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Soil Properties-Based Targeting of Soil Conditioners for Reduced Phosphorus Loading From Agriculture

Riikka Keskinen¹  | Helena Soinne²  | Risto Uusitalo¹  | Petri Ekholm³  | Timo A. Räsänen¹  |
Jaana Uusi-Kämppe¹  | Jenna Bergholm⁴  | Johanna Nikama¹  | Jari Hyväluoma¹ 

¹Natural Resources Institute Finland (Luke), Jokioinen, Finland | ²Natural Resources Institute Finland (Luke), Helsinki, Finland | ³Finnish Environment Institute, Helsinki, Finland | ⁴Southwest Finland Centre for Economic Development, Transport and the Environment, Turku, Finland

Correspondence: Riikka Keskinen (riikka.keskinen@luke.fi)

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ABSTRACT

Soil conditioning materials, gypsum, structure lime and pulp and paper mill sludges, have emerged as promising means to combat soil losses for protecting waterways. The mechanisms of impact vary between these materials, whereby the selection of the most efficient product depends on the soil type. In this paper, a soil-properties based selection method was developed for these three soil conditioners focusing on water quality impacts, specifically on particle associated phosphorus (P) losses that make the major share of the P transfer to the eutrophied Archipelago Sea. For targeting soil conditioner applications, a risk grading protocol identifying field parcels with the highest emission potential was formulated. The soil features considered in the risk grading were soil P status, aggregate stability, erosion potential, and typical soil management. In assessing the suitability of the individual soil conditioners, the soil properties considered were electrical conductivity (EC), pH, concentrations of exchangeable calcium (Ca) and magnesium (Mg), soil test P, clay percentage, organic carbon (C) content, and the ratio of clay/C. The method was applied in the Savijoki catchment in Southwest Finland mainly consisting of relatively flat, non-calcareous clay soils low in soil test P and high in clay/C ratios. Phosphorus emission risk in the area was estimated to be moderate though sporadic high-risk areas were identified. The applied selection criteria targeted fibres to 61%, structure lime to 29% and gypsum to 11% of the case study area. High clay/C ratio favoured fibres, whereas gypsum and structure lime were limited to soils with low EC. The proposed method provides means for farmers and advisors to select the most suitable soil conditioner for a given soil. For decision-makers, the method offers an instrument for policy recommendations serving, for example, in directing environmental subsidies. The method is applicable beyond the Archipelago Sea region though the suggested limit values need to be adjusted site-specifically.

1 | Introduction

Losses of nutrients from agricultural soils occur in surface runoff and subsurface flows either as dissolved forms or attached in suspended particulate material. The dominant transfer pathway depends on the nutrient, soil properties, and management practices (Mellander et al. 2012). For phosphorus (P), both surface

runoff and subsurface drainflow contribute to the transfer and the proportions of dissolved P (DP) and particulate P (PP) vary in time and space (Heathwaite and Dils 2000; Reid et al. 2018). As regards to PP, the losses are linked to the quantity of eroded soil material (Fraser et al. 1999). In the clay soil dominated regions in Southwest Finland, over 80% of the agricultural P losses occur as PP (Ekholm et al. 2024; Tattari et al. 2017), thus contributing

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Summary

- Unbiased means for targeting soil conditioners based on soil properties are lacking.
- A selection method with a principle focus of reducing soil and particulate phosphorus loss was developed.
- The method was used in distributing gypsum, structure lime, and wood fibres to a case study area.
- The proposed method is easily adjustable for different conditions.

significantly to the poor water quality of the Archipelago Sea which is by HELCOM listed as the only Finnish hot spot site in the Baltic Sea due to agricultural loading.

Traditionally, erosion control has been implemented by avoiding bare soil surface outside the growing season, which can be done by growing perennials, catch crops, or leaving plant residue cover (e.g., stubble or straw mulch) over winter (Gilley 2005). Some of these measures may cause income losses when growing annual crops; for example, if primary tillage is not possible in spring due to a short growing season. Permanently grassed pathways for runoff may fracture fields and take a part of the parcel out of production. In these cases, an alternative could be the application of amendments that stabilise soil (Garbowski et al. 2023). Furthermore, the above-mentioned traditional conservation practices may backfire when DP in runoff has an important role, as in cold regions experiencing snowmelt (Jarvie et al. 2017; Tiessen et al. 2010). Then inorganic amendments transforming DP to less readily soluble forms can be a better conservation approach (Kumaragamage et al. 2020). Of the vast range of soil conditioners, structure lime (Svanbäck et al. 2014), gypsum (Ekholm et al. 2024), and pulp and paper mill sludges (Rasa et al. 2021) are currently receiving wide interest among farmers and policymakers in Finland in search of effective and fast-acting water protection methods.

Structure lime is a mixture of ground limestone (CaCO_3) and quicklime and/or slaked lime (CaO or Ca(OH)_2 , respectively), the latter highly reactive part typically makes up 15%–25% of the product weight. It is promoted as a water protection measure to mitigate erosion and PP transport from fine-textured soils to surface waters (Svanbäck et al. 2014; Ulén and Etana 2014). Solubilisation of structure lime increases ionic strength and Ca^{2+} activity in soil solution resulting in less repulsion between negatively charged soil particles and enhanced flocculation of colloidal clay particles (Bell 1996; Cherian and Arnepalli 2015). Additionally, structure lime neutralises soil acidity, stimulating microbial activity (Curtin et al. 1998; Lalande et al. 2009), which contributes to soil aggregation and enhances structural stability (Lehmann et al. 2017). Improved aggregate stability can also result from increased soil productivity after reduced acidity as higher plant residue inputs support aggregation (Abiven et al. 2009; Amézketa 1999). On the other hand, liming and the resulting rise in pH may increase the solubility of soil organic matter (Curtin et al. 2016). In agricultural soils, structure lime applications of 5 up to 8 Mg ha⁻¹ in heavy clays are used (Berglund and Blomqvist 2015) which results in CaO or Ca(OH)_2 content of approximately 0.1–0.3 mass-% (assuming structure lime CaO

or Ca(OH)_2 content between 20% and 40%) when mixed within the topmost 10 cm. When used in stabilising problematic fine-textured soils in construction sites, high rates, 2%–10 mass-% of CaO or Ca(OH)_2 , are added (Al-Mukhtar et al. 2012; Bell 1996; Metelková et al. 2012). Then, soil pH may rise and remain above 12, which is required for pozzolanic reactions that contribute to long-term stabilisation (Bell 1996; Ouhadi et al. 2014). When available as a residue or a side product, quick lime can also be regarded as a nearly climate neutral material.

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is voluminously formed as a by-product in phosphoric acid production and in flue-gas desulfurization. In addition, it is a mineable mineral. Gypsum amendment of agricultural fields may offer a rapid cost-effective and socially acceptable measure to tackle both PP and DP load (Ekholm et al. 2012; Iho and Laukkanen 2012; Kosenius and Ollikainen 2019; Ollikainen et al. 2020). It has been found suitable for large field areas and does not interfere with farming practices, decrease the area of arable land, or negatively affect crop yield (Kauppila and Pietola 2013; Kost et al. 2018). Gypsum can decrease not only the losses of P (Anderson et al. 1995; Aura et al. 2006; Mao et al. 2023; Pietola 2008; Zhu and Alva 1994) but also those of dissolved organic carbon (DOC) (Uusitalo et al. 2012; Varcoe et al. 2010). The reduction in DP has been attributed to stronger adsorption of P promoted by increased ionic strength brought about by divalent Ca^{2+} and SO_4^{2-} ions (Uusitalo et al. 2012; Yli-Halla and Hartikainen 1996). Decrease in PP mobility occurs, similar to structure lime, due to microaggregation of soil particles by increased ionic strength (Uusitalo et al. 2012) and possibly by Ca bridges. In turn, DOC reduction may involve reactions related to Ca mediated stabilisation and complexation of organic molecules (Inagaki et al. 2017; Tavakkoli et al. 2022; Uusitalo et al. 2012). Finally, gypsum can exert an indirect effect on P and DOC losses by improving soil structure, increasing infiltration, and enhancing water retention (Kauppila and Pietola 2013; King et al. 2016; Shainberg et al. 1989; Truman et al. 2010).

