Table 4), the observed variations might not be significant due to the heterogeneity of the samples.

The water balance for the dewatering process (Electronic Supplementary Material, Table S1) is closed for 93 to 98 %, and therefore losses of water are not significant. Dewatering resulted in the removal of 72 to 52 % of the total water content of the dredged sediments. The sample with highest water dewatered was S1 which is the sample with lowest organic matter content.

From Fig. 4, most water was lost during the dewatering step, but during biochemical ripening also, a significant amount of water was lost. Part of the water during biochemical ripening might be incorporated in the organic compounds or transferred to the KNO_3 salt solution.

The water retention curves of the dredged sediments are very similar (Fig. 5). Sample S5 has the strongest water retention capacity, while S1 has the weakest water retention capacity. The results suggest that the higher the organic matter content, the strongest the water retention capacity. S5 has a strong shrinkage behaviour, resulting in a normalized (Eq. (2)) volumetric moisture ratio higher than 1, due to the very high organic matter and clay content. Samples S2 and S3 have similar

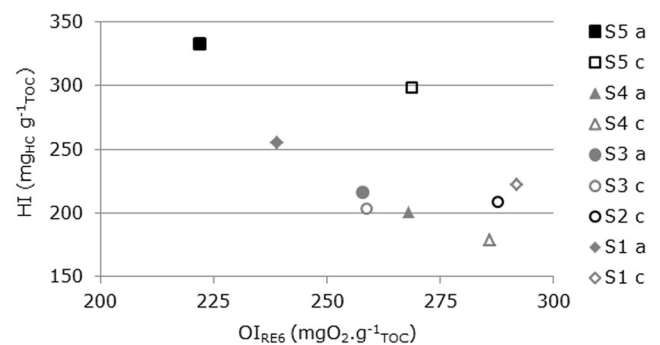


Fig. 3 Hydrogen index ($\text{mg}_{\text{HC}} \text{g}^{-1} \text{TOC}$) and oxygen index ($\text{mg}_{\text{O}_2} \text{g}^{-1} \text{TOC}$) of the dredged sediments (a) before dewatering and (c) after biochemical ripening. Hydrogen and oxygen indexes of S2. S2 (a) gave a faulty measurement

Table 3 pH, dry bulk density, aggregate stability index, undrained shear strength and calculated bearing capacity, before dewatering and after biochemical ripening

Sample	S5	S4	S3	S2	S1
pH before dewatering and after biochemical ripening	4.28	7.40	7.42	7.22	7.37
Dry bulk density (g cm ⁻³) before dewatering	0.21	0.55	0.61	0.55	0.70
Dry bulk density (g cm ⁻³) after biochemical ripening	0.32	0.81	0.88	0.69	1.07
Aggregate stability index (g _{stable aggregates} g ⁻¹ sample) after biochemical ripening	0.94	0.94	0.90	0.97	0.95
Undrained shear strength (kPa) after biochemical ripening	125	183	226	481	370
Bearing capacity (kPa) after biochemical ripening	770	1125	1388	2954	2273

organic matter content, and the difference in behaviour might be caused by highest clay content of S2 in relation to S3.

Dewatering and biochemical ripening resulted in an increase of the water retention capacity for samples S5 and S4 and in a decrease for samples S2, S1 and S3 (Fig. 5). At pF 2, biochemical ripening resulted in 43 % increase in the water retention capacity for S5 and 31 % decrease for S1. At pF 4.2, biochemical ripening resulted in 53 % decrease in the water retention capacity for S5 and 29 % increase for S1. The change in the composition of the organic matter might explain the variations in the water retention capacity of the soil samples in relation to the dredged sediments (Fig. 5). The higher the water retention capacity, the less air-filling pores which results in less oxygen diffusion and consequently less organic matter oxidation. The aggregate stability indexes obtained (Table 3) suggest that all five samples are very stable to water erosion. The undrained shear strength of the samples after biochemical ripening is presented in Table 3. The lowest undrained shear strength was observed for sample S5 which has the highest organic matter content, while the highest undrained shear strength was observed for sample S2 which has the lowest fibre content (Table 1). The calculated bearing capacity of the samples indicates that the studied dredged sediments can sustain tractors and cattle (according to the calculation in Table 2).

