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Gypsum and structure lime amendments in boreal agricultural clay soils: Do climate emissions compromise water quality benefits?

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We examine cost-effectiveness and social net benefits of using soil amendments, gypsum and structure lime, in reducing phosphorus loading while accounting for the climate emissions from both amendments. Recent field experiments and large-scale pilots in Finland and Sweden suggest that both gypsum and structure lime improve soil structure and can reduce total P loading from clayey fields but differ as soil amendments. While gypsum does not change soil pH, structure lime helps to adjust it to a desired level. Drawing on literature, gypsum is postulated to reduce both dissolved (25%) and particulate losses (50%) of phosphorus, while structure lime is postulated to reduce only particulate phosphorus (40%). Life-cycle analysis is applied to determine greenhouse gas emissions from both soil amendments. We examine 5 and 10 years impacts on phosphorus loss by choosing doses and their timing accordingly. Both amendments provide the highest water quality benefits on erodible soils or soils with high soil phosphorus. Accounting for climate issues drastically changes the picture. Greenhouse gas emissions from gypsum production are 14.43 kgCO_2e ha^{-1}, and those from structure lime from pristine materials are 1837 kgCO_2e ha^{-1}. Cost-effectiveness of P load reduction including carbon price of GHG emissions is 59 € kg^{-1}P for gypsum and 122 € kg^{-1}P for structure lime. At the national level (application to 0.54 Mha), differences in greenhouse gas emissions without soil emissions are huge and in favour of gypsum (0.048 Mt and 1.04 Mt). Structure lime from recycled zero-emission materials performs well but its supply is very limited.

Key words: phosphorus loss, water quality, soil amendment, greenhouse gas emissions, cost-effectiveness, JEL classification: Q16, Q18, Q53

Introduction

The Baltic Sea suffers from severe eutrophication due to nutrient loads from industrial and municipal point sources, and especially from agricultural nonpoint sources. For science and policy targeting water pollution, the hardest challenge is to reduce nonpoint loads from agricultural fields. Despite many efforts in both Europe and the US, success has been modest (Shortle et al. 2021). The primary challenge for agricultural water protection policy relates to agricultural areas that exhibit excessive soil phosphorus (P) status because it takes decades to “mine” this “legacy P”. In search of more efficient and rapid agricultural management practices, some countries are promoting soil amendments either using gypsum (Finland, US) or structure lime (Sweden) to reduce P loading (e.g., Ekholm et al. 2012, Ulén and Etana, 2014, Kost et al. 2018). Soil amendments can be considered an interim measure that allows time for the time-consuming lowering of legacy P.

Both gypsum and structure lime have been found to improve the structure of clay soils and promote the formation of larger soil aggregates, thus reducing P loading from fields and keeping P available for crop growth. Although gypsum ($CaSO_4 \cdot 2H_2O$) has been used for soil improvement for centuries (Shainberg et al. 1989), its role as a water protection measure was discovered only recently (Zhu and Alva 1994, Aura et al. 2006). Although lime is a traditional agronomic means to keep pH at a desired level, the use of structure lime (a mix of $CaCO_3$ and CaO or $Ca[OH]_2$) is of a more recent origin. Berglund (1971), Bell (1996), Blomqvist and Berglund (2021) and Al-Mukhtar et al. (2010), among others, established the stabilizing impacts of structure lime on clay soils and its ability to reduce P loading. As a historical anecdote we note that the farmer magazine Käytännön Maamies (no 4/1953, p. 14) advertised enriched calcium carbonate as follows: the new soil amendment is delivered in paper sacks and it contains 58% reactive lime (CaO).

Laboratory and field experiments as well as large-scale pilots have suggested that both gypsum and structure lime have a considerable ability to reduce total P (totP) loading from clayey fields (e.g., Berglund 1971, Blomquist and

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Berglund 2021, Ekholm et al., 2012, 2024). While the reductive impacts of both materials are well established, measurements concerning the effects somewhat differ across field experiments. Nevertheless, the results provide strong grounds for society to promote the use of gypsum and structure lime for water protection purposes. A feature not focused on thus far is the carbon footprint of gypsum and structure lime amendments. Given the extensive efforts to mitigate climate change in Europe, the carbon footprints of alternative management practices in all sectors, agriculture included, are receiving increasing attention. The EU is applying the “do no significant harm principle” to all environmental policies. This principle emphasizes the need to also consider the greenhouse gas (GHG) emissions from soil amendments. As is well known, the production of lime is a great source of GHG emissions (IPCC 2006, West and Marland 2002, Stork et al. 2014) , and this feature is also present in manufacturing structure lime; the emissions depend on the share of recycled materials in the production process. Gypsum in turn is a side-product of phosphoric acid production, and its carbon footprint depends on the allocation of emissions between the two products. Gypsum is also available from other sources, but those are less used in Europe.

The presence of the climate mitigation aspect raises the question of whether climate damage is so large that it outweighs the benefits from reduced P loading. Furthermore, if the use of soil amendments turns out to be desirable, on what type of field do soil amendments give the highest benefits? These questions constitute the research problem of this paper. Drawing on the literature reporting the impacts of gypsum and structure lime amendments, we assess the economics of reducing P loading using soil amendments by adding climate emissions from both materials as a new variable in the analysis. Gypsum and structure lime differ as soil amendments. While gypsum does not affect soil pH, structure lime helps to increase it. Thus, while using the former is predominantly an investment in water protection, the latter is at the same time an investment in crop production and water protection, and when used it replaces conventional agricultural lime. We account for this difference in our analysis and also note that the government provides subsidies to farmers for using structure lime in Sweden and for using gypsum in Finland. In both countries, the ground for both subsidies lies on the expected water quality benefits.

Our research questions are: i) what is the cost-effectiveness of gypsum and structure lime in reducing phosphorus loads, ii) how does accounting for climate effects of both amendments change their cost-effectiveness ratios, and iii) what are the overall net social benefits of both amendments? We build our answer to these question on a social cost–benefit analysis, but with the special feature that we also employ the principles of life cycle analysis (LCA) in determining GHG emissions (Curran 2013, Habert 2013, Boardman 2014). In this framework, soil amendment is treated as an investment in water protection, providing an annual reduction in P loading during the duration of the investment.

We use the results on P loading from the literature, especially from Sweden and Finland. For GHG emissions from using soil amendments, we provide a genuinely new analysis. Furthermore, we employ sensitivity analysis to shed new light on the management issues needed to ensure the successful use and targeting of gypsum and structure lime.

Impacts of gypsum and structure lime amendment on phosphorus loading – a literature review

Literature on the impacts of gypsum and structure lime comes mostly from Finland, Sweden and the US. Research in Finland and the US has predominantly focused on the impacts of gypsum and in Sweden on structure lime. In this section, we will review and discuss the effects of gypsum and structure lime on P loading.

Effects of gypsum on P loading

Gypsum, or calcium sulfate dihydrate ($CaSO_4 \cdot 2\,H_2O$), is a mineral that is available in nature and is also produced as a byproduct of phosphoric acid manufacturing (Ekholm et al. 2012). Another source of gypsum, widely used in the US, is formed by flue-gas desulfurization in coal-fired plants (Kost et al. 2018). When spread on the fields, gypsum is dissolved into calcium and sulfate ions. The subsequent increased ionic strength of the soil solution promotes the micro-aggregation of the soil particles and thereby reduces particulate phosphorus (PP) losses (Uusitalo et al. 2012). In addition, it increases the binding of phosphate on soil particles and favors the formation of Ca-P associations (Muneer and Oades 1989, Uusitalo et al. 2012), which lower dissolved reactive phosphorus (DRP) losses. Table 1 collects the main peer-reviewed contributions to gypsum and reports the main findings by field- and catchment scale studies on P loading from clayey soils.

Table 1. Impact of gypsum on phosphorus loads on clay soils based on peer-reviewed long-term studies on a field- or catchment scale

Source	Type of experiment	Dose t ha	Reduction, %		Duration of experiment, years
			PP	DRP	
Uusitalo et al. (2012)a)	field and lab	6	59–74	43–63	2.6
Uusitalo et al. (2012)b)	field and lab	3	58	54	2.6
Ekholm et al. (2012)	catchment	4	64	29	2.5
Ekholm et al. (2024)c)	catchment	4	35–72	–3–25	5

DRP = dissolved reactive phosphorus, PP = particulate phosphorus; a) Reduction in concentrations, means over the 31-mo study (6 tn ha^{-1} dose was applied on two fields, 3 tn ha^{-1} on one field) b) Reduction in loads. c) The reported range indicates observed differences in two measurement areas in the SAVE pilot in the Savijoki River.

In Finland, Aura et al. (2006) were the first to report the reduction in particulate and dissolved P by gypsum in clay suspensions in Finnish soil. Pietola (2008) extended lab experiments to cover different soil types. She employed a dose of 4 g kg^{-1}, which corresponds to the Finnish "standard" rate of 4 t ha^{-1}. Interestingly, gypsum also reduced P loading in fine sands and organic soils, which has not received much attention lately. Uusitalo et al. (2012) performed an experiment on clay soils in which gypsum was applied on two fields (on both at 6 tn ha^{-1} and on one of them also at 3 tn ha^{-1} rate) and undisturbed soil columns were taken to the laboratory for artificial rainfall; a typical Finnish gentle rain intensity of 5 mm h^{-1} was applied on two consecutive days. The 31-month mean impact of applying gypsum was drastic (Table 1), as the particulate P concentration in the through-flow water decreased on average by 60% (range in the individual rainfall simulations conducted in 3 subsequent years was 25 to 92% reduction) and the dissolved reactive phosphorus decreased on average by 43% (range from 16% increase to 91% decrease relative to untreated control soil). In addition, the concentration of dissolved organic carbon was reduced by one third. The effects gradually declined over the 31-month study period as gypsum leached through the soil profile. The set-up of this experiment is considered to show the effect of gypsum on mobilization of P forms from soil to runoff on the field.

