HELCOM Guidelines on
Best practices to improve soil structure and aggregate stability on clay soils

Baltic Marine Environment Protection Commission

Agriculture

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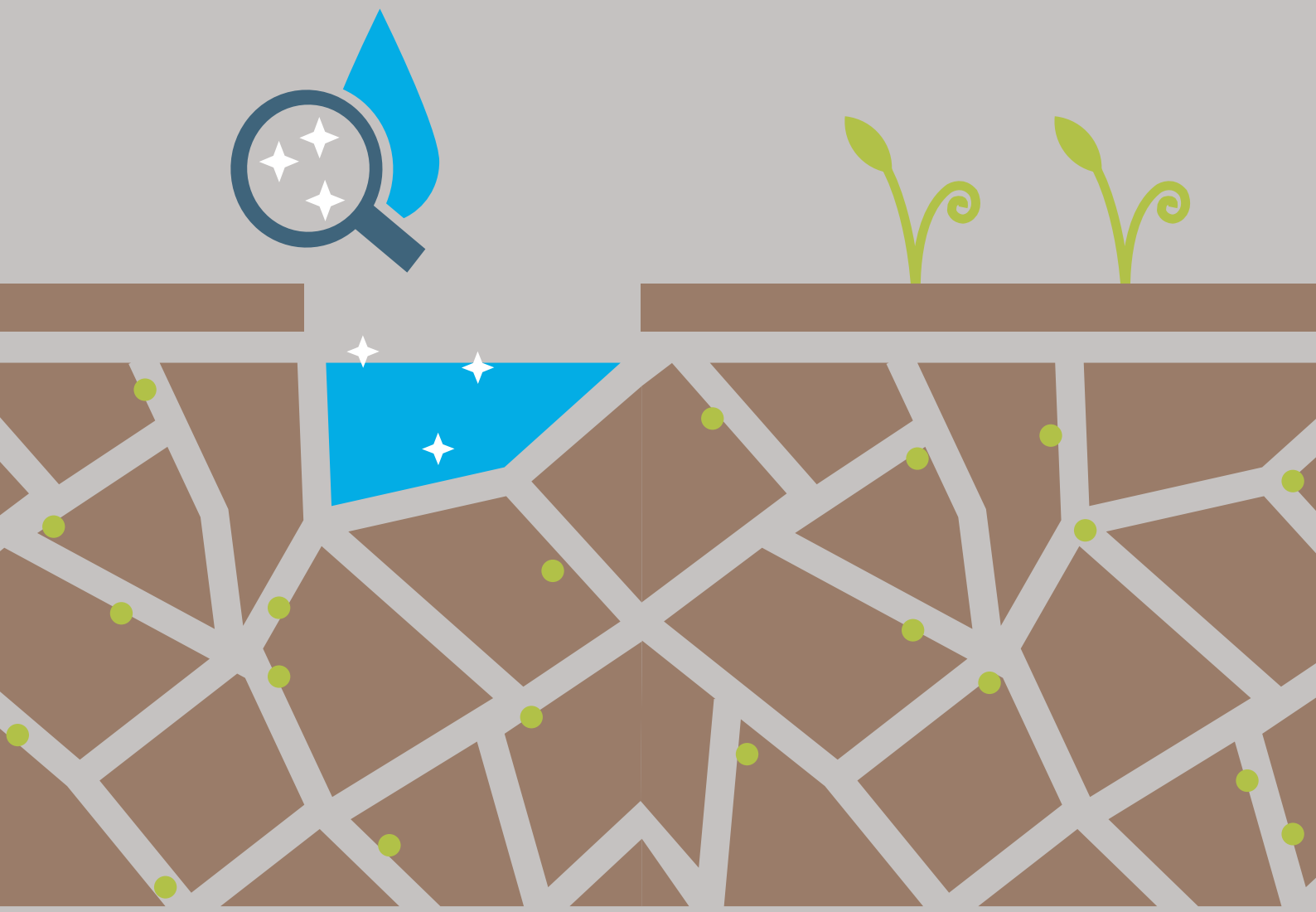

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1. Introduction

Agriculture remains a major source of nutrient inputs, phosphorus and nitrogen, to the Baltic Sea. While the farming community has already implemented many measures to reduce nutrient losses there is still a way to go, and it is important to bring the newest research findings on measures to farmers.

HELCOM Contracting Parties agreed in the 2021 Baltic Sea Action Plan to several actions to reduce nutrient loading from agriculture including action E8: *Develop by 2025 and apply by 2027 the best practices to improve soil structure and aggregate stability on clay soils to reduce phosphorus losses from agricultural lands, for example by using soil structure lime or gypsum*. This document compiles best practices to improve soil structure and aggregate stability on clay soils to reduce phosphorus losses from agricultural lands.