4 Discussion

The organic matter content of the samples did not vary significantly after 141 days of biochemical ripening. This result is opposite to earlier findings in which land subsidence of low moor peats in the Netherlands was monitored for 6 years in terms of surface elevation, bulk density, moisture and organic matter content and was 85 % attributed to organic matter degradation and 15 % to shrinkage (Schothorst 1977).

The CO₂ released from the samples during biochemical ripening, corrected to the 1.5-cm height of the samples, was 456.9 g_C m⁻³ year⁻¹ for S3 and 716.6 g_C m⁻³ year⁻¹ for S1. Therefore, the results suggest that the samples studied, without the presence of vegetation, are a source of CO₂ to the atmosphere.

Field studies performed in the Netherlands, with an average annual precipitation of 800 mm and an average annual temperature of 9.8 °C, in which the gas fluxes from histosols to the atmosphere were monitored using eddy covariance systems and closed flux chambers report varying fluxes:

- 330 g_C m⁻² year⁻¹ from an abandoned agricultural field converted into a wetland nature reserve (Hendriks et al. 2007)

Table 4 Total carbon (TC), total nitrogen (TN), total phosphorus (TP) and total sulphur (TS) content, before dewatering and after biochemical ripening

	TC (g kg ⁻¹ dry matter)	TN	TP	TS	C/N/P/S (molar ratio)
S5, before dewatering	238.60	14.66	1.21	23.48	511:27:1:19
S5, after biochemical ripening	232.00	17.70	1.21	20.13	497:33:1:16
S4, before dewatering	88.82	6.44	1.05	10.56	218:14:1:10
S4, after biochemical ripening	89.10	7.20	1.25	10.93	184:12:1:8
S3, after biochemical ripening	75.60	6.04	0.65	9.48	300:21:1:14
S2, before dewatering	67.34	4.92	1.50	6.58	116:7:1:4
S2, after biochemical ripening	67.80	5.60	1.63	5.51	108:8:1:3
S1, before dewatering	44.49	2.30	0.46	7.57	248:11:1:16
S1, after biochemical ripening	48.40	2.76	0.55	7.86	229:11:1:14

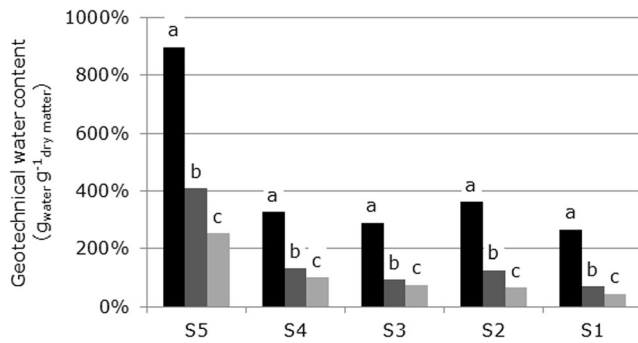
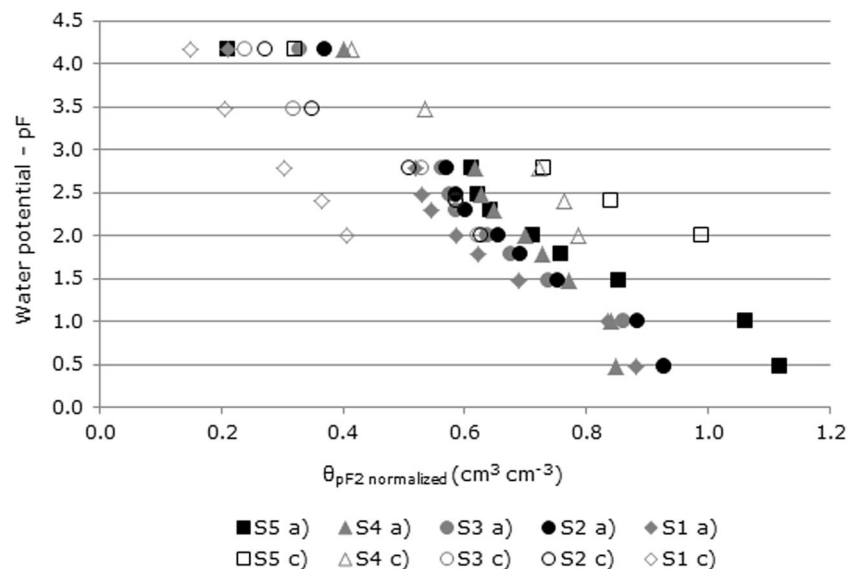