Shifting the focus to the catchment level, Ekholm et al. (2012) reported an experiment covering 101 ha of arable lands, 91% of which were amended with gypsum (4 t ha^{-1}). Gypsum amendment reduced the losses of PP by 64% and DRP by 29% as a 2.5-year average. A large catchment scale study (SAVE) in the Savijoki River treated 1 492 ha of agricultural land with 4 tons gypsum per ha (Ollikainen et al. 2020). The SAVE II project continued the measurement of P reduction in the same pilot area, and the findings suggested a wide range: a 5-year average reduction of 34–70% for PP and –3–25% for DRP, the range reflecting the observations in two neighbouring measurement areas (Ekholm et al. 2024). John Nurminen Foundation arranged an even larger pilot of 3500 ha in the River Vantaa catchment in 2019–2021. The preliminary results for the first 1.5 years suggested that gypsum amendment reduced PP by 53% and DRP and dissolved organic carbon to some extent (Vantaanjoen kipsihanke 2020). Outside Finland, only few field- or catchment scale studies have been performed on clayey soils and with several years long monitoring period.

Thus, a rather robust assumption is that gypsum reduces PP loading on average by 50%. As the results concerning DRP reduction are more uncertain, we will use 25% as the benchmark DRP reduction but also examine the case of zero impact in the sensitivity analysis. The Savijoki pilot is the first to examine a sufficiently long duration of impacts and suggests that a time period of at least 5 years, although lessening with time (Ekholm et al. 2022). Similarly, Aakriti et al. (2023) provide an LCA based review of environmental and economic impacts of various products made of flue-gas desulfurization gypsum and Endale et al. (2014) provide an analysis of gypsum with the application of broiler litter.

Effects of structure lime on P loading

The term structure lime refers to products that add a reactive component, either quicklime (CaO) or hydrated (slaked) lime ($Ca[OH]_2$), into conventional agricultural lime ($CaCO_3$) (Ulén and Etana 2014). Alternatively, it may refer to side products that are composed of quicklime/slaked lime and calcium carbonate. Structure lime is not, however, a homogenous product, and the share of reactive components typically varies between 15% and 40%. For example, the structure lime currently used in Sweden contains 15–20% hydrated lime, the remaining part being $CaCO_3$ (Blomquist 2021). In Finland, a lime containing about 19–25% reactive calcium was used by Kämäri et al. (2019) and Anttila et al. (2021) in two large pilots. Side-stream kilned lime from the forest industry, used in agriculture where available, typically contains higher shares of reactive lime ($CaO/Ca[OH]_2$), up to over 40%, determined for Finnish side-stream structure lime products (unpublished data of Luke). Structure lime may thus be manufactured from pristine materials or from recycled materials, often as a combination of both.

When mixed with a clay soil structure, structure lime creates several reactions, including increases in the ionic strength of soil water, cation exchange, flocculation and agglomeration together with slower cementing and almost irreversible pozzolanic reactions (Kavak and Baykal 2012). While cation exchange may take place within a day, the completion of pozzolanic reactions may require a year at low temperatures (Al-Mukhtar et al. 2010). Because pozzolanic reactions require very high pH, it is very uncertain if these occur at all in soil amendment use. The reactions listed result in a tighter binding of P and reduced erosion and P loading (Alakukku and Aura 2006). In general, the higher the clay content is, the higher the amount of the reactive component of the structure lime should be (Berglund 1977, Geranmayeh 2017). Structure lime effectively increases the soil pH level (e.g., Enesi et al. 2023). According to a farmer guide (Ajosenpää et al. 2021), structure lime works best on fields where the aggregate structure is poor and electrical conductivity is low. Structure lime improves the workability of soil (Blomquist et al. 2023). Soil treated with structure lime is suggested to dry up more quickly in the spring and better maintains the aggregate structure, which improves the seedbed. The more even aggregate size distribution in the topsoil reduces evaporation, which is beneficial, especially during dry summers. Table 2 reports the findings from the Swedish and Finnish studies on the impacts of structure lime on clayey soils.

Table 2. Impact of structure lime on phosphorus loads on clay soils

Source	Type of experiment		Dose t ha^{-1} (equivalent to CaO)	Reduction, %		Duration of experiment, years
				PP	DRP	
Ulén and Etana (2014)	field	topsoil	Exp. 1: 5 Exp. 2: 2	Exp. 1: 44 Exp. 2: 0	Exp. 1: 0 Exp. 2: 47	Exp. 1: 6 Exp. 2: 3
Svanbäck et al. (2014)	field	drainage flow	5	42	0	6
Andersson et al. (2016)	lysimeter	subsoil	5	50	0	3
Berglund et al. (2017)	field and lab	topsoil	3	35–50	0	2
Valkama and Mikkilä (2018)	catchment	runoff	3.5–8	seasonal variation 13–78	seasonal variation 0	4.5
Kämäri et al. (2019)	catchment	runoff	1.2	0	0	2
Norberg and Aronsson (2022)	field	drainage flow	1.6; 3.2	28$^{a)}$		3

CaO = calcium oxide, i.e., the reactive component; DRP = dissolved reactive phosphorus; PP = particulate phosphorus; totP = total phosphorus; a) Mean reduction in totP over three years.

Table 2 shows that Swedish studies performed at the field scale suggest that structure lime reduces PP losses by approximately 30–50%, while the effect on DRP varies from study to study. For example, Ulén and Etana (2014) found a 44% reduction in PP loss but no reduction in DRP loss in a field with 60% clay. However, in a field with 25% clay but a high soil P status, they found a reduction of 47% of DRP loss but no reduction in PP. Svanbäck et al. (2014) obtained a 42% reduction in PP loading in drainage flow relative to the benchmark, but no reduction in DRP. To study whether placing CaO on the subsoil could reduce P leaching through macropores, Andersson et al. (2016) found in a three-year lysimeter study that PP loading was reduced by 50% and DRP remained unaffected in two clayey subsoils, whereas DRP was reduced in a sandy soil that showed no effect on PP. Berglund et al. (2017) examined the effects of three different structure lime products in a two-year field study. A pure slaked lime product reduced PP loading by 45%, a mixture of slaked lime and agricultural lime by 50% and a recycled product by 35%. Norberg and Aronsson (2022) found that the common dose of 8 t ha^{-1} of structure lime (with about 20% of CaO) reduced total P loading in the second and third years after treatment by approximately 45% and 26%, respectively. A dose of 16 t ha^{-1} gave a higher retention for the third year (approximately 38%).

Some Swedish studies have estimated the performance of structure lime on the basis of aggregate stability tests (e.g., Blomquist et al. 2018). For example, using a dose of 8 t ha^{-1}, structure lime (with 15–20 % share of slaked lime (Ca[OH]$_2$) has been found to increase aggregate stability for 1–2.5 years by 15–35% (Blomquist 2021). There is strong spatial variability in the performance, and the stabilizing effect likely depends on, e.g., clay content and mineralogy, soil organic matter content and initial pH (Blomquist and Berglund 2021). However, such improvements in tested water-stable aggregates are not directly translated to P loss mitigation, as aggregate stability does not necessarily correlate with actual load reduction (Norberg and Aronsson 2022).

Overall, experimental periods have been too short to provide a concise estimate of the duration of the impact of structure lime amendment and the application rate (Norberg and Aronsson 2022). The effects of structure lime may be long lasting mainly due to a pozzolanic reaction, which is potentially irreversible if such reactions occur. In her survey, Geranmayeh (2017) concluded 10 years as the estimate of the duration of the impacts, with the reduction for PP being 30%.

The Finnish studies on structure lime amendments are of more recent origin and largely not yet published in scientific journals. The first results are from laboratory and field experiments. Alakukku and Aura (2006) found in an artificial rainfall study on undisturbed soil columns treated with soft lime kiln dust, a byproduct from the production of burnt lime, that lime amendment clearly decreased the concentrations of PP and DRP in surface runoff regardless of cultivation type (no-till, stubble cultivation, ploughing). The results from two catchment-scale studies have been reported. Kämäri et al. (2019) applied structure lime (5 t ha^{-1} equivalent to 1.1 t CaO ha^{-1}) to a 41 ha loamy clay soil. The concentrations of PP in runoff were already low before the treatment and were not affected by structure lime. The DRP concentrations may have decreased, but due to infrequent sampling, the finding was uncertain. In another catchment-scale study, Valkama and Luodeslampi (2020) found that structure lime (3.5–8 t ha^{-1}) decreased PP losses most strongly one year after application. The seasonal reductions ranged from 13% to 78%, and after four years, there was no effect anymore. Even though the concentration of water-extractable P in soil increased up to threefold, possibly due to lime-induced elevation in soil pH, the losses of DRP did not increase. Finally, a large pilot on structure lime is underway, and the first results on PP are promising (Anttila et al. 2021).

Drawing on the literature, we adopt the following estimates for the impacts. In the baseline case, we assume that structure lime from pristine material reduces PP loading by 40% and has no impact on DRP loading. To account for variation in measurements in Table 2, we resort to sensitivity analysis for lower (30%) and higher (50%) estimates of PP reduction. Despite small differences in the measured effect on P leaching for structure lime from pristine (40%) and recycled materials (35%), we assume that they exhibit the same effectiveness in reducing P loading. Finnish studies suggest 5 years as the duration of the P-reducing impacts (Valkama and Luodeslampi 2020), while some Swedish studies suggest that the effect might last as long as 10 years if larger amounts of structure lime are applied (e.g., Svanbäck et al. 2014, Ulén and Etana 2014, Geranmayeh 2017). In our main analysis, we postulate that structure lime has an impact over 5 years when 1.2 t ha^{-1} of reactive lime is used. As a hypothetical alternative, we also examine a case where a 10-year-long duration of the impact can be obtained. In this case, we follow the dose reported in Ulén and Etana (2014) and Svanbäck et al. (2014) and assume that this effect is obtained when 5.5 t ha^{-1} of reactive lime is used. We acknowledge that such large quantities may not be practical, unless a soil is extremely acidic, but added this scenario as a hypothetical one.