Pulp and paper mill sludges (hereafter referred to as fibres) are formed in the wastewater treatment processes of the pulp and paper industry. Their characteristics depend on the source material as well as on the process conditions (e.g., Rasa et al. 2021). Primary sludges derived from clarification of pulp and paper mill effluent have a high C to N ratio and consist mainly of cellulose fibres while secondary sludges undergo biological wastewater treatment processes with nutrient additions to curb dissolved C load in effluent (Turner et al. 2022), and are subsequently sanitised by composting or lime stabilisation. When fibre materials are added to soil, they enhance biological activity (Chantigny et al. 2000; Kinnula et al. 2024; Rätty et al. 2023) and undergo microbial decomposition that produces gums that, in turn, stabilise soil aggregates (Rasa et al. 2021). As a result of fibre amendments, Rasa et al. (2021) found a clear increase in soil fungi, such as *Tetracladium marchalianum* (DeWild.), that are considered efficiently promoting soil particle aggregation (Lehmann et al. 2020). Furthermore, Rasa et al. (2024) found that a one-time large fibre addition led to an increase in soil macroporosity, which remained detectable five years after application. An increase in macroporosity can improve soil aeration and enhance infiltration, thereby reducing the risk of surface runoff and erosion. Although the added fibre materials decompose relatively rapidly and only

a fraction of the added 8 Mg of C was recovered in soil after 4 years, Rasa et al. (2021) found that soil amended with fibre material exhibited reduced detachment of soil particles compared to untreated control soil during the whole 4-year study period. This demonstrates improved aggregate stability and reduced risk of nutrient losses from fibre-treated soil over several years.

For ensuring efficient and sustainable use of resources, allocation of the soil conditioning materials needs to be targeted most beneficially. Indices evaluating the susceptibility of a given field for P loss can be determined based on the field characteristics and used in generating regional rankings according to potential P pollution risk (Heckrath et al. 2008; Lemunyon and Gilbert 1993). Major factors influencing erosion and the loss of P to waterways include soil texture and P status, slope, runoff and drainage, connectivity to streams, tillage, vegetation cover and P applications (Bechmann et al. 2009; Sharpley et al. 2001).

In addition to defining the critical areas most in need of betterment, the amendment material most suitable for the site needs to be identified (Mulyono et al. 2022). In this selection, not only the environmental effectiveness of the measure, but any possible negative side effects for crop productivity must be considered. In addition to the costs for purchase, transport and application of the amendments, the amounts of available, climate neutral quick lime and fibres are limited. Hence, their use is to be optimised.

Different soil conditioners have partly similar and partly differing mechanisms and impacts on the soil properties as detailed above, whereby the selection of the best product for a given soil is not indifferent. The suitability of products may also depend on the goal of the soil improvement, for example, whether the aim is to enhance plant growth or reduce nutrient leaching. Also, the desired effect of amending a soil may depend on the soil type, for example, clay soils may benefit from improved aggregation and

coarser soils from increased water and nutrient retention. Most research on structure lime, gypsum, or fibres has thus far focused on one of the soil conditioners and one soil type at a time, which complicates the development of good criteria and methods for the selection of the best-fit soil conditioner. In the present work, an attempt is made to develop a method of selection among these materials. The method is tested in a case study area located in Southwest Finland. It is formulated in a generic form to allow inclusion or exclusion of criteria and adjustment of the limit values as new results on the impacts of soil amendments emerge or the method is adapted to other geographical and climatic regions with different conditions and criteria needs.

2 | Materials and Methods

2.1 | Case Study Area Description

The case study area (17.7 km²) was located in the middle reaches of the River Savijoki (Figure 1). The ecological state of the River Savijoki is poor, the second lowest category in the 5-level national classification based on the Water Framework Directive (Directive 2000/60/EC). The catchment of the River Savijoki covers a landscape typical of the Archipelago Sea drainage basin. The hills consist of bare outcrops or bedrock thinly covered by moraine and are largely forested, whereas the valleys have several metres of deep clay deposits and are mostly in agricultural use. In the case study area, arable fields covered 50% of the land area, forests on mineral soils 42% and semi-urban areas 8%. Of the field area, 75% were clay soils (Vertic Luvisol Stagnosols; Lilja et al. 2009) and the mean slope was 2.4% (Ekholm et al. 2024).

The case study area is in the warm-summer humid continental climatic region. For the meteorological period 1991–2020, according to the long-term averages from the weather station of the Finnish Meteorological Institute located ca. 20 km to west

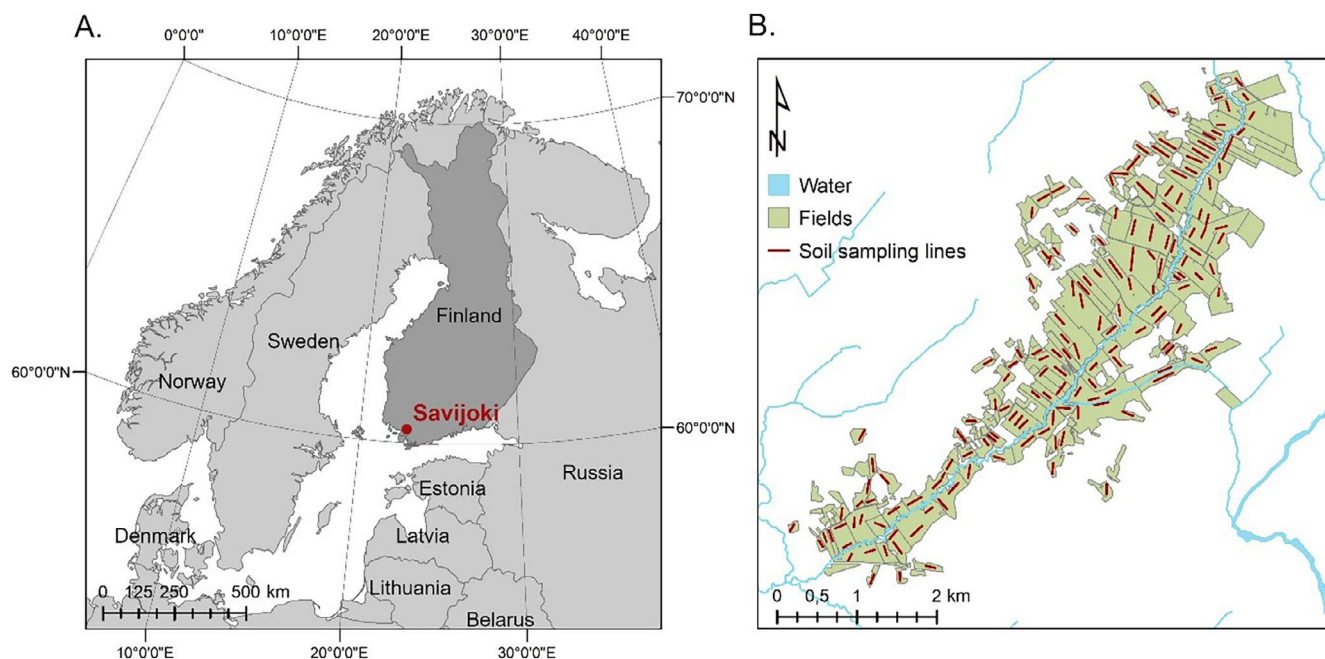


FIGURE 1 | A. The location of Savijoki and B. the fields with soil sampling lines of the case study area (60.569° N, 22.644° E; country borders: ESRI, ArcGIS Hub; field borders: Finnish Food Authority; rivers: Finnish Environment Institute).

from the area, the annual mean precipitation was 684 mm and the annual mean temperature 5.8°C (Jokinen et al. 2021). The highest monthly average temperature was 17.5°C in June and the lowest -4.5°C in February. The average snow depth was highest at the end of February (15 cm).