Fig. 4 Geotechnical water content (a) before dewatering, (b) after dewatering and (c) after biochemical ripening

- $130 \text{ g}_C \text{ m}^{-2} \text{ year}^{-1}$ from a peat pasture used for intensive dairy farming (Langeveld et al. 1997)
- $220 \text{ g}_C \text{ m}^{-2} \text{ year}^{-1}$ from grasslands (Jacobs et al. 2007)
- $113.18 \text{ g}_C \text{ m}^{-2} \text{ year}^{-1}$ from an intensively managed grassland (Schrier-Uijl et al. 2014)
- $-409.09 \text{ g}_C \text{ m}^{-2} \text{ year}^{-1}$ (minus signal means uptake) from a re-wetted former agricultural peatland (Schrier-Uijl et al. 2014)

In general, organic soils are often sources of CO_2 (Langeveld et al. 1997; Hendriks et al. 2007; Jacobs et al. 2007; Schrier-Uijl et al. 2014) while mineral soils are often a sink of CO_2 (Gilmanov et al. 2007; Jacobs et al. 2007). Since the groundwater level in the field varies significantly throughout the year and that the field cover also affects significant the gas and liquid fluxes, it is not easy to compare the results of our experiments with previously reported results since the samples used had a constant height of 1.5 cm and no vegetation was present. However, it seems that the potential of CO_2 release from the studied samples is low compared with field studies.

Fig. 5 Water retention curve of the dredged sediments (a) before dewatering and (c) after biochemical ripening



The Rock-Eval 6® method allows to follow the evolution of the humification process in sediments and soils with time. Our results confirm that there was a change in the type of organic matter since all the treated samples (soil) have lower HI and higher OI_{RE6} than the correspondent dredged sediments. This means that the treatment resulted in a decrease in free hydrocarbons and an increase in oxygen-bearing organic compounds for all the samples, i.e. the treatment resulted in more stable organic matter. The formation of recalcitrant SOM compounds increases the stability of the organic matter (Six et al. 2002). The decrease in HI and increase in OI_{RE6} indicate an increase in the humification of the organic matter (Lafargue et al. 1998; Disnar et al. 2003).

More consumption of O_2 than production of CO_2 indicates the incorporation of oxygen in the organic matter, i.e. the increase in oxygen rich compounds. For instance, sample S5 has the highest $[\text{CO}_2]/[\text{O}_2]$ ratio and also the highest increase in oxygen rich compounds. The activity of communities of microorganisms is also influenced by the pH (Berg and Laskowski 2005; Rousk et al. 2010; van Roon 2012), and, since S5 is acidic while the other samples are close to neutral, the active microorganisms can differ which also explains the difference in $[\text{CO}_2]/[\text{O}_2]$ ratios.

Considering the CO_2 production, the O_2 consumption and the Rock-Eval 6® results, it can be concluded that the loss on ignition method might not be the best method to detect changes in organic matter under such experimental conditions.

The decrease in water content during biochemical ripening together with the insignificant loss in organic matter content during biochemical ripening indicates that in 141 days of biochemical ripening, most shrinkage was caused by water loss. Sample S1 had the highest loss in total weight during dewatering and biochemical ripening, due to water removal, and is the sample with the highest increase in dry bulk density.

Sample S5 had the lowest loss in total weight during dewatering and biochemical ripening and was the sample with lowest increase in dry bulk density. Therefore, the higher the water removal, the higher the compaction of the sample which was also observed by (Teatini et al. 2011).