Most structure lime used in agriculture in Finland is manufactured from pristine sources, mainly kiln dust. Additionally, a very limited amount of structure lime from recycled materials is available. Therefore, and unfortunately, structure lime from recycled materials does not provide a feasible option to reduce Finnish P loads at the large scale in the short run. Therefore, henceforth, we develop our calculations for structure lime from recycled materials in Appendices 1 and 3 but comment on the results throughout the text. In the following analysis, structure lime refers to that originating from pristine material, unless otherwise stated.

P runoff in the Archipelago Sea catchment area

We apply the above reduction rates of gypsum and structure lime to a representative field parcel in southwest Finland. By assumption, the farm cultivates barley under typical agronomic conditions in a field with 15.9 mg l^{-1} as the soil test P value (extraction with pH 4.65 ammonium acetate; Vuorinen and Mäkitie 1955), which denotes the average soil P value in the catchment area of the Archipelago Sea. We employ the P runoff functions from Uusitalo and Jansson (2002) and Saarela et al. (1995) to determine P loads at the field edge with and without soil amendments. For both structure lime products, we assume that a 1.2 t dose of reactive lime (i.e., $CaO/Ca[OH]_2$) per hectare has the measured P load reduction for 5 years. For the 10-year effectiveness, we use a 5.5 t/ha application of reactive lime drawing on Table 2. Assumptions concerning erosion and precipitation are based on data in the Archipelago Sea catchment area (values are given in Table A2, Appendix 2). Table 3 reports the baseline P runoff (no soil amendments) and the runoff under soil amendments at the field edge.

Table 3. P runoff at the field edge with and without gypsum and structure lime amendments in the catchment of the Archipelago Sea

	P runoff, kg ha^{-1} y^{-1}		
	No amendment	Gypsum	Structure lime
DRP	0.50	0.37	0.50
PP	1.31	0.66	0.79
totP	1.81	1.03	1.28

DRP = dissolved reactive phosphorus; PP = particulate phosphorus; totP = total phosphorus

Phosphorus runoff from the average field in the Archipelago Sea is rather high, clearly exceeding the Finnish average of 1.1 kg ha^{-1} y^{-1} (Tattari et al. 2017). Gypsum provides an almost 50% reduction in totP loads, and structure lime results in a reduction of slightly more than 30%. Differences in PP reduction between the amendments are rather small. The most important difference between soil amendments is that gypsum also reduces DRP, but structure lime does not. Although smaller, DRP is readily available for algal growth and thus contributes disproportionately to eutrophication.

Determination of GHG emissions and costs from gypsum and structure lime amendments

We assess GHG emissions in terms of carbon dioxide equivalent (CO_2e) emissions. It is a metric measure that helps one to compare emissions from various GHGs on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide (CO_2) with the same global warming potential. Carbon dioxide-equivalent emissions and costs from both gypsum and structure lime amendments result from three sources: production, transport and spreading. Additionally, the application of agricultural lime within structure lime causes emissions from soil, which are, however, largely displayed since conventional agricultural lime is not applied for fields treated with structure lime (soil emissions are omitted here but included in Table 5 to calculate the net emissions from cultivation).

We employ an LCA analysis to determine the GHG emissions from the production of gypsum and structure lime (for details, see Appendix 1). For gypsum we apply the economic allocation principle for GHG emissions from the production of phosphorus acid. For structure lime, we apply emissions reported in Nordkalk's sustainability reports 2021 and 2022 for quicklime (Nordkalk 2021, 2022). Those emissions are very close to the average European assessments of GHG emissions. Nordkalk manufactures a small amount of structure lime from lime kiln dust (LKD). Economic allocation of emissions suggests that GHG emissions from this product are close to zero. This amount is, however, so small that it would not be realistic option for a nation-wide soil amendment of arable lands for water quality purposes. Given the variety of raw material sources for structure lime, we distinguish between two extremes assuming that structure lime is manufactured either using pristine materials only or alternatively using solely recycled materials. Many available products lie between these extremes, and their impacts can be approximated using these two figures (see Fig. A1 in Appendix 1).

Table 4 collects GHG emissions and costs related to the use of soil amendments when the aim is to achieve either 5 or 10 years' long reductive impact on the P loss (detailed calculations of emissions from production and transport are reported in Appendix 1). For the 5-year impact, gypsum and structure lime are applied at the beginning of the first year. For the 10-year impact, gypsum is applied in the first and sixth years, while structure lime is applied only in the first year but with an increased application rate (5 t reactive lime instead of 1.2 t). See Figure 1 for a schematic illustration.

Table 4. GHG emissions without soil emissions and costs in terms of net present value (NPV) for gypsum and structure lime: production, transport spreading and harrowing (5 and 10 years).

	Gypsum, 5 years (1 application)		Gypsum, 10 years (2 applications)		Structure lime, 5-year duration		Structure lime, 10-year duration	
	Emissions, kgCO_2e ha^{-1}	Costs, € ha^{-1}	Emissions, kgCO_2e ha^{-1}	Costs, € ha^{-1}	Emissions, kgCO_2e ha^{-1}	Costs, € ha^{-1}	Emissions, kgCO_2e ha^{-1}	Costs, € ha^{-1}
Production/Price	14.4	72.6	28.9	135	1837	173	8420	791
Transport	54.2	129	108	239	9.79	23.2	44.9	106
Spreading	19.6	26.0	39.2	48.4	19.6	26.0	19.6	26.0
Harrowing	-	-	-	-	39.2	70.6	39.2	70.6
Total	88.3	227	177	423	1906	292	8524	994

Starting with GHG emissions in Table 4, differences between gypsum and structure lime are considerable. Structure lime causes more than 21 times higher emissions for a 5-year impact, most of the emissions stemming from the production stage. The difference in emissions is even higher for a 10-year impact. For gypsum, the economic allocation of emissions from manufacturing phosphorus acid yields 3.61 kgCO$_2$e t^{-1}, giving 14.43 kgCO$_2$e ha^{-1} when 4 tons are applied. Emissions from structure lime production (with 24.6% as the share of quicklime, CaO), are much higher, 367.4 kgCO$_2$e t^{-1}, giving 1837 kgCO$_2$e ha^{-1} with 5 tons applied. Gypsum has slightly higher emissions from transport due to a longer transport distance.

In cost calculations, we use 18.15 € t^{-1} as the price of gypsum (Ollikainen et al. 2020), and 34.50 € t^{-1} as the price of structure lime (KM 2022) (see also background data in Table A1 and A2 of Appendix 2). As structure lime substitutes for agricultural lime (see Section 3, Agronomic data), agricultural lime is not applied to fields receiving structure lime. The cultivation costs are therefore reduced by the amount that would have been needed to purchase agricultural lime (9 € t^{-1} with application of 4.5 t ha^{-1}), along with the spreading cost. When structure lime reduces P loads for 10 years, agricultural lime is applied on year 6 to keep the soil pH at the desired level, and these costs are included in the analysis (see also Fig. 1). For transport, we employ an identical unit cost of 0.071 € km^{-1}; thus, costs differ because of distance, while spreading costs are 26 € ha^{-1} (Ollikainen et al. 2020). For the cost of disc harrowing of structure lime, we use 35.3 € ha^{-1}, which was the average price for 2018 (Palva 2021) and multiply this by two. Thus, we conclude that the application costs are lower for gypsum, mostly because structure lime has a higher price than gypsum and it must to be harrowed twice to ensure the P loss reducing effect.

We provide a similar analysis for structure lime from recycled materials (detailed calculations are given in Appendices 1 and 3). Recycled structure lime is assumed to reduce P loss by 40%, i.e., the effectiveness is the same as for structure lime from pristine materials. Provided that the manufacturer's reported LCA data on GHG emissions are correct, structure lime from recycled materials causes low GHG emissions, 79 kgCO$_2$e ha^{-1} (5-year duration of the impact) and 126 kgCO$_2$e ha^{-1} (10-year duration with a higher dose). Its costs are the second lowest (238 € ha^{-1}) for the 5-year impact on P loss but quite high (742 € ha^{-1}) for the 10-year impact.

Framework and data

Net benefits and cost-effectiveness

We consider gypsum and structure lime amendments as an investment in water protection (see Fig. 1 for the full outline of the investment and other decisions). Both investments are costly; thus, the environmental benefits should be higher than the investment costs. Let $\hat{\pi}$ denote annual (short-term) profit from ordinary, baseline cultivation (i.e., private profits), $d_p z(P)$ denote the eutrophication damage from total P runoff (with d_p as the marginal damage) and $d_c e$ indicate climate damage from GHG emissions from cultivation comprising emissions from fossil fuels and the soil (with d_c as the marginal damage). Therefore, the annual social net benefits (B) from cultivation without investment in soil amendments are as follows:

$$B_0 = \hat{\pi} - d_P z(P) - d_C e \tag{1}$$

Equation (1) gives the benchmark social net benefits from agricultural choices as a sum of private profits and environmental damages relating to them in the absence of water protection investment. In its simplest form, private profit, $\hat{\pi}$, is given as $\hat{\pi} = pf(F)-cF-M$, where p is the crop price, $f(F)$ denotes the yield response function, F refers to combined N, K and P fertilizer, c is the cost of fertilizer, and M is the fixed cost of cultivation (see Shortle et al. 2021). The time horizon of our analysis is 5 and 10 years, reflecting the above discussion on how long the soil amendments affect P loading. Thus, the net present value of baseline cultivation over the given years (i.e., NPV of social net benefits), that expresses the current value of future benefits and costs, provides our benchmark (t denotes years and r the discount rate):

$$B_A = \sum_{t=1}^{h} B_0 (1+r)^{-(t-1)}, \text{ h = 5,10} \tag{2}$$

An important feature of both soil amendment materials is that they do not take land out of cultivation and cause additional costs via reduced yields. Structure lime amendment may sometimes increase yields, whereas gypsum amendment is neutral in terms of yields. We denote soil amendment in general by X. Thus, X is either gypsum (G) or structure lime (S). Private profits from cultivation with soil amendment are denoted $\pi_t(X)$. Furthermore, we express P loads as a function of soil amendments $z_t(P(X))$ and all GHG emissions related to soil amendment treatment by $e_1(X)$. Cultivation emissions not related to soil amendments, as in Eq. (1), are denoted with e_t. The investment cost related to the use of soil amendments is denoted with . The social net benefits from soil amendment and cultivation are given as follows:

$$B_X = -I_X - d_C e_1(X) + \sum_{t=1}^{h} [\pi_t(X) - d_P z_t(P(X)) - d_C e_t](1+r)^{-(t-1)}, \tag{3}$$

where *X* denotes either gypsum, G, or structure lime, S. We assume that structure lime may increase crop yields and thereby also private profits ($\pi(S) \geq \hat{\pi}$), but this is not the case for gypsum ($\pi(G) = \hat{\pi}$).