2. Background

A large proportion of phosphorus (P) losses from clay soils are in particulate form and measures that improve soil structure and increase aggregate stability have potential to reduce phosphorus losses from these soils. In addition to losses of particulate phosphorus, there can be also losses of soluble phosphorus, which can be directly utilized by primary producers in the sea accelerating eutrophication. Measures to tackle the losses of different forms of phosphorus are partially different.

Wintertime soil frost and snow cover reduce erosion risks in the northern Baltic Sea region. The projected warmer winters and more extreme rainfall events are expected to increase erosion and particulate inputs to surface waters (HELCOM 2021). Already it is known from years with wet autumn followed by mild and rainy winter that erosion and phosphorus loading may double compared to years closer to hydrological average (Puustinen et al 2007). Winters becoming more unstable would as well increase the occurrence of repeated freeze-thaw cycles, which may further increase the erosion risks (Ulén et al 2012). These future predictions emphasize the need for measures to decrease the erosion sensitivity of clay soils.

Figure 1 includes a map that shows where the clay soils are situated in the Baltic Sea region (excluding Russia). The map indicates that most of the soils with highest clay content are located in Finland and Sweden.

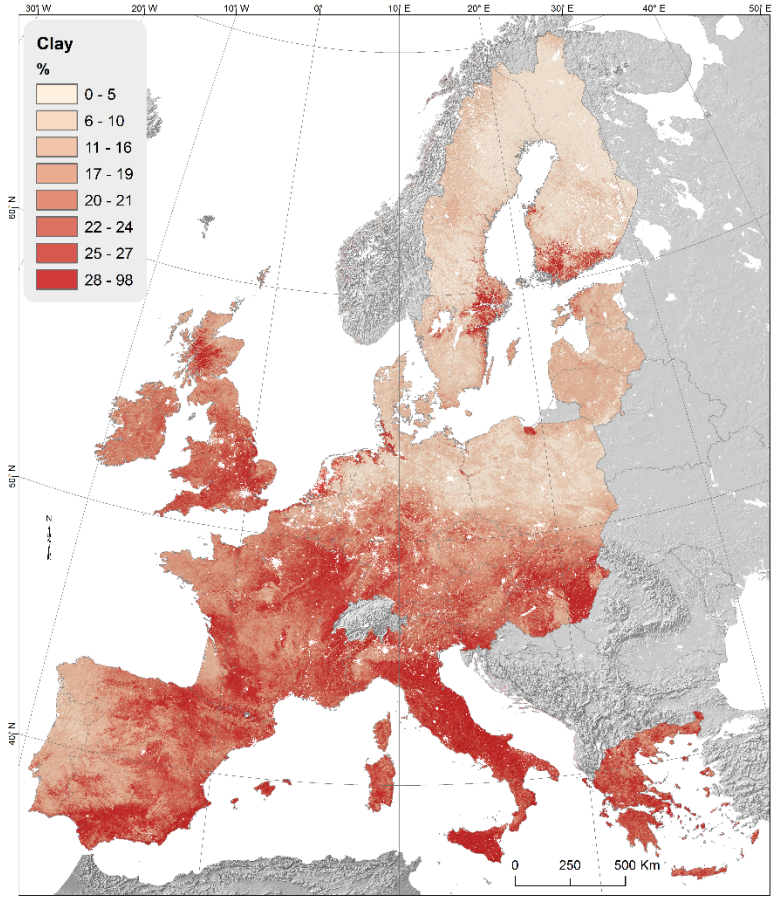

Figure 1. Clay content (%) in topsoil (0-20cm) for Europe (Ballabio C., Panagos P. and Montanarella L. 2016).

3. Well-established measures

3.1 Measures to improve soil structure on clay soils

3.1.1 Proper drainage and avoiding heavy machinery to avoid soil compaction

Avoiding and mitigating compaction on agricultural soils is useful for the farmer and for the environment, as compacted soil offers smaller yields and bigger environmental load compared to soils with good structure. For the farmer, it is beneficial to observe regularly the soil structure of their fields. The visual evaluation of soil structure is easy to do in field circumstances with a spade. Other instruments, such as penetrometer, can help to find the compacted fields or compacted parts and layers of a field. While mapping the compacted places on the fields, it is relevant also to find out the reasons for the compaction.

Soil compaction can lead to low water infiltration capacity and poor root development. The risk of standing water, surface runoff and channelized flow through cracks in the soil increases if the soil is compacted. There are several benefits if soil compaction is reduced/avoided, for example: plant uptake of nutrients and access to water can improve if the crop has a well-developed root system, which in turn can increase yields and reduce nitrogen losses. Phosphorus losses can be reduced due to increased water infiltration capacity and reduced surface erosion. In addition, carbon sequestration is more effective in soils with proper structure, compared to compacted soils.