The study area lacks field- or plot-scale measurements of erosion rates. However, measurements from other agricultural fields and experimental plots in Finland have shown long-term average erosion rates ranging from less than 100 to over 2000 kg ha⁻¹ yr⁻¹, with annual rates occasionally exceeding 7000 kg ha⁻¹ yr⁻¹ (Räsänen et al. 2023; Räsänen 2024). On a European scale, erosion rates in Finland are considered relatively low (Panagos et al. 2015), yet they still cause significant harm to surface waters and aquatic ecosystems in the northern boreal conditions through soil-bound P loading, high suspended sediment concentrations, and siltation (Hietala et al. 2023; Ulén et al. 2012; Uusitalo et al. 2001).

Due to the humid climatic conditions, the fields in the study area are efficiently drained by artificial subsurface drainage systems and open ditches. High hydrological connectivity to surface waters provides direct pathways for nutrients and sediments to enter streams, rivers, and ultimately the Archipelago Sea (Honkanen et al. 2021; Tähtikarhu et al. 2022; Uusitalo et al. 2018, 2001).

2.2 | Soil Sampling and Analyses

With the permission of the 20 farms operating in the case study area, a survey on the soil properties was implemented. In total, 165 sampling lines were placed on large scale maps to ensure representative coverage of the area (Figure 1B). The size of the field affected the number of sampling lines drafted for a particular parcel so that to the largest parcels up to four lines were drawn. The sampling was carried out on 126 field parcels. The sampling crews navigated to the sampling locations using the preliminary maps, walked along the specified line, and cored (evenly spaced) a minimum of 15 subsamples at 0–15 cm depth with a 19-mm diameter auger. The subsamples were thoroughly mixed to form one composite sample *per* line. In addition, three 200 cm³ cylinders of soil were taken along the line from the 0–5 cm surface layer and gently emptied by hand to form one composite sample for soil structural stability assessment. The coordinates of the start and end points of each line were recorded with a precision GPS. The length of the sampled lines ranged from 70 to 288 m (median 131 m).

The composite coring line samples were sent to an accredited soil laboratory (Eurofins Viljavuuspalvelu Oy) for advisory soil testing and textural analysis. Nutrients were analysed according to the protocol outlined in Vuorinen and Mäkitie (1955), which is the

standardised soil testing method in Finland. Shortly, air-dried and ground (<2 mm) soil is shaken end-over-end for 1 h in 0.5 M ammonium acetate-acidic acid solution (pH 4.65) at 1:10 volumetric soil-to-solution ratio. The suspension is then passed through a paper filter and the supernatant analysed for Ca, Mg, K, P and S. Soil pH and electrical conductivity (EC) were measured in 1:2.5 (vol/vol) soil-water suspensions. Soil particle size distribution was determined based on sieving and sedimentation as in Elonen (1971).

In addition, subsamples were analysed for total C (Leco Tru Mac Macro analyser) in Luke's soil laboratory in Jokioinen, where soil aggregate stability was also tested according to the modified procedure of Soenne et al. (2016). In brief, soil samples were sieved (<5 mm) and after air-drying, 4-g subsamples were subjected to wet-sieving using Eijkelkamp 08.13 apparatus equipped with eight 0.25 mm mesh size sieves. Sieves were immersed for 15 min in cups with 100 mL of deionised water, which was then, together with detached soil material, transferred into a centrifuge tube. The suspension was allowed to settle for 21 h, after which samples (30 mL) for turbidity analysis were pipetted from the surface of the water column. Turbidity was measured using a HACH 2100AN IS turbidimeter (Hach Company).

2.3 | Identification of Critical Areas

For all the sampled field parcels in the case study area, the severity of risk for strain on the waterways was assessed on a scale of 0 to 3, where 0 was assigned for negligible risk with no soil conditioning need, 1 for minor risk, with soil conditioning benefits in improved productivity, 2 for moderate risk, with soil conditioning benefits in water protection and 3 for a hot spot especially needing soil conditioning. The soil features considered in the risk grading were soil test P concentration (STP), structural stability, erosion potential, and management (tillage) practices. The risk grading developed is designed to be applied also outside the case study area, with a structure resembling that of the P index of Lemunyon and Gilbert (1993) and the many versions that have followed.

The risk grade limits for soil STP presented in Table 1 were set based on expert judgement guided by the meta-analyses by Valkama et al. (2015, 2009) that evaluated the likelihood of yield responses to annual P fertilisation. Soluble P concentrations in runoff waters increase linearly with ammonium acetate-acetic acid STP (see Withers et al. 2019 who used a dataset with acetate STP data from Southwest Finland) without any 'change-points' that would tell about steeply increasing P loss risks. In lack of such obvious indication of elevated DP loss risk, the cut-off value (in Table 1) between moderate and high risk grades was set at 2–3 times the STP concentration when yield responses become unlikely (Valkama et al. 2009).

TABLE 1 | Risk grade limits set for selected soil features.

Risk grade	STP (mg L ⁻¹)	NTU	Erosion potential (kg ha ⁻¹ yr ⁻¹)	Land management/tillage
0 negligible	<1.5	<2	<100	Not managed (natural state)
1 minor	1.5–6	2–10	100–300	Permanent perennial vegetation
2 moderate	6–20	10–20	300–4000	No-till or spring tillage
3 hot spot	>20	>20	>4000	Regular autumn tillage

Soil structural stability was graded based on turbidity caused by fine soil material detached from air dried aggregates during wet sieving (Soenne et al. 2016, see Section 2.2). The grade limits in Nephelometric Turbidity Units (NTU) were estimated based on studies by Soenne et al. (2023, 2016) (Table 1).

Susceptibility of the field parcels to water erosion was evaluated using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997). Estimates of long-term mean erosion potential in kg ha⁻¹yr⁻¹ were determined for each target field parcel using existing RUSLE data for rainfall-runoff erosivity (R-factor), soil erodibility (K-factor), and the slope length and steepness (LS-factor), which were available at a 2 m × 2 m grid resolution (Räsänen et al. 2023). Erosion potential was defined as the erosion rate under spring cereal crop and autumn ploughing that were assumed for all field areas in the cover and management factor (C-factor). Thus, the estimated erosion indicates potential erosion rather than actual values in practice. This approach ensured comparability between fields. The average R-factor value for the study area was 382 MJ mm ha⁻¹Mg⁻¹yr⁻¹, the K-factor value for the dominant Vertic Luvisc Stagnosol was 0.04 Mg ha h ha⁻¹MJ⁻¹mm⁻¹, and the average LS-factor value was 0.45. A C-factor value of 0.21 was used for spring cereal crop and autumn ploughing (Räsänen et al. 2023). Possible artificial sub-surface drainage was not considered in the support practice factor (P-factor) due to limited data. The resulting erosion data primarily reflect variations in erosion potential due to the effects of slope length and steepness (LS-factor), as the R-factor value showed very little variation in the small case study area, the soil data were dominated by a single soil type, and crop and management practices were parameterized uniformly across all fields. The erosion potential rates were given risk grade limits presented in Table 1 and adapted from Withers et al. (2019).

The farmers were queried for the prevailing soil management status. Field parcels set aside in their natural state were considered of negligible risk and those under permanent perennial vegetation of minor risk. For fields primarily under annual crops, the timing and intensity of soil tillage were considered to govern the severity of risk for emissions into waterways (Table 1). Here, no-till was associated with lower risk than soil surface breaking operations that are regularly conducted in fall as delayed spring sowing typically means yield losses.

An overall risk index score was calculated as a weighted sum of the four individual values using weighting factors of 30% for the soil STP and NTU, and 20% for erosion potential and land management. The weights were based on expert estimation and their sensitivity to the overall score was tested by determining the score also by giving a 40% weight for one of the features at a time, while setting the weight of all the others to 20% (the cases with 40% weight for STP, NTU, RUSLE and land management are referred to as scenarios 1–4, respectively).

