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Defining critical SOC/clay thresholds for soil health in boreal croplands using satellite-based NDVI proxies for productivity and resilience

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The European Union's soil strategy underscores the necessity for establishing feasible criteria to assess the soil health condition. In this study, we developed a method to define a critical threshold value for SOC/clay ratio on the basis of crop productivity and resilience. The study integrated data from national soil monitoring (NSM) of Finnish cropland soils (n=505) with satellite-based normalized difference vegetation index (NDVI) obtained from the Eco-DataCube (EDC) portal. The study area was confined to the boreal environmental zone to ensure consistent pedo-climatic conditions. The results show that the interannual variation in crop productivity increases rapidly below SOC/clay ratio of 0.09 (95% confidence intervals ranging from 0.07 to 0.16), whereas the corresponding threshold for mean productivity was 0.13 (0.09–0.16). The observed threshold values were found applicable for both cereals and temporary ley. The SOC/clay ratio of 1:13 (=0.08), regarded as a criterion for healthy soil in the current Soil Monitoring Law proposal, based on studies by Johannes et al. (2017) and Prout et al. (2021), is lower than the mean thresholds estimated in this study but aligns close to the lower bound of the 95% confidence intervals. In this research, Finnish agricultural land served as the case study area, but the method is easily applicable to various pedo-climatic regions and potentially to different land use types.

Key words: Soil Monitoring Law, SOC/clay ratio, cropland, NDVI, satellite data, national soil monitoring

Introduction

European Union's Soil Strategy (EC 2021) and announced proposal for Soil Monitoring Law (EC 2023) has boosted the interest on developing descriptors and criteria for healthy soil condition. In the Soil Monitoring Law, soil health means the physical, chemical and biological condition of the soil determining its capacity to function as a vital living system and to provide ecosystem services. Ideally, the criteria should precisely characterize the state of the soil in a scientifically sound manner with readily available data. Furthermore, the classification criteria should be equitable across all European regions. In practice, this necessitates the utilization of continental-scale harmonized geospatial datasets and the development of region-specific criteria (e.g. pedo-climatic zones).

The content of soil organic matter (SOM), including soil organic carbon (SOC) as a key component, and its temporal changes, are well-established indicators of soil health due to the significant impact of SOM on soil processes, such as the formation and stability of soil structure, and the storage and cycling of nutrients (Obalum et al. 2017). However, the inherent level of SOC is known to depend on various drivers, of which soil texture and especially the fine mineral fractions (fine silt and clay) are a major contributor owing to stabilization of SOC through interactions with the mineral surfaces and aggregates (Wiesmeier et al. 2019). In addition to SOC protection, the clay-sized fraction is a decisive soil structure-forming agent shown to exhibit an opposite effect to SOC in many structural parameters (Soinne et al. 2023). The higher the clay content, the more SOC is needed to sustain adequate soil structure. Consistently, the ratio of SOC to clay has been suggested to be a better indicator of soil physical properties than either of them alone (Dexter et al. 2008). Based on visual soil structure assessment and bulk volumes in Swiss arable soils, Johannes et al. (2017) found a SOC/clay ratio of 1:8 (=0.13) or higher as optimal for structural quality, whereas a ratio of 1:10 (=0.10) formed the limit between good and medium quality and 1:13 (=0.08) the threshold for unacceptable quality. These limits of structural condition were tested and found appropriate in England and Wales by Prout et al. (2021). Other studies have demonstrated an association between the SOC/clay ratio and clay dispersibility (Getahun et al. 2016), nitrogen mineralization, and cereal yield (Soinne et al. 2021).

Given the widespread impact of climate change on harvested crop yields globally, the importance of soil health is increasingly emphasized. Climate change increases the frequency, severity and duration of extreme weather events including heatwaves, drought and heavy rainfalls (IPCC 2022). Adverse impacts of extreme weather events are amplified by the increased occurrence of diseases, weeds, and insect pest outbreaks. Unhealthy soils are not

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only more susceptible to decreased crop yields but also exhibit higher interannual variations, impacting the resilience of agricultural systems.