To reduce existing compactions in clay soils, the most effective method is a combination of mechanical and biological subsoiling. This approach requires good planning. Once the compactions are removed or at least reduced, it is crucial to prevent the formation of new compactions. Compactions can develop quickly but may persist for decades if active efforts are not made to remove them.

Avoiding machinery traffic when soil is too wet is very critical to avoid soil compaction. Some technical examples of how soil compaction can be reduced are: avoiding heavy machinery in general, increasing number of axles, controlled traffic farming, low pressure tires or dual wheels with low tire inflation pressure, limit the number of trips over the field and the distances driven (e.g. more than one road junctions), and umbilical slurry systems. Avoiding heavy machinery includes situations when soil improvers and organic matter is applied. If the soil dries up earlier in spring it allows for earlier tillage and sowing, and hence a longer growing season. Proper and regularly maintained drainage speeds up the drying, improves trafficability and counteracts excessive compaction. It allows the root system to grow deeper during wet periods, which in turn increases access to water during more dry periods.

Depending on climate, soil and cropping system, the most important or economically most motivated measures to reduce soil compaction differ between regions and individual farms. Some of the measures are simple and require very small investments, such as frequently adjusting the tire inflation pressure to the loading and the driving situation, choosing suitable days for field operations in terms of soil moisture conditions, and planning harvesting, spreading and transport operations carefully in order to minimize the distance driven. Other measures may require investment in machinery or running gear with less compaction potential.

3.1.2 Crop rotation

A varied crop rotation can improve soil structure. Some crops are known to improve soil structure, for example oilseed crops. A uniform crop rotation with cereals for many years can affect soil structure and soil fertility negatively, while ley crops that are grown for several consecutive years can improve soil structure.

3.1.3 Increasing organic carbon content to improve soil structure

Soil structure in clay soils is improved by measures that increase the organic carbon content of the soil. Also, increased carbon content can lead to a higher mineralization of nitrogen and increased water holding capacity, which is good for soil fertility.

Incorporation of manure and crop residues are common management practices that increase or maintain the organic carbon content in the mineral soil. Ley and catch crops or green manure are examples of crops that can increase organic carbon content in the soil. Reducing tillage can lead to lower mineralization of organic matter in the topsoil.

Increasing the organic carbon content in the soil is a long-term process and it takes time before measurable changes can be seen.

3.1.4 No-till or reduced tillage

There are various methods for reduced tillage. One version is no-till cultivation. An example of another version is to replace mouldboard ploughing with a field cultivator or chisel plough to about half the normal ploughing depth. In clay soils this can lead to improved soil structure via a gradual development of a system of stable and continuous macropores in soil layers that are no longer disturbed.

Long-term compaction effects from machinery can decrease if the total annual traffic intensity decreases when a change is made to reduced tillage.

If reduced tillage or no-till is practiced over time it can lead to a build-up in nutrient concentration close to the soil surface, since crop residues, manure and fertilisers are not mixed into deeper soil layers. This can increase the risk of soluble phosphorus losses. No-till can lead to increased use of herbicides. Applying conservation agriculture where no-till is complemented by cover crops and proper crop rotation can help avoiding the need for additional herbicides. Occasional deeper tillage can be useful for both weed control and nutrient management (Uusitalo et al. 2024).

3.1.5 Perennial crops/winter crops/catch crops

Wintertime vegetation cover binds soil particles and utilises nutrients from the soil, reducing the risk of erosion and nutrient leaching. Heavy machinery also stays better on the ground, while plants evaporate water, and roots hold the soil in place. Root diversity (i.e. different types of plants) produces organic material to soils, which is valuable especially in clay soils with continuous monoculture of cereals. Thus, root diversity enhances soil structure and the microbiology of the soil.

Repeated freeze-thaw cycles may increase leching of dissolved phosphorus from decaying plants or soil surface saturated with phosphorus. Therefore, it is recommended to harvest the perennial crops annually and till or plough the field every fifth year to decrease soluble P losses.

3.1.6 Liming to raise the pH in soil

The commonly used liming agents contain calcium carbonate $CaCO_3$ or calcium magnesium carbonate $CaMg(CO_3)_2$. Lime is obtained by quarrying limestone or dolomite. Additionally, various by-products such as ash or steel industry slag are used as liming materials. If by-products are used for liming it is important to ensure that they do not contain high levels of heavy metals or other contaminants.