2.4 | Criteria for Amendment Material Selection

The criteria specifying the suitability of the three soil amendments for a given soil were formulated by expert judgement. The formulation was based on identified mechanisms of action of the products and selected soil properties (Tables 2 and 3). Management

TABLE 2 | Exclusion criteria for gypsum, structure lime and fibres.

Conditioner, α	Soil property, β	Clay%	Exclusion $E_{\alpha} = 0$, if
Gypsum	pH ^a		< 5.5
	Mg (mg L ⁻¹ soil) ^b	> 30	< 150
		< 30	< 80
	Ca (mg L ⁻¹ soil) ^b	> 30	> 5600
		< 30	> 4000
	Structure lime	Clay (%)	< 15
	Mg (mg L ⁻¹ soil) ^b	> 30	< 150
		< 30	< 80
	Ca (mg L ⁻¹ soil) ^b	> 30	> 5600
		< 30	> 4000
	Fibre	Clay/C	> 15
		C (%) ^c	< 15
	STP (mg L ⁻¹ soil) ^b	> 30	> 23
		< 30	> 30

^a1:2.5 soil-water suspension.

^bAcid ammonium acetate extraction (see 2.2).

^cTotal organic C by dry combustion.

factors such as costs and availability were excluded from the criteria. The emphasis was on water quality protection, but exclusionary boundaries were set to prevent any deleterious effects on soil productivity. The selection of exclusion criteria was mostly based on the limits of fertilisation recommendations used in Finland to avoid transfer to fertility classes ‘poor’ or ‘fairly poor’. Otherwise, a sliding scale of suitability for each material-specific key factor was defined from the level below or above which no beneficial effects would be expected (0) to the level above or below which the treatment would yield maximal benefits (1). These individual index values were given weighting factors according to their conceivable significance. Finally, an integrated suitability index was obtained by summing up the weighted individual indices. Rationale for the individual index values is presented in the following paragraphs for each of the soil conditioners. A calculation method for obtaining the integrated suitability index is described in Section 2.5.

In assessing the suitability of gypsum as a soil amendment, the soil properties considered significant were electrical conductivity (EC), pH, and contents of exchangeable Ca and Mg (Tables 2 and 3). As the effectiveness of gypsum is based on the increased ionic strength of the soil solution, it is most suitable for soils exhibiting low electrical conductivity, that is, soils low in soluble salts. Previous data (Uusitalo et al. 2012) have shown the effect of gypsum to wear out at ECs exceeding 175 μ S cm⁻¹. Because the abundant addition of Ca in gypsum treatment causes desorption and subsequent leaching of Mg (Uusitalo et al. 2012), the treatment is not advantageous for soils low in Mg or prominently enriched in Ca. Furthermore, gypsum treatment may cause a transient reduction in soil pH (Yli-Halla et al. 2023), wherefore its application on acidic soils should be avoided to prevent negative effects on crop growth and soil biology.

TABLE 3 | Parameters used in the selection method.

Conditioner, α	Soil property, β	Clay%	Lower breakpoint $L_{\alpha\beta}$	Upper breakpoint $U_{\alpha\beta}$	Function type in $P_{\alpha\beta}$	Weight $w_{\alpha\beta}$
Gypsum	EC ($\mu\text{S cm}^{-1}$) ^a		75	175	P_d	0.65
	Mg ($\text{mg L}^{-1}\text{soil}$) ^b	> 30	300	500	P_i	0.25
		< 30	150	300	P_i	
	Ca ($\text{mg L}^{-1}\text{soil}$) ^b	> 30	2000	3600	P_d	0.05
		< 30	1400	2600	P_d	
	pH ¹		5.5	6.0	P_i	0.05
Structure lime	EC ($\mu\text{S cm}^{-1}$) ^a		75	175	P_d	0.65
	pH ¹		6	6.5	P_d	0.2
	STP ($\text{mg L}^{-1}\text{soil}$) ^b		10	15	P_d	0.1
	C (%) ^c		1.7	3.5	P_d	0.05
Fibre	Clay/C	> 15	10	15	P_i	0.65
		< 15	1.7	3.5	P_d	
	STP ($\text{mg L}^{-1}\text{soil}$) ^b	> 30	10	20	P_d	0.25
		< 30	6	15	P_d	
	EC ($\mu\text{S cm}^{-1}$) ^a		75	100	P_d	0.1

^a1:2.5 soil-water suspension.

^bAcid ammonium acetate extraction (see 2.2).

^cTotal organic C by dry combustion.

The key soil attributes identified to dictate the applicability of structure lime were clay content, exchangeable Ca and Mg, STP, EC, pH, and organic C (Tables 2 and 3). As increased soil aggregation and aggregate stability through increased flocculation and binding action is the main effect of the treatment, it is not ideal for soils too low in clay for aggregate formation. In field conditions, aggregate formation is common in soils with > 15% clay content (Horn et al. 1994). The restrictions concerning EC, Ca and Mg are similar to those outlined with gypsum, whereas the effect on pH is the opposite, structure liming being beneficial for acidic soils (Li et al. 2019; Nyström et al. 2023). Excessive alkalinity should, however, not be sought at the expense of decreased micronutrient availability (Blomquist et al. 2018; Tyler and Olsson 2001). Increase in soil pH increases the solubility of P (Hartikainen 1981; Shang et al. 1992) and organic matter (Curtin et al. 2016); wherefore the treatment is not recommended for soils excessive in STP or enriched in organic matter.

The soil properties considered decisive in determining the suitability of wood fibre amendment were clay/C ratio in soils containing more than 15% clay in the mineral fraction, organic C content in coarser textured soils, and STP and EC in all soil types (Tables 2 and 3). In fine-textured soils, formation of organo-mineral associations between the clay sized mineral particles and organic matter creates and strengthens the aggregate structure (Totsche et al. 2018). The higher the soil clay content, the more organic compounds are needed for efficient complexation (Dexter et al. 2008; Soenne et al. 2016). According to the studies of Johannes et al. (2017) and Prout et al. (2021), clay to organic C ratio of 8 or smaller is optimal for soil structural quality,

whereas a ratio exceeding 13 indicates structural instability. For coarser soils, clay/C ratio may not be meaningful, but organic inputs may provide other benefits such as increased CEC, N use efficiency, and water retention (Räty et al. 2023, 2021; Soenne et al. 2021). Since the fibres tend to contain some P (Turner et al. 2022) and, in principle, the treatment may enhance the mobility of P through exchange reactions between added organic molecules and orthophosphate sorbed on soil particles (Hunt et al. 2007), it is not optimal for soils high in STP. In comparison to gypsum or structure lime, the importance of EC is less for the wood fibres, but the parameter was, nevertheless, included in the criteria with a small weight to increase the separating capability of the selection method.

