A CSM-Based Procedure for Identifying Segments of Agricultural Drainage Ditches to Be Prioritized in Maintenance Work

Collection
Research

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Highlights

- Maintenance of agricultural ditches is important to secure food production.
- To reduce costs, ditch segments in most need of maintenance should be prioritized.
- CSM measurements can help prioritize maintenance of agricultural ditch segments.

Abstract. *Productive agricultural land is vital for food production. To help secure the productivity of drained agricultural soils, diches need to be intermittently maintained. Maintenance work is costly, however, so ditch segments in most need of maintenance should be prioritized. Here, we present a procedure for identifying drainage ditch segments likely to need maintenance based on susceptibility to soil erosion by water flowing in the ditch, evaluated using a cohesive strength meter (CSM). An important part of the procedure is to relate the pressure of the CSM jets to pressures acting on the soil. The relationship between CSM jet pressure and pressures at the soil surface was established based on measurements made with a pressure sensor plate and was applied to obtain several values for pressure at the surface, which were used in turn to estimate critical shear stress for erosion. The results showed that the CSM-based method was able to identify differences in critical shear stress for erosion for different field soils. This information can be useful in identifying drainage ditch segments that should be prioritized for maintenance work.*

Keywords. *Drainage data acquisition, Drainage maintenance, Drainage performance evaluation, Soil erosion.*

Land drainage, or a combination of irrigation and land drainage, is an important soil management technique to maintain or improve crop yield per unit of land (Bos and Boers, 2006). The drainage structures responsible for collecting surface and subsurface water are ultimately open ditches (Dollinger et al., 2015), which are therefore vital for the proper functioning of agricultural land. However, ditches degrade over time under the action of multiple factors. For example, bank erosion modifies the cross-section of ditches, changing their hydraulic capacity, while deposition of soil transported from surrounding land by surface and subsurface flow alters the hydraulic capacity of ditches by modifying channel geometry.

Some agricultural ditches have a high demand for maintenance, while others are relatively stable. High maintenance ditch segments are those that do not properly perform their hydraulic function. Hydraulic function here refers to the ditch capacity to transport its intended water discharge rate. This discharge rate depends on ditch cross-section geometry, which is modified by soil erosion and mass movements. As soil erosion acts on the ditch and mass movements occur, generally, on the ditch banks, the soil removed will either be transported or remain as soil deposits in the main channel, which will reduce the water discharge rate of the ditch. Maintenance, thus, refers to the actions intended to restore the ditch hydraulic function, such as removing soil from the dich channel, cutting excessive vegetation from the main channel and/or the banks, and (possible) cross-section modifications. A procedure to identify ditch segments in which maintenance should be prioritized is thus required. This has prompted the development of methods to assess the status of agricultural ditches (e.g., Magner et al., 2010; Aviles et al., 2018; Joel et al., 2015; Wesström et al., 2016). The methods developed generally consider different parameters related to erosion processes in ditch banks, since the use of parameters that characterize soil susceptibility to fluvial erosion and methods to measure these in the field or in the laboratory remain a challenge.

In this paper, we present a novel procedure for identifying drainage ditch segments that are likely to need maintenance

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work and present an approach for characterizing soil susceptibility to fluvial erosion.

Materials and Methods

A method based on the use of a cohesive strength meter (CSM) was developed and calibrated, using data from three previous studies by our research group in which susceptibility to soil erosion was assessed using a CSM.

Study Sites

In the previous studies from which data were obtained, soil erosion susceptibility was assessed by CSM measurements in two agricultural plots and two agricultural drainage ditches, using soil samples obtained at two locations in Sweden (fig. 1): (1) Ultuna, 5 km south of Uppsala city (drainage ditch near Bäcklösa [Aviles et al., 2018] and two agricultural plots [Ultuna 3 and Ultuna 9] [Aviles et al., 2020]) and (2) Jönåker, around 20 km west of Nyköping city center (drainage ditch) (Aviles, 2020).