Approximately 61% of the European land area is estimated to be affected by one or more soil degradation processes, as indicated by the EUSO Soil Health Dashboard. This poses challenges in establishing suitable benchmarks for healthy soil conditions. The drawbacks of previously proposed soil indicators (Johannes et al. 2017, Prout et al. 2021, Poeplau and Don 2023, Feeney et al. 2024) stem from defining the criteria using visual interpretation of the data or determining criteria based on possibly already degraded soil i.e. threshold value of the criteria depends on the data used for prediction. In this study, we used the satellite-based normalized difference vegetation index (NDVI) as a proxy for soil productivity (Moges et al. 2005, Tenreiro et al. 2021). By examining the association between productivity and the SOC/clay ratio, our aim was to develop an objective method for defining the critical threshold value for the SOC/clay ratio, along with uncertainty estimates for the croplands in boreal environmental zone. The study assumes that when the SOC/clay ratio falls below a certain threshold, the soil becomes structurally so weak that it not only reduces soil productivity but also makes the soil more sensitive to the variable climatic conditions of the growing season.

Materials and methods

National soil monitoring

In national soil monitoring (NSM) for Finnish cropland soils, the soil sampling has been undertaken in 1974, 1987, 1998, 2009 and 2018 (Soinne et al. 2022). Soil samples were collected as a composite sample (0.5 dm^3) from the topmost 15 cm soil layer using a soil corer with a diameter of 2 cm. Each composite sample was formed by mixing 10 to 20 subsamples. Area of the sampling plot was 10 m × 10 m. Samples were air-dried at 40 °C and passed through a 2 mm mesh size sieve. The SOC content of the samples was determined by the dry combustion method using a LECO CN-2000 analyzer (LECO). Soil texture was determined using the sieve-pipette method (Elonen 1971). This study was based on the results of the latest sampling campaign in 2018, when there were 631 sampling plots in the network. The study area was confined to the boreal environmental zone based on the environmental stratification of Europe (EnS) by Metzger et al. (2005) to ensure consistent pedo-climatic conditions. Furthermore, organic soils (SOC>20%, IPCC [2014]) were omitted from the analysis, leaving altogether 505 sampling plots (Fig. 1). SOC content ranged between 9 and 112 g kg^{-1} being on average 35 g kg^{-1}, whereas clay content ranged between 4 and 830 g kg^{-1} being on average 188 g kg^{-1} (see Figs. S1, S2 and S3 in Supplement for the histograms and map presentations). Cultivated crop plants of each sampling plot between 2000 and 2020 were obtained from the database collected by the Finnish Food Authority.

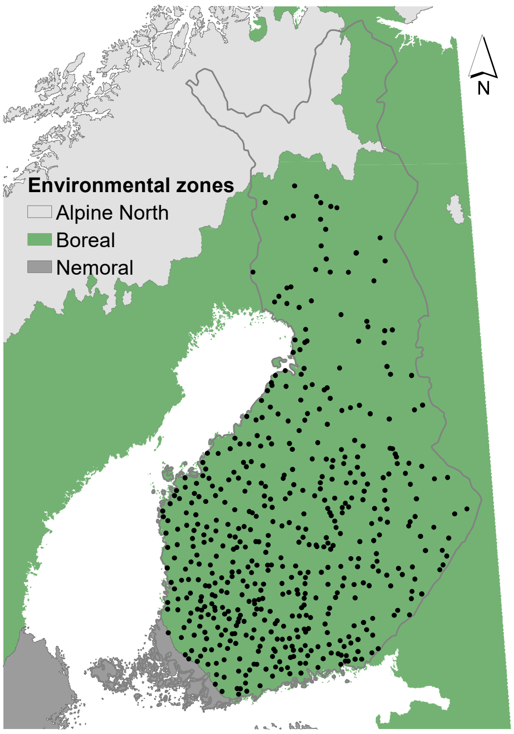


Fig. 1. Location of sampling plots (n=505) of national soil monitoring (NSM) of Finnish cropland soils used in the study. Only NSM plots located within the boreal environmental zone were included in the study to ensure consistent pedoclimatic conditions.

EcoDataCube

EcoDataCube is a data portal providing Landsat- and Sentinel-2 data in addition to a digital terrain model in an open and easily accessible format (Witjes et al. 2023). The platform offers various analysis-ready and spatiotemporally harmonized European wide environmental datasets in 30 m × 30 m grid. Temporally, the data is aggregated into four annual quarterly period medians, approximating the four seasons (winter, spring, summer and autumn). In this study we utilized the Landsat based summertime (between 25 June and 12 September) NDVI data layer covering the years 2000–2020.