We will quantitatively compare Equations (2) and (3) to see how well gypsum and structure lime perform as soil amendments relative to the baseline. Interpretation of this comparison is straightforward: if B_G and B_S exceed B_A, the use of soil amendments is socially desirable.

The above analysis also provides information to develop the required cost-effectiveness of the measures. They focus solely on investment costs and environmental benefits. A simple cost-effectiveness ratio is given in Equation (4a):

$$m = \frac{Investment\ costs}{P - reduction}\ , \tag{4a}$$

where we naturally account for the annual reduction in P loading during the five or ten years. When damage from additional GHG emissions relative to the baseline is considered, the cost-effectiveness ratio is transformed to the following:

$$m = \frac{Investment\ costs + damage\ from\ GHG\ emissions\ from\ soil\ amendments}{total\ P - reduction} \tag{4b}$$

Equation (4b) indicates that damage from GHG emissions increases the costs of using soil amendments.

Agronomic data and specification of the case study

To determine cost-effectiveness and net benefits, we need to characterize revenue from crops and costs of cultivation. Furthermore, we need to make assumptions on how soil amendments enter farmers' management plans and impact crop yields.

The use of gypsum does not change soil pH and, thus, can be treated as independent of farmers' choices concerning crops and pH. YARA conducted a series of field experiments to examine how gypsum impacts crop yields (Ylivainio 2020). No yield penalties were found, but in fields with obvious sulfur deficits, gypsum increased crop growth. For certain crops (e.g., potato and sugar beet), calcium in pH-neutral gypsum can increase the yield quality. Despite this, we conduct the calculation assuming no yield increase for gypsum. This is in line with a US meta-analysis, which did not show any negative or positive effect of gypsum on yield (Kost et al. 2018). Individual studies have suggested that in some cases, the yield can be improved (e.g., Toma et al. 1999), but this seems not to be a general pattern.

Analysis of structure lime requires some consideration. Depending on the crop, farmers aim at crop-specific pH levels. Farmers use agricultural lime to increase or maintain soil pH to desired levels. Liming improves the availability of nutrients and in acidic soils it increases yields. For instance, Uusitalo et al. (2012) applied agricultural lime on two field plots differing in P status and tillage depth and from which soil columns were taken to the laboratory for leaching studies spanning 7, 19 and 31 months after lime amendment. They did not find any statistically significant difference in the concentration of PP of percolation water from soil columns treated with agricultural lime as compared with unlimed controls through rainfall simulations. However, the concentration of DRP was 10–14% higher in the lime-treated unit than in the controls. In Finnish agriculture, farmers make maintenance liming (2–5 t ha^{-1}) roughly every five years. Given the rather high difference in prices of agricultural lime and structure lime, farmers most likely do not use structure lime for pH maintenance as a substitute for agricultural lime unless the soil structure is very labile. In the pH management plan, structure lime has the same yield effects as agricultural lime, and in addition, it provides additional benefits from improved soil structure.

Studies on the effects of structure lime on crop yields have suggested various outcomes over the years and different areas. The estimates vary from a 13% reduction to slight increases in crop yields (Svanbäck et al. 2014, Berglund et al. 2017, Blomquist et al. 2018, Ajosenpää et al. 2021, Norberg and Aronsson 2022). Blomqvist et al.

(2018) reported results from an experiment where the yield effect varied between –4 and +3% on average over four years. For our analysis, especially important is the finding by Blomquist et al. (2018) concerning barley yields; they concluded that crop yield responses were inconsistent, with changes in spring barley grain yield of ±10%. Decreased availability of micronutrients through binding in limed soil can possibly explain the observed yield decreases. Yield increases were likely attributable to a finer tilth (Blomquist et al. 2018).

Drawing on these ambiguous results, we assume that farmers use structure lime for water protection and maintenance of soil pH. Therefore, in the baseline, we do not postulate any yield effect above what would have been achieved using ordinary agricultural lime. Nevertheless, we check in the sensitivity analysis for the case where structure lime is assumed to increase yields more than agricultural lime. We employ a crop yield function estimated for barley to determine the yields (see Appendix 1 Table A2). For emissions from cultivation, we use an estimate for emissions from soil, machinery and fertilization from Lötjönen and Ollikainen (2019).

Figure 1 provides a schematic illustration of our approach. The farmer's private choice provides the baseline for the comparison of soil amendments. In year 1, the farmer invests in soil amendments. In the private solution and under gypsum amendment, agricultural lime is used to change pH, followed by four years of ordinary cultivation, and in year 6, another investment is made, followed again by four years of cultivation. Structure lime amendment does not require agricultural lime in year one but does in year 6 in the case of a 10-year duration of the impact.

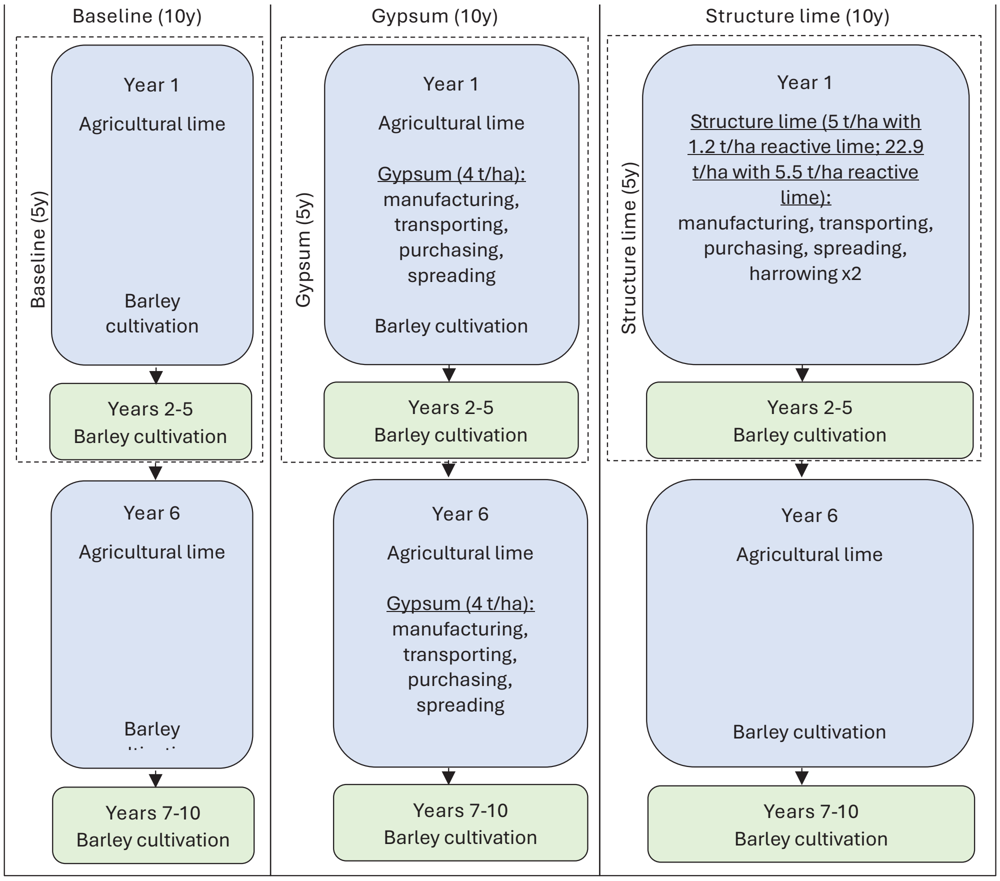

Fig. 1. Schematic illustration of the 5-year and 10-year calculations

Table 5 collects net revenue from cultivation and all employed values for climate and water quality impacts. Given that more than 90% of the Finnish farms participate in the national agri-environmental scheme, we assume that farmers apply the allowed levels of N and P fertilization (N = 100 kg ha^{-1} and P = 5 kg ha^{-1}), which imply a barley yield of 4413 kg ha^{-1}. The tight restriction on P fertilizer use reflects a field with good soil P status. Structure lime contains agricultural lime the application of which causes emissions from soil. For a 5-year duration, the share of agricultural lime is 3.8 t ha^{-1} with soil emissions of 1672 kgCO$_2$e ha^{-1}. For a 10-year duration, the share of agricultural lime is 17.4 t ha^{-1} with soil emissions of 7663 kgCO$_2$e ha^{-1}. These emissions are largely displayed since conventional agricultural lime is not applied for fields treated with structure lime. Table 5 contains soil emissions from both the direct use of agricultural lime and from its share in structure lime.