The soil pH has crucial effects for plants' ability to utilize nutrients. In acidic soil, many nutrients bind very tightly to the soil, making them inaccessible to plants, and the solubility of harmful heavy metals increases. Liming improves e.g. the availability of phosphorus to plants.

A high pH level is essential for many microbes and earthworms which activity improves the soil structure and enhances nutrient cycling.

Liming improves the structure of clay and silt soils in particular. This is based on the ionic strength of soil solution. When the soil solution contains an excess of calcium salts, some of them precipitate as calcium carbonate. This strengthens the structure of macroaggregates.

3.2 Other measures to reduce phosphorus losses

3.2.1 Buffer zones

Establishing buffer zones under perennial plants between cultivated arable land and receiving waters is a supplementary way of decreasing sediment and phosphorus losses in surface runoff. Buffer zones work in several different ways. For example, they prevent soil tillage and application of nutrients too close to water bodies since these managements are not allowed in the buffers. Perennial plant cover also controls the detachment of soil particles by decreasing the energy of falling raindrops or running water on slopes. In addition to these, they remove sediment and nutrients such as phosphorus from runoff water.

Removal of sediment and phosphorus from runoff happens in different ways in buffer zones. Firstly, dense vegetation increases the hydraulic roughness reducing the overland flow velocity and sediment transport capacity. At the same time, eroded soil particles are settled in the buffer zone and particle bound phosphorus is retained. Secondly, soluble phosphorus is adsorbed on the soil surface or infiltrates with runoff water into the ground. Thirdly, the vegetation in the buffer zone absorbs nutrients from surface runoff and roots take up phosphorus from the soil.

Buffer zones are especially effective in removing soil particles enriched with phosphorus in surface runoff from autumn ploughed clay soils having high erodibility (Uusi-Kämppä and Jauhiainen, 2010). In direct seeding, erosion is small, but the load of dissolved reactive phosphorus may be bigger than in autumn ploughed fields. Also in these cases, narrow buffer strips can be recommended to minimize sediment and nutrient transport.

The widths of the buffer zones vary depending on the site. One-meter-wide headlands are enough along the main ditches and at least 3-m-wide buffer strips are required along watercourses. Buffer zones up to 30–50 meters wide can also be established along watercourses. The longer, steeper, or more erodibility in the field slope, the wider buffer zone is needed.

In buffer zones, freezing and thawing events in spring release dissolved phosphorus into spring runoff from the decaying plant material. In addition to that, low salt concentration in snow-melt water, as well as a high water/soil ratio may favour the desorption of phosphorus from the soil of the buffer zones to water. To minimize the risk of phosphorus liberation from buffer zones their biomass harvesting in late summer is recommended.

3.2.2 Avoiding overfertilization

Optimizing plant nutrient use (=fertilization plan) combines information on plant nutrient uptake, soil fertility, fertilizer products and pre-planting effects. Needed fertilization equals plant nutrient uptake minus nutrients released from the soil. Nutrient balance calculators can be used for fertilization planning.

Phosphorus concentrations in soil change slowly and are abundant in the reserve used by plants, especially in clay soils. In fertility classes of rather poor and higher, phosphorus does not need to be added every year, and neither the quantity nor the quality of the crop on such soils will decrease if phosphorus fertilization is not applied. In the phosphorus classes good, high and excessive, phosphorus fertilization can be omitted for several consecutive years. In poor fertility classes it is important to take care of sufficient P fertilization.

4. New methods

Reducing agricultural phosphorous (P) load into the Baltic Sea calls for decreasing the use of manure and other phosphorous fertilizers in the areas where soil P content is high, and the status of waterbodies is not good. However, as soil P reserves decline slowly, there is also a need for interim measures, such as the use of soil amendments. The most suitable amendment should be chosen based on the properties of the soil, taking into account possible separate restrictions on use.

It is preferable to use industry by-products to reduce climate impacts of the use of soil amendments keeping in mind that their use should not cause release of hazardous substances. The selected soil amendment method should be chosen to best suit each region depending on the demand and availability of the material. It is not recommended to transport these materials for long distances, which increases the release of greenhouse gases (Ollikainen et al 2024). It is also good to note that some types of soil amendments contain nutrients which prevents their use as a water protection method.

4.1 Application of gypsum

4.1.1 Description

Gypsum ($CaSO_4 \cdot 2H_2O$) application to the surface of soil provides a cost-efficient measure that can effectively reduce phosphorus runoff from agricultural fields. Gypsum application increases the ionic strength of soil pore water. It creates larger aggregates of soil particles, calcium bridges and affects phosphorus binding, which reduces erosion and phosphorus losses to waterways. Importantly, phosphorus remains fully available to plants. These beneficial effects occur immediately after the dissolution of gypsum, last for about five years and are achieved without any loss of crop yields or taking land out of cultivation.