Data analysis

NDVI values of each sampling plot of NSM for years 2000–2020 were obtained by selecting the nearest grid point from each NDVI data layer based on the coordinates of the NSM sampling plots. Mean and standard deviations of NDVI over the years were calculated to describe the overall crop productivity and the crop resilience (inter-annual variation).

The association between the SOC/clay ratio and NDVI was first preliminarily studied using a moving average (Fig. 2). Based on the preliminary data assessment, a simple piecewise regression, with two straight lines intersecting at the breakpoint, was found to be feasible:

$$\boldsymbol{y} = \begin{cases} \boldsymbol{a} + \boldsymbol{b_1 x} & \boldsymbol{for\ x \le c} \\ \boldsymbol{a} + \boldsymbol{b_1 x} + \boldsymbol{b_2}(\boldsymbol{x} - \boldsymbol{c}) & \boldsymbol{for\ x > c} \end{cases},$$

where y is either mean or standard deviation of NDVI, and x is the natural logarithm of the SOC/clay ratio. Here a is the intercept, b_1 is the slope of the first regression line and the sum of b_1 and b_2 is the slope of second regression line. The breakpoint value of two regressions lines is denoted by c. Breakpoint was defined to occur within the range of observed SOC/clay ratios. The 95% confidence intervals (CI) for piecewise regression lines as well as for breakpoint value was obtained using bootstrap approach, where the data were resampled with replacement 100 000 times.

Analyses were conducted using data from all sampling plots (n=505), as well as from those plots and years when the crop was either cereals (n=307) or temporary ley (n=281). When including all sampling plots, the mean and standard deviation of NDVI were calculated across the years 2000–2020 based on the 21 observations of NDVI for each NSM plot included in the analysis. For cereals and ley, only plots with a minimum of five years of cultivation history of either cereals or ley were considered, and NDVI values were extracted solely for those years (5–21). Out of the sampling plots, 109 were included in both the cereal and ley groups. The analysis, which included all sampling plots, had 36 plots that were not part of either the cereal or ley groups. Analysis including all sampling plots consisted of altogether 10605 NDVI values (505 × 21), whereas cereals and temporary leys had 3736 and 3534 observations, respectively.