Table 5. Annual GHG emissions, water quality impacts and net revenues over different years (see Appendices 1 and 2 for details and references)

	Baseline, no soil amendment, 5-year and 10-year durations	Gypsum, 5-year and 10-year durations	Structure lime, 5-year duration	Structure lime, 10-year duration
Costs, € ha^{-1}				
Fertilizer	174	174	174	174
Variable	101	101	101	101
Fixed	362	362	362	362
Agricultural lime (purchase and spreading)	67	67	-	67*
Total costs, year 1, € ha^{-1}	703	703	637	637
Total costs, year 6, € ha^{-1}	703	703	-	703
Total costs, other years, € ha^{-1}	637	637	637	637
Soil amendment, total, € ha^{-1} (see Table 4)	0	227	292	994
Revenue, € ha^{-1}				
Crop yield	768	768	768	768
LFA	217	217	217	217
Total revenue, € ha^{-1}	985	985	985	985
Net revenue, year 1, € ha^{-1}	281	54	56	-646
Net revenue, year 6, € ha^{-1-1}	281	54	-	281
Net revenue, other years, € ha^{-1}	348	348	348	348
GHG emissions, kgCO$_2$e ha^{-1}				
Soil emissions	1855	1855	1855	1855
Management practices	489	489	489	489
N_2O due to mineral N fertilization	671	671	671	671
Mineral N fertilizer manufacture	432	432	432	432
Agricultural lime (production and soil)	2572	2572	-	2572*
Agricultural lime in structure lime (soil)	-	-	1672	7663
Soil amendment (see Table 4)	-	117	1906	8524
Total GHG emissions, year 1, kgCO$_2$e ha^{-1}	6018	6106	7024	19633
Total GHG emissions, year 6, kgCO$_2$e ha^{-1}	6018	-	-	6018
Total GHG emissions, other years, kgCO$_2$e ha^{-1}	3446	3446	3446	3446
Nutrient runoff, kg ha^{-1}				
N runoff	15	15	15	15
DRP runoff	0.50	0.37	0.50	0.50
PP runoff	1.31	0.66	0.79	0.79
totP runoff	1.81	1.03	1.28	1.28

*Only on year 6

Farmer revenue comes from selling crops. We also include the social valuation of agricultural landscapes by including a support component devoted to less favourable areas (LFAs) on the revenue side. Costs from soil amendments are expressed on a per hectare basis, and gypsum is approximately 65 € ha^{-1} cheaper than structure lime with 5-year effectiveness. The net revenue from cultivation with agricultural lime application is 281 € ha^{-1} and in other years 348 € ha^{-1}. A further notable feature is that cultivation itself causes very high GHG emissions, 6018 kgCO$_2$e ha^{-1} with agricultural lime and 3446 kgCO$_2$e ha^{-1} without. Soil amendments increase emissions slightly (gypsum) or substantially (structure lime, including soil emission from agricultural lime within the product). Owing to a lack of data, we focus only on CO_2 emissions from soil amendments, although they may also impact N_2O emissions (Nadeem et al. 2020).

We use these figures as data to solve for the cost-effectiveness properties of both soil amendments, where the costs are related to the obtained reduction in P loads. The costs comprise the annual present value of the direct cost of soil amendments or of the sum of the direct cost and climate damage from GHG emissions. We then employ the above framework to assess the social net benefits of both soil amendments. Finally, note that both soil amendments also create important environmental co-benefits. Gypsum reduces the loss of particulate and dissolved carbon loads, thus contributing to water quality, climate mitigation, and agricultural productivity. Under current limited knowledge, any comparison of climate processes taking place in soil or in water does not warrant a monetary analysis of these benefits. In a similar vein, by possibly increasing yield, structure lime may increase carbon sequestration in soil, but in this case, the size of this effect is hard to quantify.

Cost-effectiveness and net benefits of soil amendments

Cost-effectiveness in reducing P loading

Table 6 condenses the cost-effectiveness analysis for P load reduction by considering only the treatment costs of soil amendments (denoted by I) and alternatively the sum of treatment and increased climate costs from greenhouse gas emissions (I + GHG), both defined in Equations (4a) and (4b), respectively. For this analysis, the treatment cost of structure lime is decreased by the purchase and spreading costs of agricultural lime (transport cost is negligible). We report ratios for 5- and 10-year impact durations; costs are given as present values.

Table 6. Cost-effectiveness (€ kg^{-1} P reduction) of gypsum and structure lime amendments based on annual treatment costs only (I) and annual treatment costs and increased climate costs (I+GHG)

	Reduction in totP load, kg ha^{-1} y^{-1}	Cost-effectiveness (€ kg^{-1} P)	
		I	I + GHG
Gypsum (5 y)	0.78	58.2	59.0
Gypsum (10 y)	0.78	54.2	55.0
Structure lime (5 y)	0.53	86.0	121.7
Structure lime (10 y)	0.53	176.6	318.4

Table 6 shows a clear difference between the soil amendments in favour of gypsum. The difference in the cost-effectiveness figures (euros per reduced totP) between the soil amendments results from the differences in treatment costs and in the reduction of totP loads. This difference decreases if structure lime amendment increases yields beyond that of agricultural lime and this is accounted as a reduction in the investment cost. Accounting for GHG emissions as a negative externality increases the costs of both soil amendments and the wedge between structure lime and gypsum.

Private and social net benefits

Table 7 determines net private profits and ex post net social benefits (i.e., social net benefits resulting from the privately optimal management which omits water and climate externalities) from cultivation in the absence and presence of soil amendments as a net present value (NPV). To determine the social benefits in monetary terms, we need to value eutrophication and climate damages. As monetary estimates, we employ 35 € t^{-1} CO_2e for climate damage (based on Tol 2011) and, using nitrogen equivalents, Ne, to aggregate P and N, 11.6 € kg^{-1}Ne for eutrophication damage (Gren 2001, value modified to year 2023 using a 2-% discount rate).

Table 7. NPV of private profits and social net benefits over 5 or 10 years with a 3% discount rate (€ ha^{-1})

	Private profits (NPV)	Social net benefits (NPV)		
		P	GHG	P + GHG
Baseline, 5 years (€ ha/5 years)	1575	862	916	203
Gypsum, treatment on year 1 (€/ha/5 years)	1347	**942**	685	**280**
Structure lime, duration 5 years, €/ha/5 years)	1349	843	596	90
Baseline, duration 10 years (€/ha/10 years)	2933	1606	1705	378
Gypsum, treatment on years 1 and 6 (€/ha/10 years)	2510	**1755**	1277	**522**
Structure lime, duration 10 years (€/ha/10 years)	2006	1064	34	–908

Notice first that in all cases, soil amendments reduce private profits compared to the baseline without soil amendments; thus, their use for water protection is not privately optimal unless they increase yields to offset the costs. The use of conventional agricultural lime ($CaCO_3$) aims precisely at higher yields. It helps to adjust pH to the desired level and make nutrients more easily available for crops. Gypsum does not change pH but it contains a small share of P and lots of S, thus, it may increase yields only if the field is suffering from sulfur deficiency. Structure lime increases soil pH and may increase yields more than agricultural lime that it replaces. Unlike farmers, society also considers damage from P loads and GHG emissions. We account only for the P loads in the second column and only for the GHG emissions in the third column. The second and fourth columns are the most relevant for our analysis. Cultivation with gypsum amendment provides a higher net present value of social net benefits than the baseline when only P runoff or both P runoff and GHG emissions are included. The social net benefits of structure lime always remain below the baseline. To see if structure lime would become socially acceptable, we need to resort to a sensitivity analysis. We restrict the sensitivity analysis only for the case of a 5-year duration of the impact, as structure lime has negative net benefits and thus performs very poorly for a 10-year duration.

Regarding structure lime produced from recycled materials (reported in Appendices 1 and 3), it performs well for a 5-year duration, with the highest private profits after baseline, and the second highest social welfare when the P load or both the P load and GHG emissions are considered. For a 10-year duration, it performs weakly, but better than structure lime from pristine material. Regardless, structure lime from recycled materials provides an interesting alternative. Unfortunately, its availability is so restricted that it cannot be relied on for national plans.

Sensitivity analysis: the impact of exogenous variables

The above results depend on many assumptions related to environmental damage. With regard to water protection, an assumption on the rate of erosion is crucial, as structure lime mostly reduces erosion, but reduced erosion also makes the most of gypsum's impact on P loss. The soil P value especially affects the runoff of DRP but also PP (Uusitalo and Aura 2005). Also, we need to account for variation in the measured P reduction of both amendments, especially concerning DRP in the case of gypsum. Furthermore, valuation of social damage from eutrophication and climate damage plays a crucial role. Recall that in the above calculations, erosion was set at 1.1 t ha^{-1}, and the soil P value was set at 15.9 mg l^{-1} in the P runoff functions. The climate damage estimate was 35 € $t^{-1}CO_2e$, an undervaluation in the presence of current policies, and runoff damage was set to 11.6 € kg^{-1}Ne. Table 8 provides relevant results for lower and higher values of erosion and soil P and higher values for damage estimates. In the analyses, only one parameter is changed at a time, everything else being the same as in the basic calculations above.

Sensitivity analysis helps us characterize under what conditions soil amendments could play an especially important role. For gypsum, a lower 34% reduction in PP and no reduction in DRP would make its social net benefit fall below the baseline, where no action is taken for water protection, while the higher reduction of PP by 50% makes it an extremely beneficial water protection measure. With a 2% yield increase above what agricultural lime would do, or a higher, 50% PP reduction, the net benefits from structure lime also become higher than the baseline. Concerning the state of arable soils (lower erosion or lower soil P status) and for the eutrophication damage estimate used, the social net benefit of gypsum and structure lime decrease. However, with lower erosion gypsum still provides higher social net benefits than the baseline. For low erosion or low soil P status, the baseline P runoff is rather small, making soil amendments less effective (total P runoff without soil amendments: 1.54 kg ha^{-1} for low erosion and 1.15 kg ha^{-1} for low soil P value). For other cases, where erosion and soil P status are high, soil amendments play an important role. Both gypsum and structure lime amendments outperform the baseline, while the social net benefits from gypsum remain the highest. This suggests that soil amendments should be used in fields with high soil erosion and high soil P values (total P runoff without soil amendments: 2.14 kg ha^{-1} for high erosion and 2.37 kg ha^{-1} for high soil P value).