4.1.2 Effectiveness and cost-effectiveness

Previous research, and the large-scale gypsum project (SAVE-project) in Finland have demonstrated that gypsum amendment of fields reduces phosphorus loads, both particulate and dissolved phosphorus, from fields by around 50% (Ekholm et al. 2024). A vital additional benefit is reduction in the loss of dissolved organic carbon. In the Finnish gypsum project, the applied amount has always been 4 tonnes per field hectare.

Gypsum has no effect on the suitability of soil phosphorus for plants, and no changes were observed in phosphorus concentrations in crops. Gypsum does not affect the acidity of arable land.

The costs of gypsum amendment will depend on the local conditions. The costs of gypsum amendment have been ascertained in several projects using gypsum that was a by-product from the fertilizer industry (Ollikainen et al. 2024). In the Finnish conditions the unit cost for gypsum amendment is about 70 €/kg P reduced. This figure is based on measured phosphorus reduction assumed to last for five years and the actual gypsum amendment costs (gypsum, its transportation and spreading) of 220 €/ha.

Because gypsum amendment does not reduce yields or the utilized arable area, it does not result in loss of income for farmers. In addition, no equipment investments are required, since gypsum can be spread using existing equipment.

4.1.3 Suitability of the measure

Gypsum contains sulfate, which is gradually flushed away from soil to nearby waterways. Therefore, gypsum should not be used in areas that drain into lakes or within groundwater areas. It should also not be applied in Natura 2000 areas. As sea water naturally contains sulfate, it is safe to use gypsum in arable fields along waterways discharging into the sea.

The suitability and safety of gypsum application has been tested in Finnish projects. Using multiple indicators of aquatic biota, environmental research in the River Savijoki gypsum pilot area showed that sulfate losses do not cause any harm to biota in rivers. The research showed that sulfate concentrations, even at markedly higher levels than those observed in the pilot, do not impact trout (*Salmo trutta*), the thick-shelled river mussel (*Unio crassus*) and the common water moss (*Fontinalis antipyretica*). Also, the mean increase in sulfate levels in the river turned out to be minor and the higher temporary peaks short-lived. Gypsum amendment increased the electrical conductivity and sulfur concentration in topsoil for one to two years after the amendment. In addition, the sulfur concentration of the cultivated plants increased for two years, but other effects on the soil and plant chemistry were minor. The monitoring of seven private wells showed that gypsum had not leached into the ground water during the five years. If a well is used as a drinking water source, then an untreated buffer zone should be left around the well as a precautionary measure, especially on coarse textured soils. This applies also to other soil amendments. A snow simulation study showed that gypsum should not be spread on snow or frozen soil because P, an impurity in the phosphogypsum used, may result in elevated losses of dissolved P. Such a risk is eliminated if P-free gypsum is used, but the desired effect may still be low if gypsum does not have contact with surface soil in winter due to frozen ground or snow.

If by-products of industry are used it is important to make sure that they do not contain harmful substances. In the Finnish example, gypsum is a by-product of phosphorus acid production that uses igneous phosphorus rock as source material. However, there is a risk of impurities, hazardous and radioactive substances ending up in the by-product if the origin of the phosphorus rock used in production is sedimentary. Currently, gypsum that is an industrial by-product, cannot be used in organic production in EU countries due to EU regulations. While gypsum that originates from industrial by-product is prohibited to be used in organic production, gypsum of natural origin is allowed in some cases.

Gypsum amendment does not affect soil pH value. Therefore, the amendment should be directed to fields that have a pH value of 5,5 or above, to ensure that the amendment has the desired effect on reducing phosphorous runoff from agricultural fields.

Gypsum is also a good sulfur fertilizer. Many fields lack sulfur, which impairs plant growth and the utilization of other nutrients.

4.1.4 Examples of policy measures from the countries

Finland

The current government programme (2024-2027) states that the government aims to diversify the use of soil improvers, to enable farmers to choose the best-suited options for them. Improving soil structure is one of the main themes in the Ahti programme, aiming for improved status of waters and the marine environment in Finland. The use of soil improvers (gypsum, structure lime and fiber sludge) is also listed as a water protection measure for agriculture in the river-basin managements plans (2022-2027), with ambitious goals (in hectares).

Research projects aiming to enhance the use of structure liming and fiber sludge have been carried out in southern and south-western Finland and the continued monitoring of their effects is ongoing. There is also ongoing, government funded research (AIN3 project) to investigate the suitability of different soil improvers on different types of fields.