Assessment of Soil Erosion Susceptibility by Cohesive Strength Meter (CSM)

A CSM was used to assess susceptibility to soil erosion in all three background studies. The CSM is a device that applies water jets of incremental pressure to a soil surface and records jet pressure and the amount of soil detached by the action of each water jet (expressed as decay based on light transmittance values inside the testing chamber). The device has many different settings, each of which defines the pressure increment of each jet, the duration of application of each jet, and the period over which the amount of soil detached (light transmittance) is recorded. Details of the settings used in the three previous studies are presented in table 1.

The test starts with a low pressure, which is gradually increased, and values of CSM jet pressures and light transmittance are measured at each step. From these readings, a critical CSM jet pressure is defined as the CSM jet pressure that causes the light transmittance value to fall by 10% (Tolhurst et al., 1999). However, the 10% threshold was derived for coastal soils that are more sensitive to erosion by water. Therefore, in this work, we used a 30% drop in light transmittance as a threshold value.

Work by Vardy et al. (2007) showed that it is difficult to compare critical CSM jet pressure values from different CSM devices and indicated that better estimates can be obtained by first acquiring an equivalent critical CSM jet pressure acting at the soil surface ($P_{surface\_crit}$). Using this $P_{surface\_crit}$ value, an empirical relationship, such as that

Table 1. Details of the Cohesive Strength Meter (CSM) settings (Partrac, 2011) used in obtaining data in the three previous studies on which method development was based.

Description	Sand 1	Sand 17	Fine 1	Mud 9
Jet duration (s)	0.3	1.0	1.0	1.0
Data logged for (s)	3.0	3.0	3.0	30.0
Data logged every (s)	0.1	0.1	0.1	1.0
Starting pressure(kPa)	2.1	13.7	0.7	3.4
Pressure increment (kPa)	2.1	13.7	0.7	3.4
Up to (kPa)	82.7	413.7	16.5	34.5
Then from (kPa)			18.6	41.4
Increasing by (kPa)			2.1	6.9
Up to (kPa)			41.4	413.7
Then from (kPa)			55.1	
Increasing by (kPa)			13.7	
Up to (kPa)			413.7	

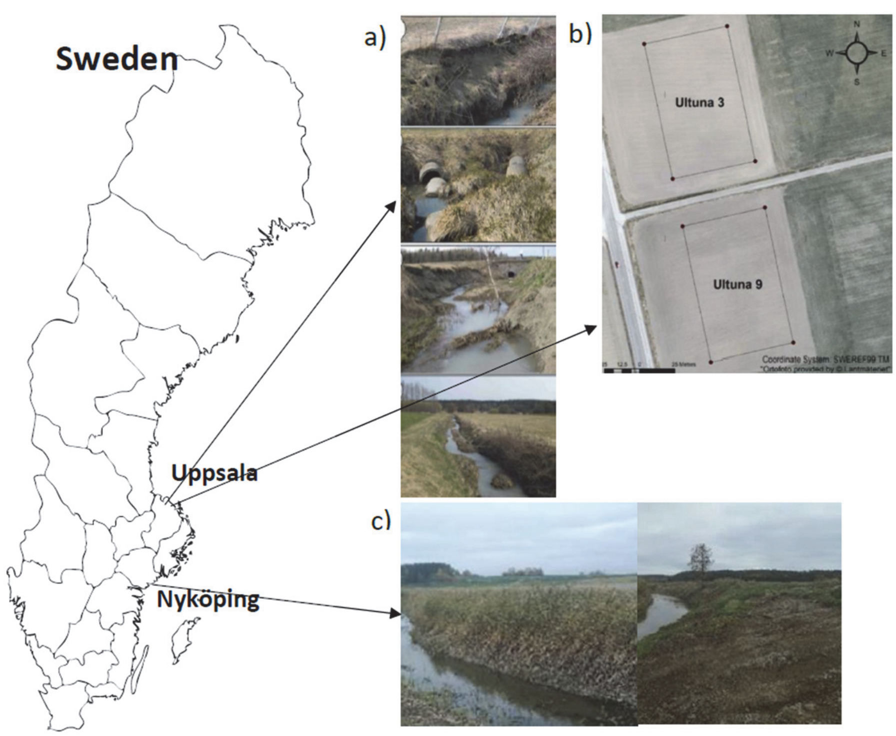

Figure 1. Locations of study sites in the three previous studies from which data were taken: (a) an agricultural drainage ditch near Bäcklösa, (b) agricultural plots in Ultuna, Uppsala, and (c) an agricultural drainage ditch in Jönåker, Nyköping. Modified from Aviles, 2020.