2.5 | Selection Method

The developed selection method is based on a 'goodness' function g_α , which describes how well the soil conditioner α is considered to suit a given soil. The values of g_α are bound between values 0 and 1, corresponding to a fully unsuitable and best-fit conditioner, respectively. Here, we write the goodness function in a generic form,

$$g_\alpha = E_\alpha \sum_{\beta} w_{\alpha\beta} P_{\alpha\beta}$$

where the weight factors for conditioner α are normalised as

$$\sum_{\beta} w_{\alpha\beta} = 1$$

Above, index β refers to those soil properties that are considered for the conditioner in question. The factor E_α is used to exclude the conditioner α if any of the set exclusion criteria are fulfilled, that is,

$$E_\alpha = \begin{cases} 0, & \text{if any exclusion criterium is fulfilled} \\ 1, & \text{otherwise} \end{cases}$$

Function $P_{\alpha\beta}$ is defined as a piecewise linear function, which is either an increasing or decreasing function depending on the soil property and conditioner. $P_{\alpha\beta}$ is confined between values 0 and 1, where the former is for a fully compatible and the latter for a fully incompatible soil conditioner for the soil property β . The decreasing function is defined as

$$p_d(\beta, U_{\alpha\beta}, L_{\alpha\beta}) = \begin{cases} 0, & \beta > U_{\alpha\beta} \\ 1, & \beta < L_{\alpha\beta} \\ \frac{U_{\alpha\beta} - \beta}{U_{\alpha\beta} - L_{\alpha\beta}}, & \text{otherwise} \end{cases}$$

The breakpoint values $U_{\alpha\beta}$ and $L_{\alpha\beta}$ are defined for each conditioner and soil property separately. Similarly, the increasing function is defined as

$$p_i(\beta, U_{\alpha\beta}, L_{\alpha\beta}) = \begin{cases} 1, & \beta > U_{\alpha\beta} \\ 0, & \beta < L_{\alpha\beta} \\ \frac{\beta - L_{\alpha\beta}}{U_{\alpha\beta} - L_{\alpha\beta}}, & \text{otherwise} \end{cases}$$

The model parameter values selected for the soil conditioner and soil properties considered in the present work are given in Tables 2 and 3. Note that for some cases parameter values are defined differently for fine and coarse textured soils (defined by clay content).

3 | Results

3.1 | Soil Properties in the Case Study Area

The histograms of the soil properties obtained through the soil sampling and analyses are shown in Figure 2. In the sampling lines, the clay content varied from 6% to 61% with a median value of 43%, whilst 80% of the samples had clay content over 30%, showing that the case study area mainly consists of clay fields. The organic carbon contents varied between 1.3% and 5.5% with a median of 2.6%, and the clay/C ratio ranged from 2.9 to 28, with a median of 15. As 72% of the samples had a clay/C ratio exceeding 13, the organic matter contents can be considered low regarding

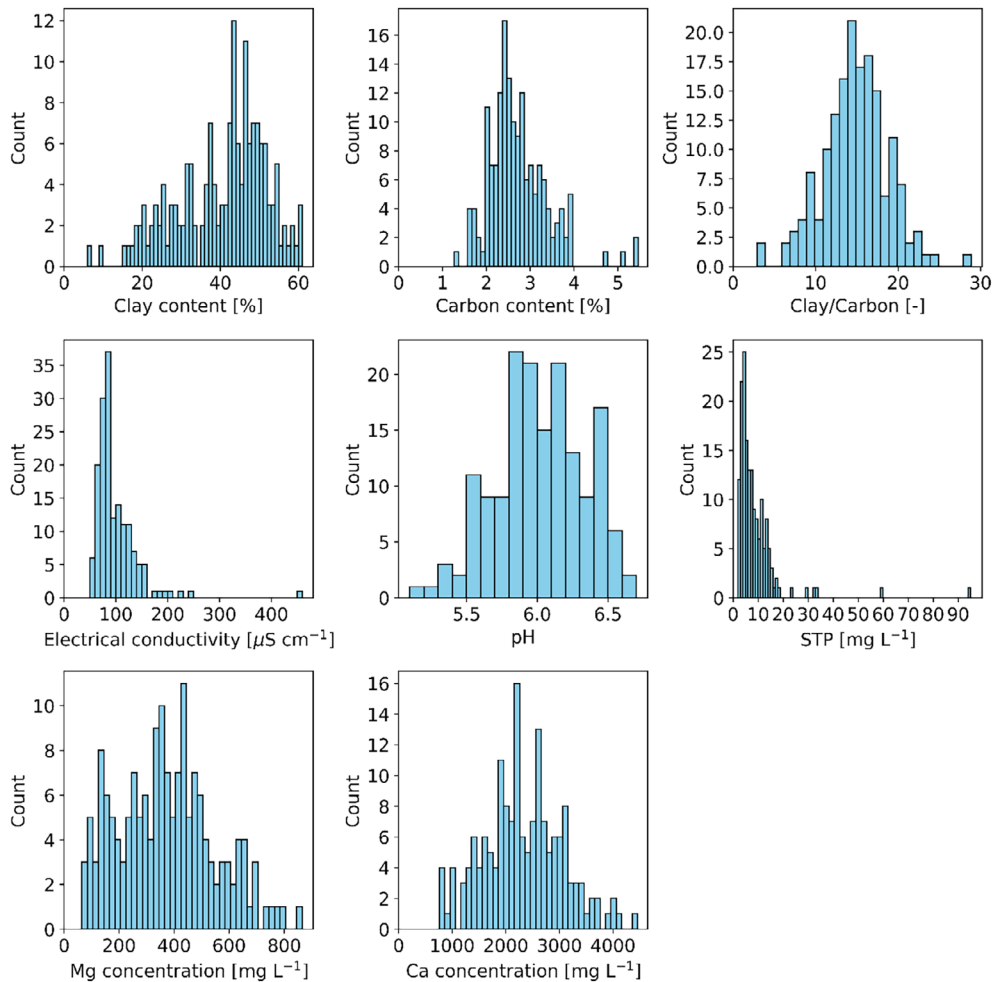


FIGURE 2 | Histograms of soil properties in the case study area ($n = 165$).

the high clay content in the case study area. The electric conductivity varied between 50 and 460 $\mu\text{S cm}^{-1}$ with a median of 80 $\mu\text{S cm}^{-1}$. Electrical conductivities can also be considered to be on a low level, as 34% of samples had EC below 75 $\mu\text{S cm}^{-1}$ and only 4% above 175 $\mu\text{S cm}^{-1}$. Soil pH varied between 5.1 and 6.7, with a median value of 6.0. Values of STP were between 1.9 and 94 mgL^{-1} soil, with a median of 6.4 and a positively skewed distribution that indicates the presence of potential P loss hotspots despite the generally moderate STP levels. Soil Mg concentrations varied between 65 and 860 mgL^{-1} with a median of 310 mgL^{-1} , and 14% of the samples were below the value of 150 mgL^{-1} soil, which for clay soils was set to prevent the use of gypsum and structure lime. Calcium concentrations varied between 760 and 4400 mgL^{-1} soil, with a median of 2200 mgL^{-1} , that is, the Ca levels in all fields were under the gypsum and structure lime exclusion criteria set for Ca.

3.2 | Occurrence of Risk Areas

The risk grades were determined for four factors considered (STP value, NTU value from wet sieving, erosion potential from RUSLE and land use, Table 1). For the case study area, the distributions of risk grades are shown in Table 4. Regarding NTU and RUSLE, most fields had risk grade 2 indicating moderate erosion risk. Considering the STP values, most were in risk classes 1 and 2, whereas land use indicated elevated erosion risk.

RUSLE analysis revealed how the spatial distribution of erosion risk varies according to terrain topography (Figure 3). High-erosion areas were predominantly located within 60m of rivers and streams and, in some cases, in the middle of field parcels where surface runoff concentrated. The RUSLE estimated erosion potential within 60 m of rivers and streams was 5320 $\text{kg ha}^{-1}\text{yr}^{-1}$, compared to 1420 $\text{kg ha}^{-1}\text{yr}^{-1}$ across all field areas. Field areas within the 60 m riparian zone accounted for 46% (555 Mgyr^{-1}) of the total erosion (1210 Mgyr^{-1}) in the case study area, despite comprising only 17% of the total field area. On field parcel scale, the estimated erosion varied between 100 and 14,670 $\text{kg ha}^{-1}\text{yr}^{-1}$. The spatial distribution of high-erosion areas is largely explained by the steep slopes near rivers and streams. Otherwise, the fields are relatively flat. Thus, while the average of the case study area indicates risk grade 2 (moderate risk) the steeper slopes near the river are hot spot areas according to the selected grading.

3.3 | Allocation of the Soil Conditioning Materials According to the Selection Criteria

The selection criteria and the soil properties in the case study area resulted in uneven allocation of the soil conditioners so

TABLE 4 | Distribution of risk grades for the four considered erosion risk factors.