Damage estimates complement the analysis. The higher the marginal damage of nutrient loading, the higher the benefits from soil amendments. Combining this finding with the above result, we conclude that the higher the P loads are, the larger the area that should be treated with soil amendments. Higher climate damage reduces benefits from gypsum and structure lime, as both entail a slight increase in GHG emissions over the baseline. Nevertheless, P loading and GHG emissions combined still suggest that gypsum performs better than structure lime and the baseline. As a final note, when soil P is approximately 8 mg l^{-1}, that is, quite close to the identified social optimum in the presence of P loads (Iho 2010), the use of soil amendments does not increase social welfare.

Finally, if the prices of fuels and fertilizers increase, they reduce the profitability of all alternatives. Accounting for P damage only, a higher fuel price resulting in a 10% increase in transportation costs decreases the NPV from gypsum by 13 € ha^{-1} (1.4%) and from structure lime by 2 € ha^{-1} (0.3%). Fuel prices affect gypsum the most, as it has the longest transportation distance, but gypsum still yields the highest NPV. A higher fertilizer price would reduce the NPV in all cases by the same amount since fertilization rate is equal.

We provide sensitivity analysis of the cost-effectiveness ratios presented in Table 6 using the same parameter changes as above in Table 8. The resulting cost-effectiveness range (considering only the investment cost and investment costs amended with changes in GHG emissions; see details in Table A6 in Appendix 4) for gypsum is 42.5–103.2 € kg^{-1}P and for structure lime 68.8–177.8 € kg^{-1}P. Thus, the range is quite large for both amendments.

Table 8. Sensitivity results (€ ha^{-1}), NPV of private profits and social net benefits over 5 years with a 3% discount rate (values exceeding baseline NPV are bolded)

	Private profit NPV	Social net benefit NPV		
		P	GHG	P + GHG
Changed P runoff reduction and yield increase				
Baseline (totP load 1.81 kg ha^{-1})	1575	862	916	203
Gypsum, lower P reduction (PP 34%, DRP 0%)	1347	811	685	149
Gypsum, higher P reduction (PP 72%, DRP 25%)	1347	**1056**	685	**394**
Structure lime: 30% PP reduction	1349	791*	596	39
Structure lime: 50% PP reduction	1349	**895**	596	142
Structure lime, 2% yield increase	1421	**915**	669	163
Lower erosion (875 kg ha^{-1})				
Baseline (totP load 1.54 kg ha^{-1})	1575	968	916	309
Gypsum	1347	**995**	685	**333**
Structure lime	1349	906*	596	154
Higher erosion (1375 kg ha^{-1})				
Baseline (totP load 2.14 kg ha^{-1})	1575	733	916	74
Gypsum	1347	**878**	685	**216**
Structure lime	1349	**765**	596	**13***
Lower soil P status (8 mg l^{-1})				
Baseline (totP load 1.15 kg ha^{-1})	1575	1122	916	463
Gypsum	1347	1096	685	434
Structure lime	1349	1038	596	285
Higher soil P status (25 mg l^{-1})				
Baseline (totP load 2.37 kg ha^{-1})	1575	643	916	-16
Gypsum	1347	**805**	685	**143**
Structure lime	1349	**667**	596	-86*
Higher climate damage (50 € t^{-1}CO$_2$e)				
Baseline (totP load 1.81 kg ha^{-1})	1575	862	633	-79
Gypsum	1347	**942**	402	**-4**
Structure lime	1349	843*	274	-232
Higher runoff damage (15 € kg^{-1}Ne)				
Baseline (totP load 1.81 kg ha^{-1})	1575	653	916	-6
Gypsum	1347	**823**	685	**161**
Structure lime	1349	**695**	596	-58*

*) If structure lime increases crop yields by 2%, it provides higher social net benefits than the baseline for the marked cases.

Scaling up the use of soil amendments

To assess the overall potential of soil amendments in reducing P loading under the “do no significant harm” principle, we scale gypsum and structure lime applications to a national level. Table 9 collects the P load reductions and GHG emissions (without soil emissions) in one scenario. The potential area of gypsum application in Finland is approximately 1.05 Mha (Ekholm et al. 2022), covering all cultivated fields on mineral soils and excluding catchment areas around lakes. The total potential area (Ekholm et al. 2022) comprises of the following areas in different catchments: 196 000 ha for the Gulf of Finland, 225 000 ha for the Archipelago Sea, 263 000 ha the Bothnian Sea and 370 000 ha for the Bothnian Bay (based on Huttunen, unpublished data). In the Savijoki gypsum pilot, 51.5% of fields in the area were amended with gypsum by farmers (Ollikainen et al. 2020). The figure reflects the fact that not all soils are suitable for gypsum, and not all farmers were willing to participate (Ollikainen et al. 2020). Thus, we employ 51.5% of the potential area in each catchment for the scaling of both soil amendments. The potential area for structure lime may be somewhat higher than that for gypsum because it includes fields upstream of lakes. On the other hand, most clay soils are in the coastal areas in Finland, which lack numerous lakes. For the Archipelago Sea catchment area, the baseline loading is 1.81 kg totP ha^{-1} according to the model and chosen parameters used in our calculations. For the other catchments (Gulf of Finland, Bothnian Sea and Bothnian Bay), we use a specific annual load of 1.1 kg totP ha^{-1}, averaged from three studies looking at agricultural load carried by agricultural rivers and streams (Rankinen et al. 2016 [1.1 kg ha^{-1}], Röman et al. 2018 [0.83 kg ha^{-1}], Tattari et al. 2017 [1.26-1.58 kg ha^{-1}]). The baseline annual total P loading is thus 680 tons (total areas based on Huttunen, unpublished data).

The required amount of soil amendments is considerable if they are used as the only material over the entire land area. Small differences in P load reductions scale up to much larger differences in the achieved P loading reduction measured at the field edge. Gypsum reduces national P loads almost one-third more than structure lime. This results partly from a higher reduction in PP loading and its ability to reduce DRP loading. This finding is important for P policy. This suggests the use of gypsum and structure lime in combination, with structure lime targeting fields unsuitable for gypsum. For instance, amending 0.54 Mha soils by gypsum and complementing it on the no-go areas, approximately 0.45 Mha, would half the need for structure lime but would reach 0.99 Mha. Here, we have not accounted for the higher availability of DRP to algae (Iho et al. 2023), which further suggests the use of gypsum as a primary choice. The Archipelago Sea is Finland’s only hot spot in Helcom’s loading list, and in a recent report, Fleming et al. (2023) suggested 126 t as the maximum upper limit for its total P loads. As total P loading to the sea area is reported at 470 t y^{-1}, the required reduction is 344 t y^{-1}. Applying gypsum on all feasible fields in the catchment would result in 90 t y^{-1} reduction and structure lime to 61 t y^{-1} reduction, which are considerable shares of the required reduction.

Looking at GHG emissions shows that gypsum causes only negligible climate impacts, whereas structure lime is a considerable GHG emission pulse. A comparison to emissions from transport illustrates the climate impacts. Light-duty vehicles produced 5.3 MtCO$_2$e in 2021 in Finland (Statistics Finland 2023). Emissions from structure lime treatment on the 0.54 Mha (soil emissions omitting) are equal to approximately 16% of these emissions, while those of gypsum would be only 1%. Turning the differences from the production of soil amendments to emissions from driving, emissions from gypsum production per ha are equal to emissions of light-duty vehicles traveling only 87 km, while emissions from structure lime production per ha are as high as emissions from a 11020 km drive (calculations based on the Autokalkulaattori of the Finnish Climate Change Panel, https://www.ilmastopaneeli.fi/autokalkulaattori/). This scale emphasizes that the only source of structure lime that is in line with the “do no significant harm” principle is structure lime from recycled materials. Therefore, a final note on the use of soil amendments relates to their availability. The supply of gypsum and structure lime from pristine materials is adequate at the national level. The availability of structure lime from recycled materials depends on the supply of pre-used material from the forest industry. That capacity is annually very limited, preventing the large-scale use of this structure lime variant.

Table 9. Reduction in P loading (tons per year) and associated GHG emissions without soil emissions (million t) when gypsum or structure lime is applied to 543 000 ha

	Gypsum	Structure lime, 5-year effectiveness	Structure lime, 10-year effectiveness
Quantity applied, Mt	2.2	2.7	12.4
DRP reduction, t year^{-1}	34	0	0
PP reduction, t year^{-1}	273	218	218
TP reduction, t year^{-1}	306	218	218
GHG emissions, Mt CO$_2$e year^{-1}	0.048	1.04	4.63

Discussion

Our study relies on the existing literature examining the reductive impact of soil amendments on P loads. There is still uncertainty concerning the impact and its duration for both amendments, gypsum and structure lime. In general, controlled lab experiments show the highest impacts, and shifting to field experiments and pilot areas increases the number of uncontrolled variables, leading to lower impacts. Most studies of gypsum demonstrate reduction of both PP and DRP loading but the duration of their reductive impact differ. Some studies on structure lime find reduction of both PP and DRP but many do not find any DRP reduction. We resolved these ambiguities in the literature by using reduction rates of 50% (PP) and 25% (DRP) for gypsum and 40% (PP) and 0% (DRP) for structure lime and by adopting 5 years impact as the base case. The impacts of uncertainty were checked by a sensitivity analysis. It led to a crucial finding that the desirability of soil amendments as a water protection investment is lost if the reduction of P load remains below 30% for PP and is 0% for DRP. Most studies, however, have demonstrated higher impacts, providing support for the use of soil amendments.