proposed by Grabowski et al. (2010), can be applied to obtain an estimate of the critical shear strength for erosion (τ_{crit}):

$$\tau_{crit} = 0.0013 P_{surface\_crit} + 0.047 \quad (1)$$

Calibration of Cohesive Strength Meter Pressure

We performed a calibration to relate CSM jet pressures to equivalent pressures acting at the soil surface, which were measured using a pressure sensor plate that detected the pressure applied upon any part of its sensing area (4 mm x 4 mm) (fig. 2). By directing the CSM jets at this sensing area and covering the full range of CSM jet pressures, we obtained measurements of the pressures acting at the soil surface for each CSM pressure. Using the values obtained, we developed an empirical relationship between CSM jet pressure and the equivalent pressure acting at the soil surface (pressure values in Pascal):

$$P_{surface} = 0.005 \cdot P_{CSM\ Jet} \quad (2)$$

Study 1: The Ultuna Plots

Data from the agricultural plots in Ultuna were used to evaluate the CSM capability to distinguish soils with different erosion resistance. In the previous study (Aviles et al., 2020), the soil in these plots was treated with different soil amendments aimed at enhancing aggregate resistance and thus erosion resistance (Amézketa, 1997), and therefore it was known that these soils had increased aggregate resistance. Here, we assessed whether the CSM was able to detect these differences. Three soil amendments were used in the original study: (1) Mixed lime, comprising approximately 15% slaked lime ($Ca(OH)_2$) and 85% calcium carbonate ($CaCO_3$), (2) slaked lime, and (3) tunnel kiln slag, which is a mixture of around 20% calcium oxide (CaO), charcoal, and silica oxides. The doses used were based on achieving an equal supply of calcium with a liming rate of 3 t CaO ha^{-1}, irrespective of the liming product (Aviles et al., 2020).

Each of the two plots at Ultuna (Ultuna 3, Ultuna 9) was subdivided into 16 subplots, each of which was treated with a different amendment chosen at random (Aviles et al., 2020). A total of 96 samples (48 samples per plot, 3 samples per subplot) were taken from the topsoil (5-10 cm depth, as the soil was disturbed by tillage) using cylinders with 7.2 cm diameter and 5 cm height. Each of the 96 samples was saturated and then drained to a drainage equilibrium pressure of 4.9 kPa (0.5 m. water column) to bring the soil sample to a standard moisture content before testing. The 96 samples were, then, subjected to CSM measurements using the Fine 1 setting (see table 1).