To encourage the use of soil improvers, a guide has been published for farmers. It provides information on the various types of soil improvers, their suitability for different soil types, their impact on soil, their environmental effects (including on water bodies), and practical application methods.

Around 540 000 hectares of farmland have been identified as suitable for gypsum treatment in Finland according to an analysis conducted by the Finnish Environment Institute (Syke). The gypsum treatment as a

water protection measure has been studied in Finland since 2008 and catchment level gypsum treatment has been piloted at river Savijoki in southwest Finland since 2016. Gypsum treatment has been used as a full water protection measure in southwest Finland since 2020 and in other Finnish coastal areas since 2022. By the end of 2024, gypsum had been applied to approximately 67,500 hectares. The goal is that by the end of 2025, 100 000 hectares of agricultural land will be treated with gypsum in Finland.

Currently, gypsum is the most widely applied soil improver in Finland. However, if gypsum is an industrial by-product, it cannot be used in organic production. Gypsum treatment is free of charge for the farmers with eligible fields for the gypsum treatment. It is also a tax-free subsidy, and it does not affect the agricultural subsidies. The application of gypsum is not included in the current CAP Strategic Plan in Finland (2023-2027) but is a separate subsidy that aims to improve the soil structure and reduce nutrient runoff. Gypsum treatment is state aid for farmers, but instead of money, the aid is given in the form of gypsum treatment of agricultural fields that have been identified suitable for it. The aid includes the gypsum (4 tons/ha) and the logistics regarding the spreading to the chosen parcel(s).

The use of gypsum is promoted to farmers through various channels, e.g. a project website, social media and in relevant farming venues, but also through phone call campaigns where farmers are contacted directly. It is important that the knowledge from long term research on gypsum treatment and its water protection effects are distributed to the farmers.

The state aid authority is the Centre for Economic Development, Transport and the Environment for South-West Finland (ELY Centre). The contractor for gypsum supply, transport and distribution services is selected through a tendering process.

The state aid (in the form of gypsum treatment) is given to the farmers according to agricultural block exemption regulation (EU 2022/2472), where EU commission requires that the conditions for state aid are in binding legislation. Thus, there is a government decree on the gypsum treatment of agricultural land during years 2020-2025 (510/2020) that enables granting state aid for farmers according to the conditions set by the commission and the EU state aid regulation.

The gypsum treatment has received government funding though the Ministry of the Environment since 2020 as part of a programme aiming for more effective water protection (today called Ahti programme). In addition, gypsum treatment of fields has received funding from the EU Recovery and Resilience Facility (RRF), as a part of the investments for green transition.

4.1.5 Climate effects

Application of gypsum has a minor climate impact if by-products of industry or circular materials are used. However, the climate impact is more substantial if mined gypsum is used.

4.2 Structure liming

4.2.1 Description

Structure liming is used to improve aggregate stability and mitigate phosphorus losses on clay soils. Structure lime is a mixture of agricultural lime and reactive lime. Agricultural lime is ground limestone i.e. calcium carbonate ($CaCO_3$). The reactive lime is quicklime (CaO) or slaked lime ($Ca(OH)_2$). Less than half of structure lime (15-20%) consists of highly soluble reactive lime. A suitable application rate of structure lime is around 5-9 tons/ha. The changes in soil structure induced by structure lime are attributable to three mechanisms: cation exchange, lime carbonation and pozzolanic reactions. Structure liming differs from regular liming, intended to increase the soil's pH level, in that it aims to have a quick and long-term impact on the aggregate structure of clay soils.

Recent results from field trials in Sweden indicate that the soil structure was improved and the risk of phosphorus losses reduced approximately as much with finely ground limestone of young geological origin, as with structure lime (Olsson Nyström et al. 2023). More results from the ongoing field trials are awaited.

4.2.2 Effectiveness and cost-effectiveness

The positive impact of structure lime on environment has been shown in several field trials and at structure limed sites in Sweden and Finland.

Structure liming reduces leachate turbidity and concentrations of phosphorus bound to soil particles in ditches, in subsurface-drainage water and surface runoff.

Cost-effectiveness of different amendments depends on their efficiency in various soil conditions and usage costs. Results on the cost-effectiveness of using gypsum and structural lime in boreal conditions have been published by Ollikainen et al. (2024).

4.2.3 Suitability of the measure

Structure lime is recommended for clay soils. A tentative recommendation is that clay soils (excluding gyttja soils) with pH below 7 and clay content above 25% should be given priority in structure liming schemes (Blomquist 2021). The best conditions for spreading structure lime exist when the soil is dry and suitable for cultivation. The weather should be warm with low winds and without any rain. As a result, warm weather will accelerate reactions between structure lime and the soil. Summer months or early autumn are suitable for spreading. A quick and thorough incorporation of the structure lime is important for a good result, for example by tilling twice in different directions with a cultivator. Even better effects on soil structure are likely achieved if structure lime is applied after a crop that improves soil structure, such as a ley crop or oilseed crop.