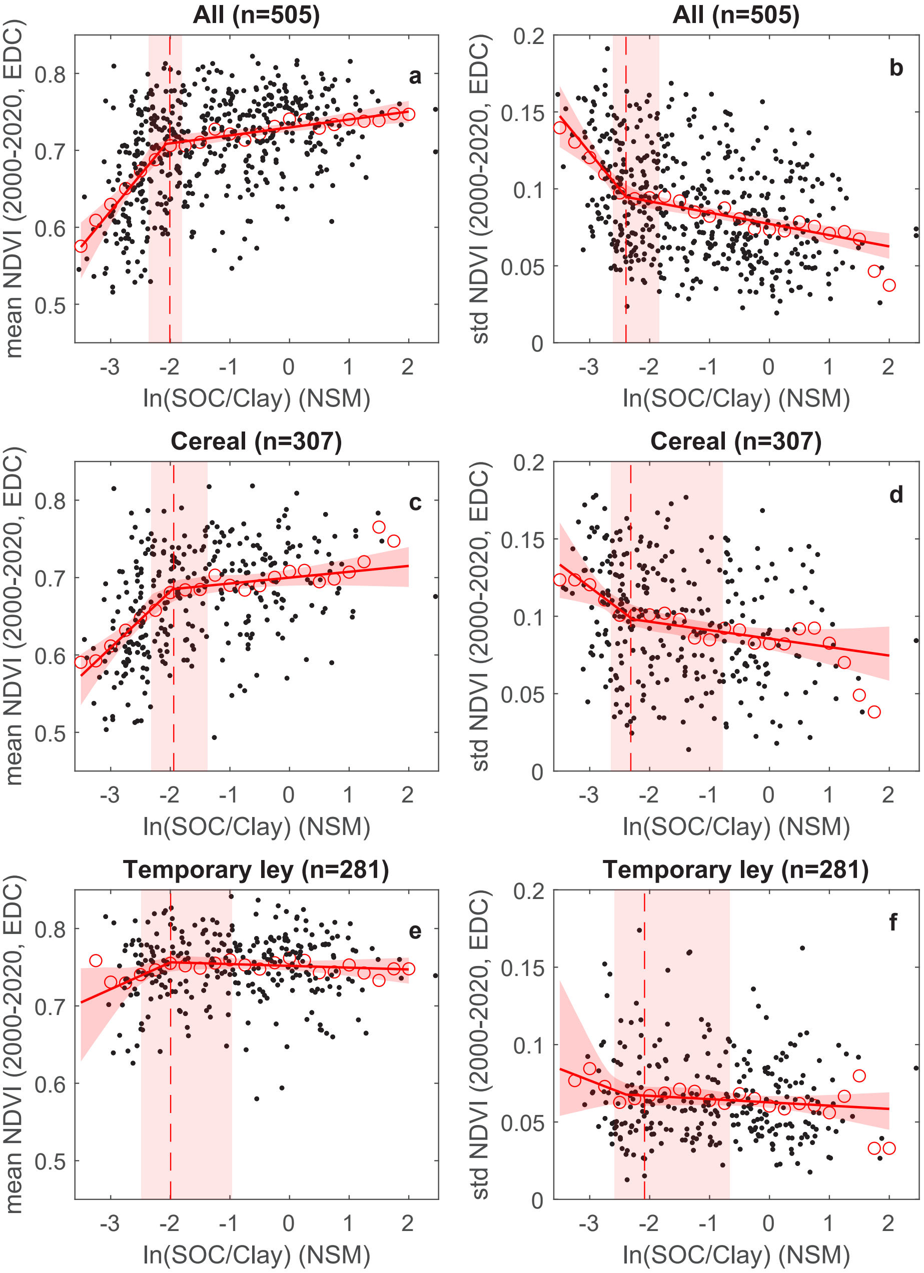
Results

The average NDVI (reflecting overall productivity) between 2000 and 2020 increased with increase in the SOC/clay ratio. The increase was sharp until the breakpoint value of the piecewise regression line, after which the increase leveled off (Fig. 2a). In log-transformed scale the breakpoint (parameter c) occurred at –2.0 (95% CI between –2.4 and –1.8) corresponding to SOC/clay ratio of 0.13 (0.09–0.16) in original scale.

In contrast to mean NDVI, the standard deviation of NDVI (=reflecting resilience) tended to decrease with an increase in the SOC/clay ratio (Fig. 2b). However, as with mean NDVI there was a change in the slope of the regression line (parameter $b_2>0$ with greater than 95% confidence) at the breakpoint value of –2.4 (95% CI between –2.6 and –1.8). At original scale the breakpoint value corresponds to SOC/clay ratio of 0.09 (0.07–0.16).

The association between the SOC/clay ratio and NDVI for cereals (Figs. 2c and 2d) and temporary ley (Figs. 2e and 2f) exhibited a similar pattern to that observed when using all data, although the uncertainty was greater. In the case of cereals, the breakpoint occurred at SOC/clay ratio of 0.14 (0.10–0.25) in mean NDVI and at SOC/clay ratio of 0.10 (0.07–0.46) in the standard deviation of NDVI. In temporary ley, the breakpoint occurred at the SOC/clay ratio of 0.14 (0.08–0.38) in mean NDVI and at the SOC/clay ratio of 0.12 (0.08–0.51) in the standard deviation of NDVI.

In case of all observation and cereals the slope of the latter segment of regression line was gentler (parameter $b_2<0$ in mean NDVI whereas parameter $b_2>0$ in case of standard deviation of NDVI) than that of the first segment with higher than 95% confidence. In case of temporary ley the parameter b_2 is smaller than zero with 98% confidence in mean NDVI and greater than zero with 70% confidence in standard deviation of NDVI. The results are presented on a log-transformed scale, but on the original scale, the relationship between the SOC/clay ratio and NDVI appears heavily tailed.