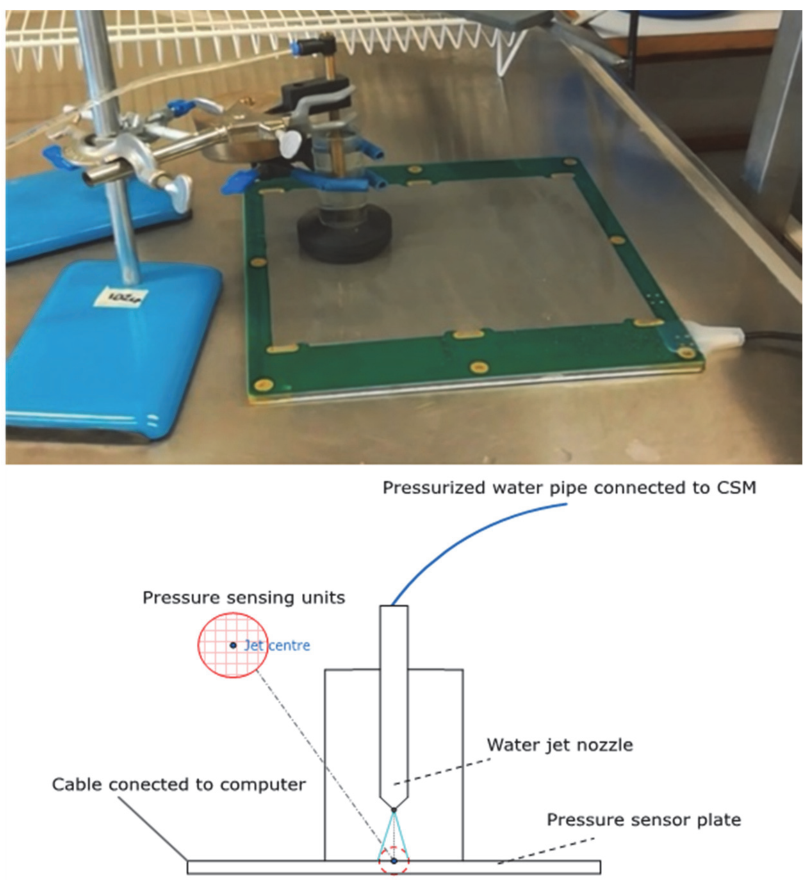

Figure 2. (Upper image) Cohesive strength meter (CSM) positioned above the pressure sensor plate, ready for (lower diagram) measurement of pressures at the soil surface.

STUDY 2: THE BÄCKLÖSA DITCH

In the previous study (Aviles et al., 2018), the ditch near Bäcklösa was first evaluated visually using the Minnesota Agricultural Ditch Research Assessment (MADRAS) procedure (Magner et al., 2010). The parameters considered in the visual evaluation were bank stability (erosion from surface runoff, mass failure, and seepage), over-widening or undercutting, and deposition. Each of these parameters was given a score on a scale from 0 to 10 points. Bank stability was scored based on the presence of (1) bank erosion from surface runoff, (2) mass failure, and (3) groundwater intrusion (Aviles et al., 2018). If no indicator was observed, a score of 0 was given. If three indicators or 10% of the ditch segment were affected at any point, the ditch was given a score of 10 points. Over-widening or undercutting was evaluated considering two indicators: (1) a bank evenly shaped across the ditch segment, with no undercutting visible, and (2) one of the following indicators visible: irregular ditch shape, irregular channel width, vertical bank, where if three indicators or 20% of the banks were undercut and had fallen into the channel, the segment was given 10 points. Deposition was assessed considering four indicators: (1) no significant deposition (0 points), (2) sediment depth exceeding on average 7.5 cm (3 points), (3) sediment deposits in the channel (5 points), and (4) banks in the water channel (10 points). The scores given to each parameter were then added together to give a final score ranging from 0 to 30 points, where 0-8 points indicated a ditch segment considered to be in good condition; 9-15 indicated a ditch segment marginally affected by erosion; 16-20 points indicated a ditch segment affected by erosion; and a final score above 21 points indicated a ditch segment in poor condition (Aviles et al., 2018). Based on field observations, the ditch was divided into seven segments (A, B, C, D1, D2, E, F), and each segment was given a score.

Visual assessment was used to select a group of three ditch segments in which complementary CSM measurements were made. For the CSM tests, 12 undisturbed samples per segment (36 in total) were taken from the upper soil layer (5-10 cm depth) on the ditch banks to a depth of 80-120 cm, using cylinders with 7.2 cm diameter and 5 cm height (Aviles et al., 2020). Each sample was saturated and then drained to a drainage equilibrium pressure of 4.9 kPa (0.5 m. water column) to bring the soil sample to a standard moisture content before testing. Each sample was tested with the CSM using the Sand 1, Sand 17, Fine 1, and Mud 9 settings (see table 1).

STUDY 3: THE JÖNÅKER DITCH

The ditch in Jönåker was surveyed to further test the capability of CSM measurements to identify soils that may be more easily eroded. The ditch was first assessed visually to identify segments where erosion and mass movements were active and segments that appeared stable. Unstable segments had vegetation removed from their ditch banks, whereas stable segments had their ditch banks covered with vegetation (Aviles, 2020). Five segments were identified in this manner, and six undisturbed samples (cores 7.2 cm diameter, 5 cm height) were taken from the ditch banks in each segment for CSM tests (3 samples each for saturated and drained moisture conditions). Six additional samples were taken for root density measurements. All these samples were taken from the upper soil layer on the banks, at an approximate depth of 5-15 cm and at an approximate distance of 100 cm from the top of the ditch bank (Aviles, 2020). After testing with the CSM, each sample was used to measure root density in the soil, i.e., a total of 12 samples were used to determine average root density. This parameter was measured because it is reported to be a factor that can increase soil erosion resistance (Wang et al., 2022). The CSM tests in Jönåker were made under two moisture conditions, saturated and drained (to a drainage pressure of 4.9 kPa (0.5 m water column)), to test the hypothesis that saturated soil will erode more easily than drained soil. In addition to moisture content, the CSM tests were carried out for different soil root densities (Aviles, 2020). All CSM tests were performed using the Fine 1 setting (see table 1).