Risk grade	NTU	RUSLE	Land use	STP
0	2%	0%	0%	0%
1	14%	8%	13%	48%
2	72%	86%	36%	48%
3	11%	6%	52%	4%

that fibres, structure lime and gypsum were targeted for 471 ha (61%), 221 ha (29%) and 82 ha (11%) of the field area, respectively. Even though the treatments would be targeted only to the fields with the highest risk grade, the distribution would not change notably (Figure 4). Examples of the treatment areas in the catchment, if only the field parcels with risk grade exceeding a given limit were treated, are given for each soil conditioner in Table 5, together with amounts of conditioners needed for the treatments

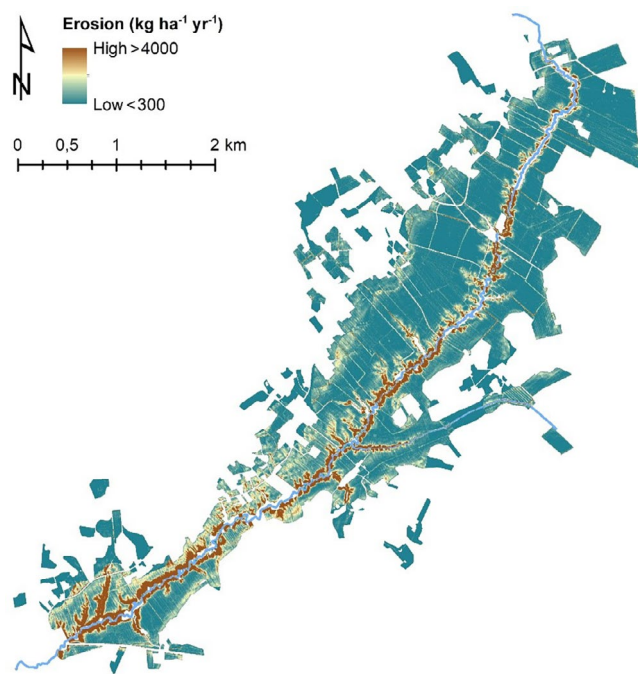


FIGURE 3 | Estimated erosion potential in 2m \times 2m grid resolution in the case study area fields according to RUSLE. Hotspot risk areas are shown with dark brown colours (grade 3: $> 4000 \text{ kg ha}^{-1}\text{yr}^{-1}$), negligible and minor risk areas with dark green colours (grades 0 and 1: $< 300 \text{ kg ha}^{-1}\text{yr}^{-1}$), and moderate risk areas with colours in between (grade 2: $300\text{--}4000 \text{ kg ha}^{-1}\text{yr}^{-1}$) (Table 1).

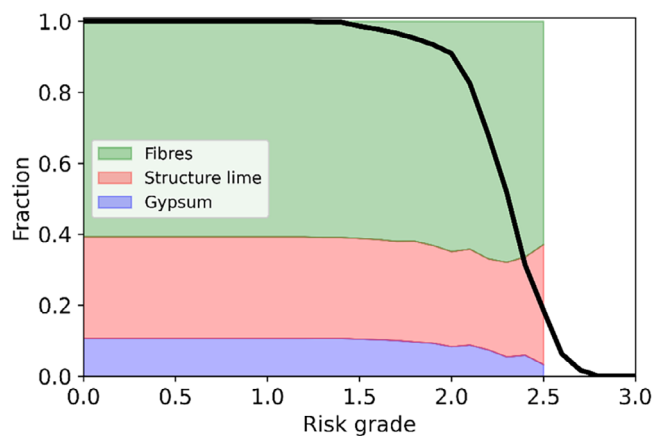


FIGURE 4 | Normalised cumulative histogram of risk grade (fraction of field area with risk grades greater than a particular grade). Colour coding shows the distribution of the case study field area for the three soil conditioners when fields with risk grade exceeding the particular risk grade are treated. For risk grades ≥ 2.6 , none of the fields are treated with gypsum.

assuming typical treatment levels of 4, 5 and 30Mg ha⁻¹ for gypsum, structure lime, and fibres, respectively.

The distributions of soil conditioners considering the four selected soil properties are shown as stacked histograms in Figure 5. The distributions indicate that the clay/C ratio had a clear effect on conditioner selection so that fibre amendment is predominant for soils with a clay/C ratio exceeding 15. At the

same time, gypsum and structure lime were primarily selected for soils with a lower clay/C ratio. Regarding the EC, the selection of gypsum and structure lime was limited to soils with a low EC value whereby fields with fibres as the primarily selected conditioner have a more even distribution of EC. STP concentration and pH, in turn, did not have an equally clear effect on the selected soil conditioner even though gypsum was mostly allotted to low-P fields.

TABLE 5 | Treatment areas and needed amounts of soil conditioners in cases where only case study area fields with risk grades exceeding a given limit are treated. The amounts were calculated using treatment levels of 4, 5, and 30Mg ha⁻¹ for gypsum, structure lime, and fibres, respectively.

Risk grade	Area [ha]			Amount [Mg]		
	Gypsum	Structure lime	Fibres	Gypsum	Structure lime	Fibres
> 2.5	5	49	91	20	245	2730
> 2.2	39	135	353	156	675	10,590
> 2.0	59	188	457	236	940	13,710
> 1.5	80	216	468	320	1080	14,040
> 0	82	221	471	328	1105	14,130

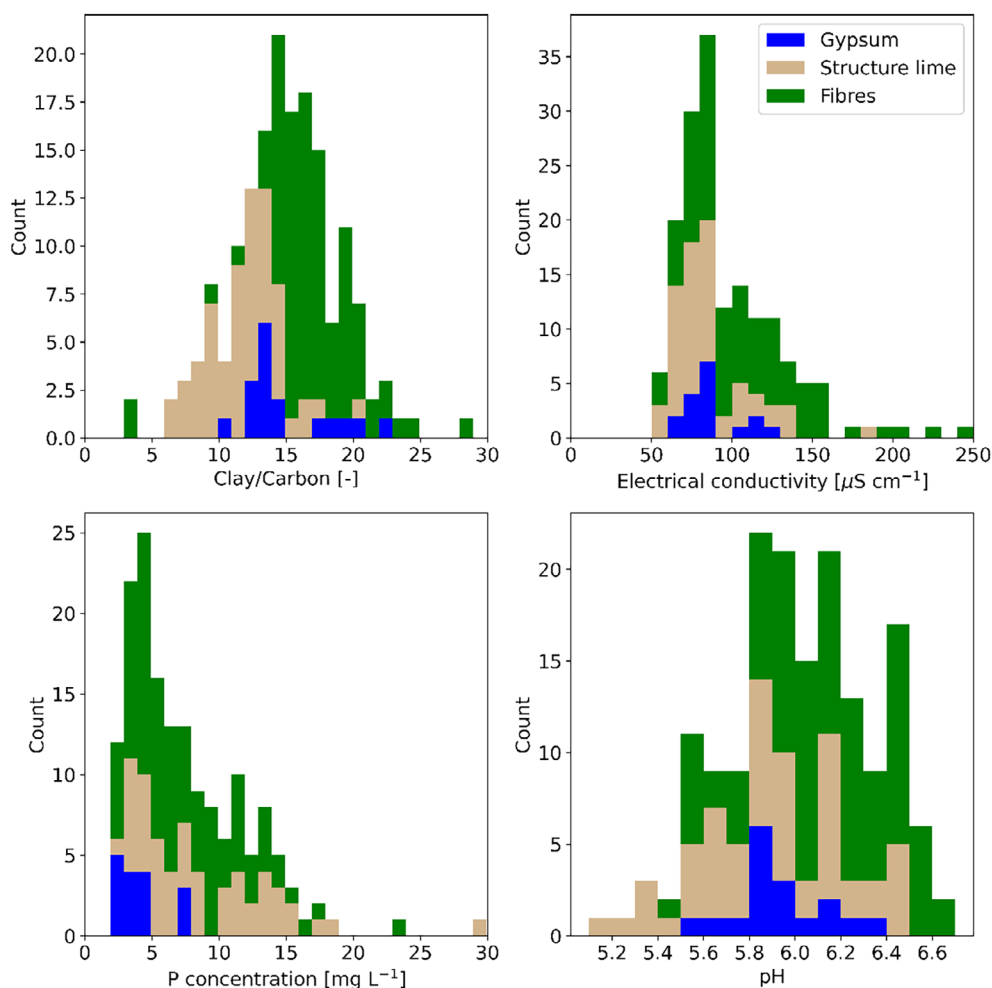


FIGURE 5 | The distribution of four selected soil properties for the three soil conditioners. Due to tailed distributions, the sampling lines with P concentration > 30 mg L⁻¹ (one line allocated to gypsum (5 ha) and three lines (in total 8 ha) to structure lime) are not visible in the histogram, as well as one line with electrical conductivity 460 μS cm⁻¹ allocated to fibres (7 ha).