Our cost-effectiveness results ranged between 54–59 € kg^{-1}P for gypsum and 86–177 € kg^{-1}P for structure lime when GHG emissions are not included. These figures can be compared to other measures available for agriculture. Omitting gypsum, the reduction in DRP is possible only in a longer time span and under consistent and tight P fertilization restrictions that facilitate mining of excess soil P reserves. Buffer strips reduce PP loading in the short run (Uusi-Kämppä and Jauhiainen 2010). Expanding the size of buffer strips to achieve 40% and 50% PP reduction at the field edge would cost 116 € kg^{-1}P (40%) and 161 € kg^{-1}P (50%) via lost farm income (see Appendix 5 for details of the calculations). This is double relative to the costs of gypsum but stays within the range for structure lime.

Another measure suggested for agriculture is to improve the drainage water management (DWM) (Frankenberger et al. 2023). DWM may provide a win-win solution, as good drainage improves crop growth and at the same time reduces especially N but also P losses from fields to waterways. The review of Frankenberger et al. (2023) suggested approximately 0.1 kgP ha^{-1} as the reduction in total P (0.04 kg ha^{-1} for DRP and 0.06 kg ha^{-1} for PP). These figures are low when compared to both soil amendments. Frankenberg et al. (2023) determine the cost-effectiveness ratio for N but not for P. Hjerppe and Väisänen (2015) provide a comprehensive analysis for multiple water protection measures under the Finnish circumstances (five different rivers). They provide a large range for costs. Cost-effectiveness of drainage water management ranges between 500–3000 € kg^{-1}P, while cost-effectiveness of buffer strips is about 200 € kg^{-1}P. Thus, our estimations for both soil amendments are lower than those.

Sihvonen et al. (2020) apply a dynamic optimization framework with a simultaneous choice of N and P fertilization, the use of gypsum and including cover crops in the presence of legacy P. The socially optimal solution reduces soil P reserves from the privately choice (36 mg l^{-1}) to the social optimum (8.6 mg l^{-1}), thus, reducing especially DRP loads over a 120-year time horizon. While these results are not directly compatible with our results, it is interesting to note that gypsum plays a short run role in their model. Their work demonstrates well how important it is to have a consistent policy to reduce legacy P over time to complement the use of soil amendments.

Finally, our calculations are the first one to provide estimates of GHG emissions in the context of soil amendments. We built our analysis on the work by Stork et al. (2014), Kämäri et al. (2019), Anttila et al. (2021) and IPCC (2006) for structure lime and on the standard LCA approach with economic allocation principle for gypsum (Belboom et al. 2015). One should note, however, that local production conditions differ. Therefore, GHG emissions from gypsum and structure lime differ depending on their origin. For instance, gypsum may come directly from mining or from flue gas desulfurization. Also, structure lime can be produced from multiple sources from pristine materials to several times recycled material. Furthermore, the carbon price plays important role for climate damages of both soil amendments. We employed a modest value 35 € t^{-1}CO$_2$e. Higher carbon price would considerably reduce the social desirability of using structure lime from pristine materials.

For structure lime the share of recycled materials turned out to be crucial. Our work facilitates a linear description for emissions from structure lime, assuming almost zero emissions to manufacture structure lime from recycled materials (see Figure A1 in Appendix 1). This helps one to adjust GHG estimates to better reflect cases in which recycling of raw materials increases in the production of structure lime.

Conclusions

We examined the role and targeting of two soil amendments, gypsum and structure lime, in reducing P loads from arable fields. Recent field experiments and large-scale pilots in Finland and Sweden suggest that both gypsum and structure lime can reduce total P loading from clayey fields. While Sweden has promoted the use of structure lime, Finland has done the same with gypsum. In the spirit of the EU's green transition, we followed the "do no significant harm" principle and included GHG emissions in the analysis. Thus, we asked if the use of soil amendments is socially desirable when benefits from reduction of P loads and climate damages from GHG emissions are considered.

We condense our key findings on water protection as follows. First, the cost-effectiveness ratios for gypsum and recycled structure lime are in general lower than those of other measures reducing P runoff from agriculture. Including GHG emissions, if structure lime is manufactured using pristine material, its cost-effectiveness ratio is high compared to gypsum. Second, the social net benefits (accounting only damage from P load) from reduced P loading by gypsum and by structure lime with at least a 2% increase in crop yields exceed the current agricultural baseline, showing that society should promote their use. Again, including GHG emissions clearly reduces the social net benefits for structure lime from pristine materials. Third, sensitivity analysis emphasizes targeting the use of both soil amendments on erodible soils or high soil P values. For sites with low erosion or low soil P values, benefits from soil amendments remain below the baseline. Accounting for climate issues does not substantially change the above results. GHG emissions from soil amendments increase the cost-effectiveness ratio and lower social net benefits. This impact is minor for gypsum and recycled structure lime but considerable for structure lime from pristine materials. If the prices of fuels and fertilizers increase, they reduce the profitability of all alternatives, but the case of higher gasoline prices in transport reduces the profitability of gypsum the most, as it has the longest transportation distance.

Drawing on the analysis, we make the following conclusions. Both soil amendments provide high potential to reduce P loads to waterways especially on fields that have high soil P values or high erodibility. Their use is not, however, profitable for farmers without government subsidies under current agri-environmental policies. Thus, active promotion of amendments is economically justified. Accounting for climate impacts of both amendments reduces both cost-effectiveness and net social benefits of both amendments. Nevertheless, gypsum and structure lime from recycled materials perform well even when GHG emissions are taken into account, thus accounting for GHG emissions and climate damage does not hinder their use. In contrast, structure lime from pristine materials has a high carbon footprint. There are no environmental grounds for promoting the use of structure lime from pristine materials on a large scale for water protection unless its GHG emissions are radically reduced. Thus, for the case of structure lime from pristine materials, climate emissions do compromise water quality benefits.

The literature forming the basis of our estimates for the reductive impact of soil amendments on P loads covers only a limited combination of agri-environmental mosaic found in boreal lands. With increasing knowledge on the effect of soil amendments on PP and DRP, it is possible to get more valid assessments of their potential role in attaining lower agricultural P loads and improved ecological state of coastal waters, considering the climate impact. An equally important question is how to create incentives to strengthen environmentally friendlier agricultural practices.

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Appendix 1.
GHG emissions from the production and use of gypsum and structure lime

Emissions from gypsum production

GHG emissions for gypsum production are determined using the economic allocation principle (Habert 2013). The economic allocation coefficient, ω, is defined as: $\omega = \frac{p_2 m_2}{p_1 m_1 + p_2 m_2'}$ where $p_1 m_1$ refers to the mass value of the primary product (market unit price times the produced/sold mass) and $p_2 m_2$ to that of the side product. The coefficient indicates the share of the sales of the side product in total economic benefits.

For gypsum, GHG emissions relate to the production of phosphoric acid. Belboom et al. (2015) estimated that the production of fertilizer grade phosphoric acid (H_3PO_4) generates approximately 626 kgCO_2e t^{-1} when the wet di-hemihydrate process is used. YARA calculations for the production in Siilinjärvi suggest a value slightly less than 600 kg CO_2e t^{-1} (pers. communication, Soile Ylisuutari 2021). Therefore, 600 kgCO_2e t^{-1} is used in the calculations. The price of gypsum is 18.15 € t^{-1} and its annual sales are 80 000 t (Yara 2024, pers. communication, Gunilla Stedt, 2024). The annual phosphorus acid production is 300 000 t and its price, taken from international data (Intratec 2022), is 800 € t^{-1}. Thus, the coefficient is $\omega = \frac{18.15 * 80\,000}{800 * 300\,000 + 18.15 * 80\,000} = 0.0361$.

Using this value for emissions yields 0.0361 × 600 = 3.61 kgCO_2e t^{-1} gypsum produced. For the 4 t ha^{-1} application rate, the emissions from production of 14.43 kgCO_2e ha^{-1}.

Emissions from structure lime production

For structure lime, GHG emissions are calculated directly from the production of reactive and agricultural lime and their shares in structure lime (Anttila et al. 2021).

For structure lime from pristine materials, we target a 1200 kg dose of reactive lime ($CaO/Ca[OH]_2$) per hectare and use 24.6% as the share of CaO in the structure lime product (Kämäri et al. 2019). It requires that 5 t of structure lime is spread on a hectare (Anttila et al. 2021). The average emission factor for quicklime production in Europe is approximately 1092 kgCO_2e t^{-1} (Nordkalk 2022, Stork et al. 2014). For agricultural lime (CaCO3), we use an emission factor of 131 kgCO_2e t^{-1} (West and Marland 2002). Its share is 75.4% of the product. Using the relative shares in structure lime gives: 0.246 × 1092 + 0.754 × 131 = 367.4 kgCO_2e t^{-1}. Using the 5 t ha^{-1} application yields 1837 kgCO_2e ha^{-1}, while the 22.9 t ha^{-1} application yields 8420 kgCO_2e ha^{-1}.

For structure lime from recycled materials, we also target a 1200 kg dose of reactive lime per hectare for a 5-year duration, but now the share of CaO in the structure lime product is 33.3%. Thus, the spread amount of structure lime is 3.6 t for recycled materials. For a 10-year duration, the amount of reactive lime is 5.5 t ha^{-1} reflecting structure lime application of 16.5 t ha^{-1}. Emissions estimate for recycled structure lime production is based on the manufacturer's LCA showing that emissions are 3.65 kgCO_2e t^{-1} (pers. communication Ossi Kinnunen 2023; average moisture content of 17.75% from Mustonen [2022]). For an application rate of 3.6 t ha^{-1}, emissions from production are 13.13 kgCO_2e ha^{-1}, which is slightly below the estimate for gypsum.