RESULTS AND DISCUSSION

THE ULTUNA PLOTS

The CSM results were used to compare the detachment resistance of the soils from different experimental treatments. This was done by comparing the amount of soil detached by the action of CSM water jets at different pressures with soil without treatment (control) (Aviles et al., 2020). The CSM jet pressures were expressed as equivalent pressure at the surface using the equation based on sensor plate measurements (eq. 2, table 2). For samples from all treatments, it was found that more soil eroded as CSM jet pressure increased (table 2).

The critical jet pressure for erosion was identified using the 70% threshold (30% decay in light transmittance). It was found that the critical jet pressure for erosion was higher for mixed lime than for the other amendments tested or for control soil ($p<0.01$) (Aviles et al., 2020).

The CSM curves for the two agricultural plots in Ultuna indicated that the control soil detached more than the soils in the different treatments (fig. 3). The Mixed Lime treatment resulted in soil that could withstand higher pressures with less detachment compared with the other treatments, as can be seen from the curves in figure 3.

THE BÄCKLÖSA DITCH

The results from the visual assessment of segments in the Bäcklösa ditch using the MADRAS method (Aviles et al., 2018) are shown in table 3. The higher the total MADRAS

Table 2. Values of pressure at the surface of soils in different soil amendment treatments in the Ultuna plots, calculated using equation 2. All values are in kPa. (Source: Aviles et al., 2020)

	Transmittance:	<90%	<70%	<50%
Control	CSM Jet pressure:	0–1.4	5.0–10.0	5.0–10.0
	Psurf :	0–0.007	0.025–0.05	0.025–0.05
Mixed lime	CSM Jet pressure:	0–1.4	15.0–20.0	50.0–55.0
	Psurf:	0–0.007	0.075–0.1	0.25–0.275
Slaked lime	CSM Jet pressure:	0–1.4	5.0–10.0	20.0–25.0
	Psurf:	0–0.007	0.025–0.05	0.1–0.125
Tunnel kiln slag	CSM Jet pressure:	0–1.4	5.0–10.0	10.0–15.0
	Psurf:	0–0.007	0.025–0.05	0.05–0.075