3.4 | Sensitivity Analysis

Sensitivity of the risk classification was tested by determining the risk classes with five sets of weight factors defined in Section 2.3 (expert estimation and scenarios 1–4). The risk classification turned out to be fairly insensitive to the selection of the weight factors as all four alternative scenarios had only minor impact on the risk class in comparison to the ‘expert estimation’ scenario as shown in Figure 6.

The sensitivity of the goodness function on the values used for weight factors $w_{\alpha\beta}$ was tested by considering two additional sets of weights in addition to those given in Table 4. In the set of weights used in the actual computations, the ‘main factor’ had a weight of 0.65 and the ‘minor factors’ shared the remainder weight of 0.35. Two alternative parameter sets were considered to test the sensitivity of the model to the selected weights. In the first alternative scenario, the main factor had a weight of 0.80, and in the second scenario, this weight was 0.50. The weights used in the two parametrizations are given in Table S1. When using scenario 1, the recommendation for soil conditioner was changed in 7% of the fields, and with scenario 2, the recommendation changed in 5% of the fields.

4 | Discussion

4.1 | Availability of the Input Data

For the developed method to be usable in practice, the input data needs to be easily available (Bechmann et al. 2009). The existence, coverage and quality of soil information, and the access to this information, varies greatly between countries (Cornu et al. 2023). Therefore, the features included, and their limit values, need to be set site-specifically. In Finland, majority of the farmers (86% of active farms in 2018) conduct regular soil testing every fifth year (Finlex 2023; Hyvönen et al. 2020). Consequently, soil testing data (EC, pH, Mg, Ca and STP) included in the present selection method do exist from nearly all field parcels, but the geolocation of these data is only accessible for farmers (community level distributions are published at intervals), for example, Lemola et al. (2023, 2018).

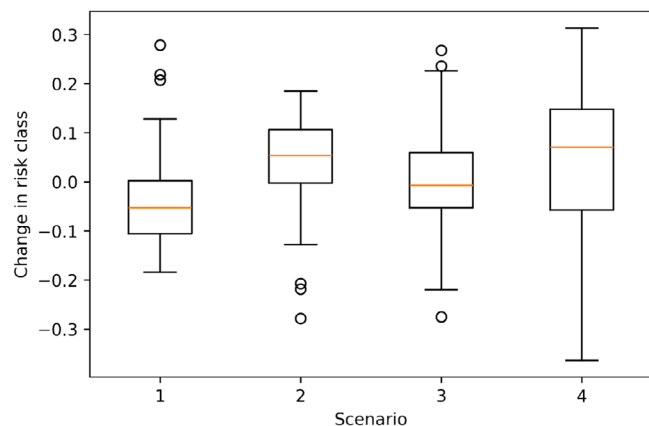


FIGURE 6 | The change in risk class in different weighting factor scenarios from the expert estimation set to the soil conditioner selection method.

Currently, the organic matter content of the tested soils is assessed by feel, but C measurements are rapidly emerging. Direct measurement of soil particle size distribution (clay content) is too costly for routine use, but a reasonable estimate for clay soils can be calculated from the basic soil testing data, especially if the C content is known (Räty et al. 2021). As for the water pollution risk grading, wet sieving-based aggregate stability test was used to indicate the susceptibility of the soil to water erosion (Barthès and Roose 2002). Specifically, the turbidity component of the test, indicating water clarity, that is, the amount of suspended soil particles, was used (Sun et al. 2001). This approach is scientific and not accessible for the farmer. To enhance data availability, an endeavour to replace the detailed laboratory test with a simpler methodology within public reach should be made. For example, a smartphone application (SLAKES) has been developed for soil aggregate stability assessment (Fajardo et al. 2016). However, its test results have been somewhat inconsistent (Adetsu et al. 2024; Flynn et al. 2020; Poeplau et al. 2024) and comprehensive testing in the targeted conditions would be needed for formulating valid grade limits.

For all agricultural lands in Finland, high-resolution erosion estimates have been calculated using the RUSLE model (Räsänen et al. 2023). This spatially consistent dataset, independent of variations in crops, management practices, and erosion mitigation measures, highlights the topographic dimension of erosion potential. RUSLE is the most widely used erosion model globally (Batista et al. 2019; Borrelli et al. 2021) and has been applied in many countries for erosion management and policy support (Schmaltz et al. 2024). However, using existing data in the developed method, the availability and format may need to be improved. The dataset may not be publicly accessible or in the appropriate format, such as ensuring equal reflection of erosion potential across all areas regardless of annual changes in crops and management. Spatial resolution is also critical; high-erosion areas are often highly localised, necessitating digital elevation models (DEMs) with adequately high resolution (e.g., $\leq 10\text{m} \times 10\text{m}$) (Karimimejad et al. 2024; Räsänen et al. 2023). Despite these challenges, the ease of applying RUSLE and the growing availability of high-resolution DEMs enable the preparation of erosion datasets with reasonable effort in many countries.

4.2 | Uncertainty of the Selected Grade Limits

Though the selection method was built largely on attributes with rather strong background both in research and advisory soil testing, only limited support was available for setting the numerical criteria for the amendment material selection as studies comparing the materials under consideration in differing soils are non-existent. Consequently, the values for suitability thresholds were set on expert judgement during discussive workshops based on knowledge gained from separate studies of these materials. In modelling, relying on the best professional judgement is often needed in imposing parameters not known with certainty (Krueger et al. 2012). Similar to the suitability values, their weights were set on expert judgement. However, the sensitivity of the overall indices on the selection of individual weights was tested and the indices were found to be rather robust on the weights of the

features. In the end, the criteria are meant to be updated with knowledge gained.

4.3 | Characteristics of the Case Study Area and Allocation of the Soil Conditioners

The soils in the case study area are mostly clay soils which are typical for the region but differ from the predominant soil types in many other parts of Finland. For example, 76% of agricultural soils in the Southwest Finland region, where the case study area is located, are clay soils whereas in the whole Finland only 28% (Lemola et al. 2018). As for the STP results, in the case study area the P level was low (median 6.4 mg L^{-1} soil) in comparison to the soils in Southwest Finland (10.4 mg L^{-1} soil, Lemola et al. 2018) or whole Finland (9.0 mg L^{-1} soil), which likely results from the absence of animal production and consequently non-existent manure application to the fields, and rarity of P intensive plants in the crop rotations. The soils were quite acidic, and the pH level is similar to that observed in the Finnish national soil monitoring (Keskinen et al. 2016). In a major share of the fields the pH level indicated a need for liming according to national recommendations.

The soil properties resulted in occasional exclusion of some soil conditioners due to the selected exclusion criteria, but such cases were reasonably rare. For example, Mg concentrations were in 14% of the sampling lines below the value of 150 mg L^{-1} soil, which was set as an exclusion limit for gypsum application, but Ca levels did not limit gypsum or structure lime selection. Only occasional sampling lines had pH levels under the exclusion limit used for gypsum application. Similarly, the low STP levels did not practically limit the selection of fibres in the case region.