Figs. 2 a-f. Association between the log-transformed SOC/clay ratio in sampling plots of national soil monitoring (NSM) and the mean and standard deviation of NDVI between 2000–2020 obtained from EcoDataCube (EDC). Shaded zone around the piecewise regression line denotes the 95% confidence interval, whereas vertical shaded regions denote the 95% confidence interval of the breakpoint value. Open circles indicate the moving average and was used for preliminary data analysis. The SOC/clay ratios were transformed using the natural logarithm.

Discussion

The present study demonstrated that below the SOC/clay ratio of 0.09, the interannual variation in crop productivity increased sharply, whereas the corresponding threshold for mean productivity was 0.13. In 108 and 174 out of 505 plots in the NSM data, the SOC/clay ratio is lower than the threshold obtained for resilience and overall productivity, respectively. This suggests that approximately 21–34% of NSM plots can be considered unhealthy. However, the geographical distribution of NSM plots does not fully coincide with the agricultural area of Finland as cultivation is concentrated in southwest Finland, where soils with high clay content are common (see e.g. Keskinen et al. (2016) for geographical distribution of basic soil properties). Thus, the actual proportion of unhealthy agricultural soils in Finland is likely higher than estimated based solely on NSM data.

Johannes et al. (2017) and Prout et al. (2021) defined the thresholds for SOC/clay ratios of 1:8 (=0.13), 1:10 (=0.10), and 1:13 (=0.08) to indicate the boundaries between ‘very good’, ’good’, ‘moderate’, and ‘degraded’ soil structural conditions, respectively. The mean threshold values for SOC/clay ratios (0.09 and 0.13) observed in this study would thus correspond to the ‘moderate’ and ‘good’ categories. The mean thresholds are higher than the SOC/clay ratio of 1:13 (0.08), which is considered a criterion for healthy soil in the current proposal for the Soil Monitoring Law. However, the uncertainty in the estimated thresholds is high, and the SOC/clay ratio of 1:13 (=0.08) falls within the 95% confidence interval for resilience and near the lower bound of the interval for productivity. Soinne et al. (2021) investigated the impact of SOC and soil texture on cereal yields in mineral soils of Finland. They discovered a notable positive linear correlation between the SOC/clay ratio and both grain yield and net nitrogen mineralization specifically in clay soils. However, the variation in yield levels and nitrogen use efficiency showed an increase at SOC/clay ratios below 1:15 (=0.07), indicating the emergence of growth limitations due to poor soil structure. In a previous study, Soinne et al. (2016) identified water saturation as particularly detrimental to aggregate stability in soils with SOC/clay ratios below 1:10 (=0.10). Schjønning et al. (2012) reported a similar threshold value for clay dispersibility in a Danish soil. This ratio aligns with the findings by Dexter et al. (2008), which also showed that SOC/clay ratio correlate better than total SOC with soil bulk density, water retention, and the presence of readily dispersible clay.

Consistent criterion for the SOC/clay ratio across all soil types, land covers, and climatic conditions may not accurately capture the soil health status in diverse European regions. For example, studies by Johannes et al. (2017) and Prout et al. (2021) were conducted in different environmental zones than the present study, although the study by Prout et al. (2021) aligns closely with present study in terms of soil texture and SOC content. The suitability of the SOC/clay ratio as an indicator in the first place has been questioned in studies e.g. by Poeplau and Don (2023), Mäkipää et al. (2024) and Rabot et al. (2024). Nonetheless, the present study demonstrated that the SOC/clay ratio is a feasible metric for the soil health condition in the inherently acidic and relatively weakly developed soils of Finland that are rather homogenous regarding mineralogy (Keskinen et al. 2022).

The reflectance of vegetation cover varies among crop species (Tittebrand et al. 2009). In this study, NDVI tended to be higher for temporary ley than for cereals. Furthermore, the NDVI values of cereals are likely more affected by poor growing conditions, such as drought or waterlogging, resulting higher interannual variation in NDVI and highlighting that cereals may be more sensitive for SOC/clay ratio than ley. This can be attributed to the fact that perennial grasses are known to have a deep and extensive root system (Jackson et al. 1996), making grass vegetation less sensitive to e.g extreme weather conditions. Furthermore, temporary ley usually consists of mixtures of several grass and legume species, ensuring that at least some of the plant species thrive under varying growing conditions. Despite the high uncertainty in ley results, a similar and consistent pattern in the association between NDVI and the SOC/clay ratio, as observed using data from all plots and plots growing cereals, indicates that the observed threshold values are applicable to various types of crops in boreal conditions. Approximately equal variability in NDVI values across the observed range of SOC/clay ratios, in turn, indicates that the SOC/clay ratio is a feasible metric for predicting crop productivity and resilience in soils with variable clay content levels.