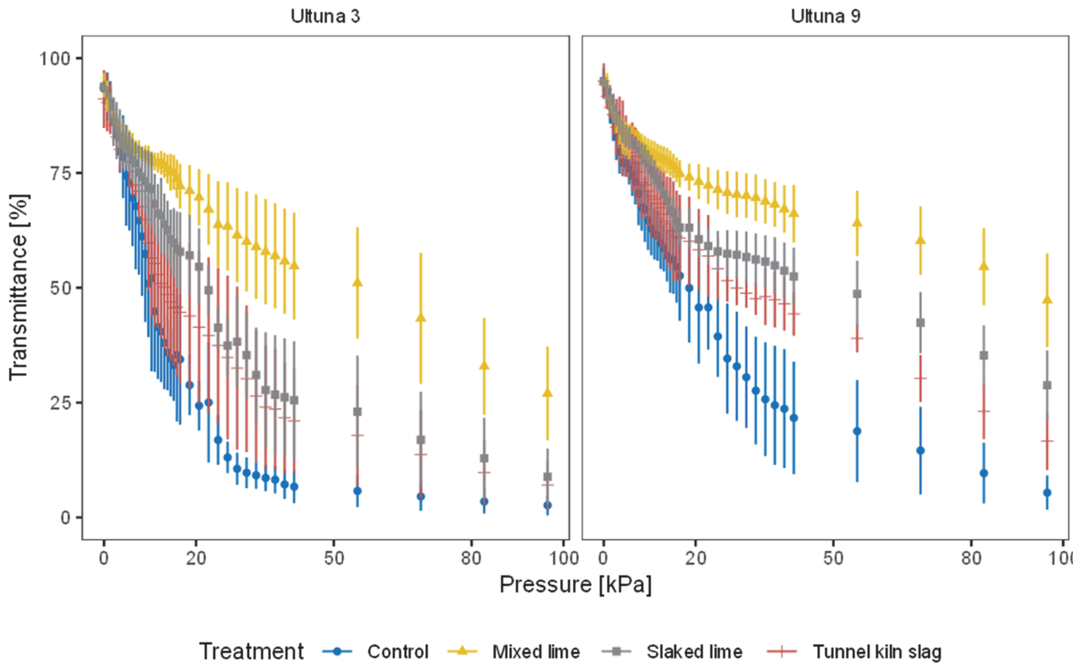

Figure 3. Cohesive strength meter curves for the agricultural plots at Ultuna (Ultuna 3, Ultuna 9). Points are averages, vertical bars indicate standard deviation (N=3). (Aviles et al., 2020).

Table 3. Results of visual assessment of Bäcklösa ditch segments using the Minnesota Agricultural Ditch Research Assessment (MADRAS) method. (Source: Aviles et al., 2018)

	Ditch segment						
	A	B	C	D1	D2	E	F[a]
Bank stability	0	5	5	5	10	10	-
Over – widening or undercutting	3	3	10	10	10	10	-
Sediment deposition	0	0	3	5	10	10	-
Total score	3	8	18	20	30	30	-

[a] Segment F was extremely degraded.

score, the poorer the condition of the ditch segment (Joel et al., 2015).

From among the seven segments of the ditch at Bäcklösa evaluated by Aviles et al. (2018), three (C, D1, D2) were selected for testing with the CSM approach because of their proximity to each other. According to MADRAS, segment C was marginally affected, D1 was in poor condition, and D2 was marginally affected. The CSM results for the three ditch segments are shown in figure 4. The critical jet pressure for erosion (70% transmittance or 30% decay in transmittance value) was found to be significantly higher for segments C and D2 than for segment D1 (p<0.1). The results were consistent regardless of the CSM settings used, with the curves for segments C and D2 always lying above the curve for D1, indicating that the soil in segments C and D2 was more resistant to erosion than that in segment D1. This behavior was similar to that found for soils from the Ultuna plots (see fig. 3).

Comparisons of the CSM results with hydraulic shear stress values obtained from HEC-RAS simulations for each ditch segment in the previous study (Aviles et al., 2018) showed that segments classified as degraded according to MADRAS did not display higher values of hydraulic shear stresses. Therefore, the forces exerted by water flowing in the ditch were not sufficient to explain the differences in the degradation status of the ditch sections.

The Jönåker Ditch

The CSM curves for the five segments and the two moisture conditions studied at the Jönåker site are shown in figure 5, while the average root densities for the five segments are shown in table 4. In terms of the critical jet pressure (70% transmittance or 30% decay in transmittance value), there was no difference between saturated and drained conditions (p>0.1 in all cases). However, the critical jet pressure for erosion was higher for segments 3 and 1 (p<0.1), which had higher soil root densities (table 4).

In the segments with higher root densities (stable segments), the soil detached less readily under the action of higher CSM jet pressures than in the soils with lower root densities (unstable segments) (fig. 5). In addition, the CSM curves for the stable segments (segments 1 and 3) lay above those for the unstable segments (segments 2, 4, and 5) (fig. 5). This was a similar trend to that found for the Ultuna plots (fig. 3) and the Bäcklösa ditch (fig. 4).

The Three Studies

Using the calibration obtained from measurements with the pressure sensor plate (eq. 1), we estimated the critical pressure at the surface for soils in the three previous studies, using 30% transmittance decay as a threshold. Using the value obtained for critical pressure at the surface and equation 2, we then estimated the critical shear stress for erosion. The results showed that, in general, the CSM approach was able to identify soils with higher critical shear stress for erosion in all three studies (table 5).