Products that contain burnt lime or slaked lime are not accepted in organic farming in EU countries due to EU regulation. Only ground limestone is accepted in organic farming.

4.2.4 Examples of policy measures from the countries

Finland

The use of structure lime is currently recommended as a measure to improve soil structure and mitigate phosphorus losses. Currently there are no subsidies for using structure liming in Finland. The application of structure lime is not included in the current CAP Strategic Plan in Finland (2023-2027).

Sweden

Structure liming is recommended in the water management plan for Sweden and is subsidised in national environmental schemes with the general aim of mitigating phosphorus losses. Approximately 65 000 ha of clay soils were treated with structure lime in Sweden between 2010 and 2020.

Poland

Liming is a crucial practice in Poland due to natural conditions and agricultural practices. In the years 2019-2024, there was a programme called "National program for environmental regeneration of soils through liming". The programme enjoyed great interest among agricultural producers. The programme included all types of lime that are listed in Annex I to Commission Regulation (EU) No 463/2013 of 17 May 2013 amending Regulation (EC) No 2003/2003 of the European Parliament and of the Council on fertilizers in order to adapt its Annexes I, II and IV to technical progress addressing both liming to increase soil pH and structure liming.

Since 2023, in the Strategic Plan for the Common Agricultural Policy for 2023-2027 (CAP Strategic Plan), within the framework of voluntary eco-schemes for farmers and additionally paid, farmers can use the eco-

scheme Carbon farming and nutrient management, which includes, among others, the practice "Development and adherence to a fertilization plan in a variant with liming".

4.2.5 Climate effects

The production of structure lime causes greenhouse gas emissions. Structure liming has a smaller climate impact if by-products of industry or circular materials are used. If by-products or circular materials are used it is important that they do not contain harmful substances.

4.3 Application of fiber sludge

4.3.1 Description

Fiber sludge is a concept that covers different wood fiber containing forest industry side streams, some of which can be utilized in agriculture as soil amendments. Fiber sludges are generated at pulp, paper and board mills as primary and/or secondary sludges. Depending on the industrial process, fiber sludges comprise of lignin and short chain cellulose or pulp fines and possibly fillers such as kaolinite and calcium carbonate. Secondary and combined mixed sludges also contain additional plant nutrients and microbial biomass which originate from the aerobic activated sludge treatment. The short chain fibers are not suitable to produce the desired products and are commonly disposed by incinerating with other materials. High moisture content decreases the energy yield from incineration. (Turner et al. 2021)

The dewatered fiber sludges have dry matter content of 30-40%. Mixed sludges can be further processed by composting or lime stabilization. Dewatered and processed fiber sludges can be stored in piles or windrows following the instructions from local authorities. Solid manure spreaders are suitable for field application of fiber sludges, and the effective application rates vary between 20 to 50 t/ha depending on soil and soil amendment properties as well as cropping system. Shallow incorporation after application is beneficial. (Turner et al. 2021, ProAgria 2022)

Fiber sludges are utilized in agriculture to increase soil organic matter, improve soil physical properties, and depending on the sludge type, provide plant nutrients and increase soil pH. The benefits of increased soil organic matter can be expected especially on mineral soils with low organic matter content (Rasa et al. 2024).

4.3.2 Effectiveness and cost-effectiveness

Based on research results from field experiments at different scales, fiber sludge application significantly reduces clay soil erodibility and losses of suspended solids and particulate phosphorus (Rasa at al 2021, ProAgria 2022). The added organic matter feeds soil microbes and increases soil microbial activity. Increased soil microbial activity results in microbial polysaccharides and glycoproteins and fungal hyphae and actinomycete filaments flocculating clay particles, building and holding soil aggregates together and stabilizing them (Weil and Brady 2017).

Cost-effectiveness of fiber sludge application is site-specific. Due to high application rates and moderate moisture content, the transport cost and distance define the overall cost and cost-effectiveness. This results in better cost-effectiveness in regions with forest industry, such as many areas in the Baltic Sea region.

4.3.3 Suitability of the measure

Fiber sludges are suitable for all mineral soils. The benefits can be expected especially where low soil organic matter content is limiting aggregate stability. When fiber sludge is processed for agricultural utilization, the supplier provides a product data sheet including the properties of the soil amendment product. When assessing the suitability of the measure, the most important properties are nutrient contents, including ammonium/soluble nitrogen, carbon to nitrogen ratio and the amount of wood-derived cadmium in the

product. Soil amendment properties, soil properties and the cropping system define the suitability of a specific soil amendment product. Legislation and the instructions from local authorities can affect the suitability and application rate.