The water retention capacity of any material is related with the porosity and the nature of the bonding between water and soil. Coarse-grained materials have water binding mainly by capillary forces, while fine-grained soils have water binding by adhesive and osmotic forces. As a consequence, fine-grained soils need higher water potentials to release water than coarse-grained materials. At any given water potential, organic soils usually retain more water than fine-grained soils (Sumner 2000). Our results show that sample S1, with 6 % (dry weight) organic matter and 14 % (of the mineral fraction) clay content, is the sample that retains less water. Sample S5 has 46 % (dry weight) organic matter and 48 % (of the mineral fraction) clay content and is the sample that retains more water until pF 2.75. For higher water potentials, sample S4, with 16 % organic matter and 10 % clay content, is the sample that retains more water. This might be due to the strong shrinkage behaviour observed for sample S5 (laboratory observation). In general, the results confirm that the higher organic matter content results in more water retention capacity.

Some studies highlight the importance of clay content on the decomposition of organic matter. The clay can physically protect soil organic matter from decomposition when the soil matrix is characterised by a large amount of small pores that create a barrier to decomposing microorganisms. Furthermore, the clay can also chemically protect organic matter from decomposition since the clay particles are active soil components in the production of organo-mineral complexes and the microorganisms are less efficient in decomposing the organic matter protected in these complexes (Krull et al. 2003; van Lützow et al. 2006; Wei et al. 2014). From the particle size distribution and the average total CO₂ released and O₂ consumed, there is no direct relation between the clay content of the samples and the organic matter decomposition. The pH was not affected by dewatering and biochemical ripening.

The organic matter decomposition depends also on the availability of nitrogen, phosphorus and sulphur. There is evidence for a constant stoichiometric ratio of C/N/P/S for the stable portion of the soil organic material across a wide range of global soils. Such a ratio should provide a reliable basis with which to determine the fraction of stable organic matter in soils (Kirkby et al. 2011). In addition, sediments in ditches and canals can accumulate nutrients leached from the adjacent agricultural sites and therefore the agriculture land can benefit from the recycling of these nutrients. Sample S5, S4, S3 and S1 are very rich in carbon and can therefore be representative carbon sinks if the decomposition of organic matter is minimized. Other authors studying Dutch dredged sediments found TC varying from 118 to 53 g kg⁻¹_{dry matter}, TN varying from 6.9 to

5.0 g kg⁻¹_{dry matter}, TP varying from 2.5 to 0.9 g kg⁻¹_{dry matter} and TS varying from 18 to 8 g kg⁻¹_{dry matter}.

The dredged sediments have a water content ranging from 898 % for S5 to 268 % for S1 (Fig. 4) and, as a consequence, it is not possible to determine the stability and undrained shear strength. Since during dewatering and biochemical ripening of the dredged sediments the excess of water is removed, a structure is developed and the aggregate stability and undrained shear strength can be determined for the newly formed soil.

One indicator of soil degradation is the aggregate stability which can be defined as the resistance of the soil against the external destructive effects of water and wind (Deviren Saygın et al. 2012). The results obtained indicate that the soils formed from biochemical ripening dredged sediments are very stable to water erosion and, as a consequence, the organic matter occluded within the aggregates is protected against biochemical degradation. However, from the observation of the samples in the laboratory during the wet sieving with the dispersant solution, most material was retained in the sieves as if the cohesive forces of the aggregates could not be broken down by the dispersant solution. No literature was found addressing this topic, and therefore these results should be interpreted carefully.

The load-bearing capacity of the biochemically ripened dredged sediments varies between 770 kPa for S5 and 2954 kPa for S1, which is enough to sustain cattle and tractors, meaning that the soil can be used for husbandry (crops and/or animals).

5 Conclusions

The studied dredged sediments have the potential to mitigate land subsidence in delta areas when spread on land since:

- The mass of organic matter did not change after dewatering and biochemical ripening.
- Most volume lost during dewatering and biochemical ripening can be attributed to water loss and pore water reduction and not to organic matter loss.
- Biochemical ripening resulted in an increase in oxygen-bearing compounds and decrease in hydrocarbons which indicates an increase in the fraction of stable organic compounds.
- The water retention capacity is higher for samples with higher organic matter which is a valuable condition to decrease the oxygen diffusion through the matrix.
- The total C, N, P and S concentrations are high and therefore the dredged sediments can be considered as fertilizer when added to a soil.
- The aggregates formed during biochemical ripening are very stable to water erosion and can protect organic matter against oxidation.

- The load-bearing capacity after biochemical ripening is enough to sustain cattle and tractors, meaning that the soil can be used for husbandry (crops and/or animals).

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