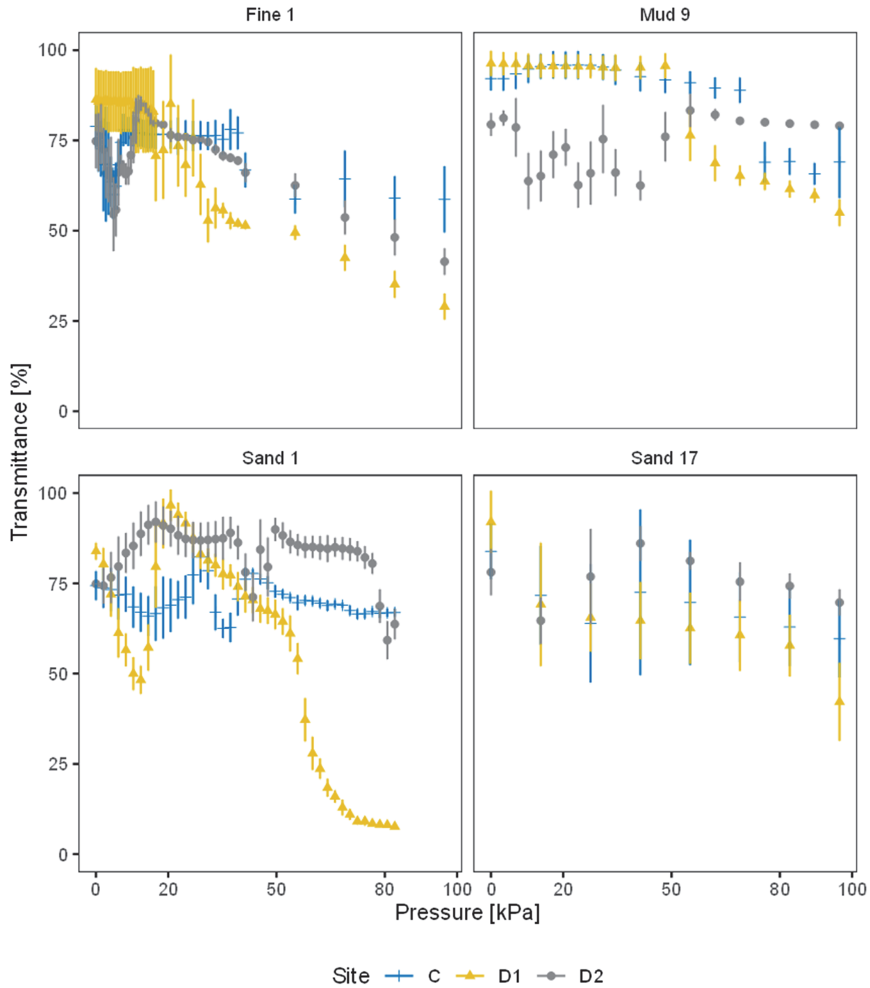

Figure 4. Cohesive strength meter curves for neighboring segments C, D1, and D2 of the Bäcklösa ditch. Points are averages, vertical bars indicate standard deviation (N=3). (Aviles et al., 2018).

Table 4. Average root densities in the five segments of the Jönåker ditch. (Source: Aviles, 2020)

Segment	Root Density[a] (Kg/m3)	Vegetation Status
1	17.4 ± 3.4	Present
2	2.5* ± 1.3	Removed
3	12 ± 2.2	Present
4	2.2* ± 1.0	Removed
5	1.8 ± 0.9	Removed

[a] Root density values are averages ± standard deviation (n = 12).
* An outlier was removed prior to calculation of the mean and standard deviation.

Table 5. Values of pressure at the surface (eq. 1) and critical shear stress for erosion (eq. 2). Modified from Aviles et al., 2018; Aviles, 2020; Aviles et al., 2020).

Study Site	Segment Name [a]	Critical CSM Pressure (kPa)	Critical Pressure at Surface (kPa)	Critical Shear Stress (kPa)
Bäcklösa ditch	Segment C	41.4	0.207	0.00032
	Segment D1	13.8	0.069	0.00014
	Segment D2	68.9	0.3445	0.00049
Uppsala plots	Control	4.82	0.0241	0.00008
	Mixed lime	14.85	0.07425	0.00014
	Slaked lime	9.3	0.0465	0.00011
	Tunnel kiln slag	6.9	0.0345	0.00009
Jönåker ditch	Segment 1 (17.4)*	41.4	0.207	0.00032
	Segment 2 (2.5)	4.14	0.0207	0.00007
	Segment 3 (12.0)	193	0.965	0.00130
	Segment 4 (2.2)	4.14	0.0207	0.00007
	Segment 5 (1.8)	4.83	0.02415	0.00008

[a] Values in brackets are average root density in the soil(kg/m^3).
* An outlier was removed prior to calculation of the mean root density.