Depending on the regulation, phosphorus, total nitrogen, ammonium/soluble nitrogen or cadmium contents in the product can restrict the application rates. Fiber sludge based soil amendments can have slowly releasing fertilizing effects, but they can also cause transient nitrogen immobilisation in the soil. Depending on the carbon to nitrogen ratio of the product, the suitable product can be chosen, and the timing of application can be adjusted to support the crop rotation and to improve nutrient use efficiency. Termination of green manure crops and grass-clover leys and after harvesting crops leaving residual nitrogen, a soil amendment with high carbon to nitrogen ratio can immobilise nitrogen that would be otherwise be sensitive to leaching. Even spreading, shallow incorporation, functioning drainage and the absence of soil compaction make sure that added organic matter decomposes evenly in aerobic conditions, providing the beneficial effects to soil physical properties.

4.3.4 Examples of policy measures from the countries

Finland

The use of fiber sludge is currently recommended as a measure to improve soil structure.

In Finland's CAP Strategic Plan (2023-2027), as part of the agri-environment-climate payment scheme, there is a measure called "Promoting circular economy". This measure targets the application of organic material to fields on mineral soils. The payment level is 37 €/ha/yr. The list of acceptable soil amendments is long, including nutrient-rich and nutrient-poor fiber sludge, as well as manure and biogas digestate.

Poland

Waste management, including possible direct use in agriculture, is regulated by the Act of 14 December 2012 on waste (Journal of Laws 2023, item 1587) and by the Regulation of the Minister of the Environment of 20 January 2015 on the recovery process R10 (Journal of Laws 2015, item 132) and the Regulation of the Minister of the Environment of 10 November 2015 on the list of types of waste that individuals or organizational units other than entrepreneurs may recover for their own needs, and permissible methods of their recovery (Journal of Laws 2016, item 93).

In accordance with abovementioned legal regulations, waste plant mass and bark waste may be used directly on agricultural land provided that the permissible dose of waste has been determined taking into account the soil fertility, the method of its use, the quality of the waste and the demand for nutrients by plants, as well as the principles of good agricultural practice referred to in Article 103, paragraph 2 Act of 20 July 2017 – Water Law (Journal of Laws 2017, item 1566).

As a rule, forestry waste, sawdust, shavings, cuttings, wood, not subjected to chemical treatment, biodegradable waste from green area maintenance, waste plant mass cannot be directly spread on the surface of arable land if they have not previously been subjected to the decomposition of organic matter by microorganisms – aerobic bacteria, nematodes, fungi, etc. in the presence of oxygen and have not been introduced into market (i.e. as soil improvers), assuring their quality and safety.

These measures reflect Poland's commitment to sustainable agriculture and soil health while reducing pollution and improving soil productivity.

4.3.5 Climate effects

The alternative to utilization of fiber sludges in agriculture is disposal by incineration. High moisture content decreases the net energy yield from fiber sludge incineration, and it usually requires co-incineration with other materials and further dewatering (Turner 2021). A single fiber sludge application of 20-50 t/ha adds 3-

9 t of organic carbon per hectare. Over half of the applied carbon is lost from the soil during the first 5 to 10 years due to decomposition (Heikkinen et al. 2021), providing the benefits of improved aggregate stability and other improvements in soil properties. Part of the added carbon ends up to the soil mineral surfaces and the stabile aggregate structures, contributing to the more stable soil carbon storage.

4.4 Summary: Choosing the right measure

	Gypsum	**Structure lime**	**Fiber sludge**
Suitability	Especially clay soils Not suitable for organic farming if industry by-products are used Not suitable for drainage areas of lakes or groundwater areas due to sulphate releases	Clay soils Not suitable for organic farming	Mineral soils Suitability to organic farming to be verified Utilization in groundwater areas requires a permit, but the use of nutrient rich fiber sludge is not recommended
Effectiveness and cost-effectiveness	Gypsum application has reduced P losses from clay soils up to 50 % in large scale field trials in Finland	Structure lime application reduces leachate turbidity and concentrations of phosphorus bound to soil particles in ditches, in subsurface-drainage water and surface runoff	Fiber sludge application significantly reduces clay soil erodibility and losses of suspended solids and particulate phosphorus Transport cost and distance define the overall cost and cost-effectiveness
Climate effects	Small if gypsum is an industrial by-product, larger for mined gypsum	Production of structure lime causes greenhouse gas emissions, but the climate effects of industry by-products are smaller	Contributes to soil carbon storage

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