The NDVI maps used in the study were constructed using aggregated median data from a relatively long time period, spanning from 25 June to 12 September. During this period ley is still in the vegetative growth stage, whereas cereals, depending on species, may have started ripening in August. The analysis could potentially be improved by using a shorter NDVI time frame or, alternatively, by identifying and utilizing the seasonal NDVI maximum, which would better capture the geographical variation in crop growth progression throughout the growing season—although this would come at the expense of reduced data accessibility and increased computational demands.

Boreal cropland soils are known to be rich in SOC compared to soils in central and southern Europe (Heikkinen et al. 2021). The low proportion of SOC-depleted soils in Finland increases the uncertainty in the estimated threshold for SOC/clay ratio, as the number of observations below the breakpoint is limited (concerns especially temporary ley, see Figs. 2e and 2f). This uncertainty could be reduced by simply adding more sampling plots to the NSM network. However, a more cost-effective approach for improving accuracy would be to increase the number of observations where the SOC/clay ratio is low. It is also important to emphasize that the presented thresholds are influenced by the depth at which soil samples are taken. In mineral soils, the SOC content declines with depth, meaning that deeper sampling is likely to yield lower estimated thresholds. Clay content in the soil profile also varies (Yli-Halla et al. 2000), although the vertical gradient is less distinct compared to SOC content. Ideally, soil samples should be collected from the root zone most critical to crop growth, as this would most likely also reduce uncertainty in the threshold estimates.

In this study, the area of interest was limited to the boreal region to ensure that the analyzed data was uniform with respect to continental-scale pedoclimatic conditions. Furthermore, the effect of crop plant was controlled by analyzing data for cereals and temporary ley separately. However, soil productivity is also influenced by several other highly variable management-dependent factors, such as soil hydrological conditions, fertilization strategies, and acidity, which were not included in this study. It is also important to note that the SOC/clay ratio and the factors affecting plant growth may exhibit geographical patterns, which might potentially have an influence on the results. The occurrence of sampling sites with low SOC/clay ratios is most common in the clay-rich soils of southern Finland (Lemola et al. 2018, see also Figs. S1, S2 and S3 in Supplement). At the same time, the distribution of farming and cropping systems across different parts of the country (Luke Statistics 2025) may influence e.g. nutrient status of the soil. Since farmers optimize fertilization and liming based on the needs of the crops, nutrient availability may not explain the observed geographical patterns. Information on the use of nitrogen, which is most often the limiting nutrient, or the amount of nitrogen in the soil are not available in the dataset used for the study. Thus accounting the possible impact of fertilization was not possible. Although the study area was confined to boreal zone, also smaller scale climatic gradients may exist within the zone. However, it is unlikely that climatic gradients explain the observed relationship between the SOC/clay ratio and NDVI, as low SOC/clay ratios are generally found in the climatically most favorable regions of southern Finland, where the accumulated temperature sum during the growing season is highest (Peltonen-Sainio et al. 2009). Nevertheless, it would be highly desirable to test the approach introduced in this study using data collected from different climatic and growing conditions to assess the applicability and consistency of the method. Finally, it should be noted that this analysis relied on NDVI data as a proxy for soil productivity. A more accurate and trustworthy assessment could be achieved using direct measurements of biomass or harvested yield—provided such data were available and covered a sufficient range of SOC/clay ratios.

Conclusion

In this study, we introduced a simple yet scientifically sound approach using easily accessible satellite-based seasonal NDVI data to determine the critical threshold value for the SOC/clay ratio along with uncertainty estimates, aiming to assess the health condition of the soil. While Finnish agricultural land served as a case study in this research, the method is easily applicable to various pedo-climatic regions and potentially to different land use types. Results of the study have also agronomic importance, proposing that elevating SOC content has a positive effect on soil productivity, benefiting both crop yields and the resilience of the cropping system.

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