Conclusions

A CSM-based method developed in this study for identifying ditch segments in most need of maintenance was able to identify differences in critical shear stress values between different soils in three previous studies. For the agricultural soil plots in Ultuna, the CSM method was also able to detect differences resulting from the use of different soil amendments to improve the soil structure. For the drainage ditch near Jönåker, the method was able to identify differences in soil resistance to erosion caused by different root densities in ditch bank soil. However, the CSM results showed high variability, as seen from the different CSM curves obtained for the soils studied, emphasizing the need to include replicates when planning to use this tool.

Overall, the CSM-based method provided information that can assist in identifying drainage ditch segments that should be prioritized for maintenance work, especially when erosion by water flow is a particular concern.

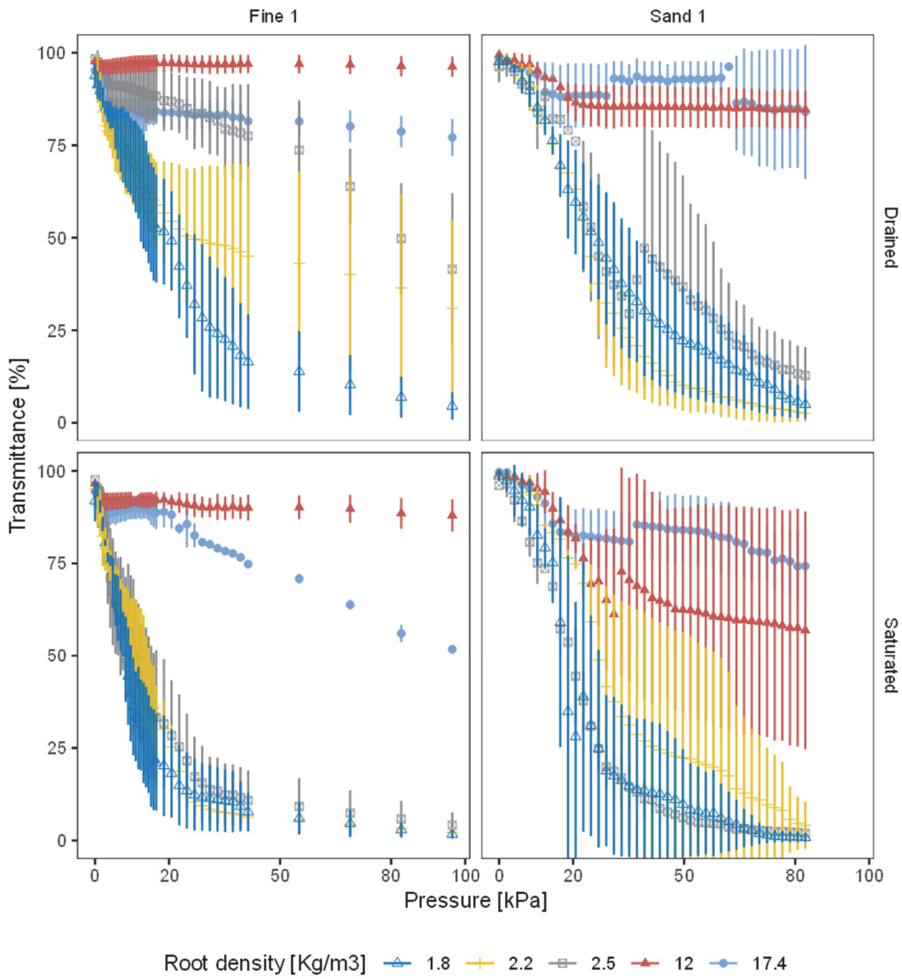

Figure 5. Cohesive strength meter curves for the five segments in the Jönåker ditch. Points are averages, vertical bars indicate standard deviation (N=3). (Aviles, 2020).

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