As a result of the used selection criteria, the largest share of the field area was allocated to fibre amendment. This selection stemmed from the high clay content in the area and with that respect low C content. High clay/C ratios indicate potential structural instability and an increased risk of colloidal particle dispersion (Dexter et al. 2008; Soenne et al. 2016). For these soils, increasing C content could enhance structural stability, reducing both erosion and PP losses. Organic molecules can support microaggregate formation (Totsche et al. 2018), which helps mitigate dispersion of clay particles. However, the quality of organic matter plays a critical role. Nitrogen-rich microbial metabolites and relatively labile organic molecules have a high affinity for mineral surfaces, while organic molecules with a high C/N ratio exhibit lower affinity (e.g., Kopittke et al. 2020). Fibre amendments have been shown to reduce erosion, indicating improved soil structural stability (Rasa et al. 2021). Nonetheless, in a study by Rasa et al. (2024), a large, single application of a fibre product did not alter pore structure within soil aggregates but did increase soil macroporosity. In high-clay soils, increased macroporosity has potential to enhance soil aeration (Soenne et al. 2023) and improve water infiltration, thereby reducing erosion risks through decreased surface runoff (Rasa et al. 2024). Moreover, clay soils with high clay/C ratios generally have lower crop yields compared to fields with lower ratios (Soenne et al. 2021). This indicates that higher C contents could improve nutrient uptake and decrease also the risk of soluble nutrient losses.

All the three soil amendment materials have been found effective in decreasing soil erosion and associated particulate P losses (Ekholm et al. 2024; Rasa et al. 2021; Ulén and Etana 2014), and gypsum has also been found to moderate dissolved P and DOC in field discharges. In our selection criteria most of the variables considered were associated with erodibility. Even though high STP was also a variable to consider in risk indexing, of these amendments only gypsum would thus be expected to alleviate dissolved P losses from hot-spot areas. Nonetheless, increasing STP also means that the eroded soil contains increasing P concentrations and thus, if erosion is unaffected, elevating STP for a small part increases PP losses.

4.4 | Rationale Behind Targeting Efforts

Typically, the land area contributing to nutrient emissions into waterways is disproportionate to its share of the total catchment area (Gburek et al. 2000; Uusitalo and Jansson 2002). Therefore, targeting the conservation measures into the high-risk field parcels or specific areas within a field is the most effective way to protect waterways. In the current inspection, fields within the 60 m riparian zone (17% of the total field area) bore nearly half of the total erosion risk burden, while in the most extreme areas the estimated erosion exceeded the overall average eightfold. Though our scoring of risk index attempted to identify high-risk parcels, without knowledge of the realised erosion and nutrient losses, there is no way to tell how successful the presented scoring is.

Availability of the considered soil improving materials also creates a need for targeting the measures. The pulp and paper industry in Finland produces about 400,000 Mg (dry weight) of fibres annually, which, using the 30 Mg (wet weight, with about 30% dry matter content) application rate, would be enough to cover an area of ca. 40,000 ha. However, part of the larger mills are located far off the areas where fibre amendments would be needed. Given the large application rates, transportation costs over long distances become easily prohibitive. As for quick lime, availability of climate-sound material may be an issue (Ollikainen et al. 2024; Powlson et al. 2011; Tepes et al. 2021). It is available as a side-stream of CaO manufacturing and of pulp, paper and steel mills, but the amounts are not available. Side-stream quick lime may also have other potential uses, which compete with agricultural use. Making pristine quick lime from calcium carbonate is not meaningful because of the considerable climate footprint (Ollikainen et al. 2024). Of these three amendments, the only material without shortage in Finland is gypsum, which keeps piling up as a by-product of fertiliser manufacturing in the eastern part of the country. As a result of relatively low application rates of 4 Mg ha^{-1} , the costs of transport and use remain reasonable, despite the main region of use being Southwest Finland, 450–500 km away from the fertiliser plant. However, in Finland, gypsum is allowed for use only in areas where discharges end up in the sea, as sulphate input may disturb sediment P retention in lakes (Smolders and Roelofs 1993), excluding its use from many inland catchments.

Soil conditioners provide a quick remedy for soil and P losses, but since their effectiveness is temporary, repeated applications may be needed. Long-term solutions rely on proper soil management,

including permanent vegetation cover, no-till on erodible slopes, nutrient management, mulching, anti-compaction measures, and crop rotations (Powlson et al. 2011; Tepes et al. 2021). Still, soil amendments can play a crucial role in preventing off-site soil and P losses until long-term practices take effect.

4.5 | Decision Support Tools

The aim of this paper was to generate a method for soil conditioner selection to provide unbiased means for farmers, advisors, and policy makers for assessing the suitability of gypsum, structure lime, or wood fibres for a certain soil from the perspective of water quality protection. On their farm level, farmers tend to value the protection of soil fertility over the protection of water resources (Sattler and Nagel 2010), which gives an advantage to soil conditioners entailing plant nutrients and/or liming agents. Consequently, the adoption of a soil conditioner from the viewpoint of environmental friendliness requires an understanding of the relative differences in their effectiveness. In the Archipelago Sea catchment area encompassing the current Savijoki case study area, water protection methods are being introduced to achieve the Finnish government's goal of removing the sea area from the HELCOM Baltic Sea hot spot list by 2027.

Decision support tools (DSTs) can provide valuable assistance in farming decision-making (Bartkowski and Bartke 2018), particularly as farmers face increasingly complex challenges and demands (Mihailescu and Bruno Soares 2020; Pe'er et al. 2020). Ideally, tools such as the one presented here should be integrated into broader DSTs that support farmers in achieving their farming and economic goals while simultaneously improving soil health and managing environmental impacts. The present method is constructed to be easily modifiable so that features can be added and removed, and the weighting factors adjusted according to the objective of the choice, or the realizer of the measure. The preference may vary depending on whether the operation is subsidised or if it is financed solely by the farmer (Claassen et al. 2008; Zhou et al. 2021).

5 | Conclusions

The presented method is intended to serve in selecting the most efficient soil conditioner among gypsum, structure lime and wood fibres from the water protection point of view considering soil features governing their effectiveness. The method did not account for the costs of the amendments, their transport or spreading. Incorporating the availability and costs of each amendment would further increase the applicability of the instrument in planning cost-effective water protection measures. The method was built, as much as possible, on data easily accessible to the end-users, but especially the assessment of soil structural stability requires simplification before widespread implementation is possible. In the autumn of 2024, roughly half of the total field area of the Savijoki case catchment was amended with gypsum, structure lime and wood fibres following the present allocation results. Monitoring the impacts on the water quality of the river Savijoki will in due course reveal the effectiveness of the measure. However, improving and

validating the selection method calls for structured experiments simultaneously assessing all the target materials in variable conditions to recognise the most responsive conditions for each of the materials.

Author Contributions

Riikka Keskinen: conceptualization, investigation, writing – original draft, writing – review and editing, methodology. **Helena Soinne:** conceptualization, investigation, writing – original draft, methodology, writing – review and editing. **Risto Uusitalo:** conceptualization, investigation, funding acquisition, writing – original draft, methodology, writing – review and editing. **Petri Ekholm:** conceptualization, funding acquisition, writing – original draft, writing – review and editing. **Timo A. Räsänen:** writing – original draft, methodology, visualization, writing – review and editing. **Jaana Uusi-Kämppe:** conceptualization, funding acquisition, writing – review and editing, project administration. **Jenna Bergholm:** writing – review and editing, investigation, funding acquisition. **Johanna Nikama:** conceptualization, investigation, writing – review and editing, methodology. **Jari Hyväluoma:** conceptualization, investigation, writing – original draft, writing – review and editing, visualization, methodology, formal analysis, data curation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the [Supporting Information](#) of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.