Figure A1 presents a linear relationship between the production emissions of two extremes for cases studied here: structure lime produced only from pristine material or only from recycled materials. Given that structure lime products sold in the markets may contain different shares of pristine and recycled materials, this figure helps to assess the realized production emissions as a function of the share of recycled materials.

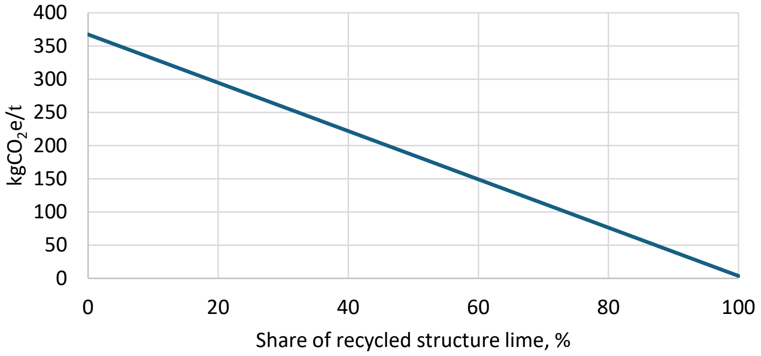

Fig. A1. Emissions from structure lime production as a function of the share of recycled materials

Emissions from transport and spreading

Emissions from transport depend on the distance and the size of trucks. For gypsum, we use the distance from the YARA Siilinjärvi factory to fields in southwest Finland, on average 450 km (Ollikainen et al. 2020). For structure lime, the distance is 65 kilometres, as it is produced at multiple sites in southern Finland. Emission factor for full trailers with a carrying capacity of 40 tons is 1.205 kgCO_2e km^{-1} (VTT 2020). This leads to 54.23 kgCO_2e ha^{-1} for gypsum, 9.79 kgCO_2e ha^{-1} for structure lime with 5 years impact and 44.9 kgCO_2e ha^{-1} for structure lime with 10 years impact. Emissions increase linearly with distance; for every 50 kilometres, emissions increase by 1.51 kgCO_2e t^{-1}.

Spreading of soil amendments by manure or lime spreading equipment causes emissions from fossil fuels. For gypsum, only the spreading is needed. After spreading structure lime, the field must be harrowed twice within 48 hours to mix it fully with soil. Both spreading and harrowing consume 7.2 l ha^{-1} diesel (Mikkola and Ahokas 2009), with emissions from fuel 2.723 kgCO_2e l^{-1} (VTT 2020). These figures yield 19.61 kgCO_2e ha^{-1} for the spreading of soil amendments and 39.21 kgCO_2e ha^{-1} for harrowing structure lime twice.

Soil emissions

A final note concerns how structure lime works when spread in soils. Upon reaction with CO_2, CaO or $Ca(OH)_2$ undergoes a partial (re)carbonation process (Campo et al. 2021). For soil stabilizing treatment at a construction site, Campo et al. (2021) reported carbonation rates of 37% and 80% in natural and enhanced (laboratory) CO_2 atmospheres, respectively. In agricultural topsoils, where active microbial decomposition is maintained by continuous inputs of root exudates and dead plant material, the CO_2 concentration in the soil gaseous phase is higher compared to atmospheric concentrations, especially in wet periods (Simojoki et al. 1991). In our case, the added reactive lime might be initially able to bind a considerable proportion of the CO_2 lost in the calcination step. However, in noncalcareous soils, $CaCO_3$ is an unstable mineral, and in Finland, the maintenance of soil pH has been calculated to require lime amendment with $CaCO_3$ at an annual rate of 300 kg ha^{-1} (Elonen et al. 1991, Sallasmaa 1991). The requirement for pH maintenance is due to the acidifying effects of ammonium-containing mineral fertilizers, natural soil forming processes and plant uptake of nutrient elements (see van Breemen et al. 1983). At present, the mean pH values of Finnish agricultural soils are approximately 6.0 in mineral soils and 5.5 in organic soils (Keskinen et al. 2016). Hence, we do not expect that carbonation of the active component of structure lime would be a permanent sink for CO_2. Note, however, that the application of agricultural lime within the structure lime causes soil emissions of 440 kgCO_2e t^{-1} (IPCC 2006). Gypsum may enhance carbonation of CO_2 in alkaline soils (Zhang et al. 2016). However, we assume that carbon sequestration by gypsum is negligible in the slightly acidic Finnish soils.

Appendix 2. Data

Table A1. Soil amendments: GHG emissions and costs

Parameter	Value	Unit	Reference
Values employed for both gypsum and structure lime			
Transport cost	32.14	€/450 km	Ollikainen et al. (2020)
Gypsum			
Price	18.15	€/t	Ollikainen et al. (2020)
Used amount	4	t/ha	Ollikainen et al. (2020)
Transportation distance	450	km	Ollikainen et al. (2020)
Transport	32.14	€/t	Ollikainen et al. (2020)
Spreading	6.5	€/t	Ollikainen et al. (2020)
Structure lime			
Price	34.5	€/t	KM (2022)
Used amount, pristine, 5-year duration	5	t/ha	Anttila et al. (2021)
Reactive lime	1.2	t/ha	24.6% of structure lime, Kämäri et al. (2019)
Agricultural lime	3.8	t/ha	
Used amount, recycled, 5-year duration	3.6	t/ha	based on average share of reactive lime
Reactive lime	1.2	t/ha	33.3% of structure lime
Agricultural lime	2.4	t/ha	
Used amount, pristine, 10-year duration	22.9	t/ha	based on average share of reactive lime
Reactive lime	5.5	t/ha	24.6% of structure lime, Kämäri et al. (2019)
Agricultural lime	17.4	t/ha	
Used amount, recycled, 10-year duration	16.5	t/ha	based on average share of reactive lime
Reactive lime	5.5	t/ha	33.3% of structure lime
Agricultural lime	11	t/ha	
Transportation distance	65	km	distance between Vampula and Lieto
Transport	4.64	€/t	based on transport distance and Ollikainen et al. (2020)
Spreading	10	€/t	assumed same as for gypsum
Disc harrowing	35.3	€/ha	Palva (2021)

Table A2. Parameters used in the simulations

Parameter	Value	Unit	Reference
Barley cultivation			
Barley market price	0.174	€/kg	Luke (2019)
NPK fertilizer price (YaraMila Y3)	0.4	€/kg	ProAgria (2019)
Share of N in NPK fertilizer	23	%	ProAgria (2019)
Variable cost	138	€/ha	ProAgria (2019)
Fixed cost	362	€/ha	ProAgria (2019)
Price of agricultural lime	9.0	€/t	KM (2022)
Used amount of agricultural lime	4.5	t/ha	average, every five years
N fertilization limit	100	kg/ha	Finnish Food Authority (2020)
P fertilization limit	5	kg/ha	Finnish Food Authority (2020)
LFA support payment	217	€/ha	Pro Agria (2019)
Barley N yield response			Lehtonen (2001)
Nutrient runoff			
PP runoff function, kgPP/ha	$\frac{\Delta[\zeta\{250\ln(\sigma+0.01)\,P-150\}]}{10^6}$		based on Saarela et al. (1995) and Uusitalo & Jansson (2002)
DRP runoff function, kgDRP/ha	$\frac{\psi[\phi 0.021(\sigma+0.01P)-0.015]}{100}$		based on Saarela et al. (1995) and Uusitalo & Jansson (2002)
N runoff function, kgN/ha	$\varphi e^{b_o+b_1\frac{n}{100}}$		Simmelsgaard (1991)
P fertilization	5	kg/ha	set to the limit according to Finnish Food Authority (2020)
Soil phosphorus	15.9	mg/l	Eurofins (2017)
Erosion	1100	kg/ha	chosen to represent average value in the study area
Runoff	247	mm	
Plant- and technology specific parameter	0.6		Puustinen et al. (2010)
Plant- and technology specific parameter	2.2		Puustinen et al. (2010)
N runoff at average fertilization	15	kg/ha	Lankoski et al. (2006)
Constant for N runoff,	-0.7		Simmelsgaard (1991)
Constant for N runoff,	0.7		Simmelsgaard (1991)
PP reduction, gypsum	50	%	literature review (this study)
DRP reduction, gypsum	25	%	literature review (this study)
PP reduction, structure lime	40	%	literature review (this study)
DRP reduction, structure lime	0	%	literature review (this study)
GHG emissions related to barley cultivation			
Soil emissions	1855	kgCO$_2$e/ha	Ervola et al. (2012)
Mineral fertilizer manufacture	4.32	kgCO$_2$e/kgN	Ervola et al. (2012)
Soil N$_2$O emissions from mineral fertilization	6.71	kgCO$_2$e/kgN	Ervola et al. (2012)
Management practices (incl. tillage, harrowing, seeds, planting, weed control, harvesting, transport of harvest to drier)	489	kgCO$_2$e/ha	based on Ervola et al. (2012)
Agricultural lime, production	131	kgCO$_2$e/t	West and Marland (2002)
Agricultural lime, soil emissions	440	kgCO$_2$e/t	(IPCC, 2006)
Agricultural lime, spreading	2	kgCO$_2$e/t	based on Ervola et al. (2012)
Other parameters			
P to Ne (Redfield-ratio)	7.2		Kiirikki et al. (2003)
Marginal runoff damage	11.6	€/kgNe	based on Gren (2001), prolonged to year 2023 using 2 % interest rate
Marginal climate damage	35	€/tCO$_2$e	based on Tol (2011)

Appendix 3. Results for structure lime from recycled materials

Impacts on P load and GHG emissions

The impact on the P load is the same as that of structure lime from pristine materials: 40% PP load and 0% DRP load (see Table 3 in the text). Table A3 provides data on GHG emissions without soil emissions drawing on the critical assumption that emissions from the production of recycled materials are close to zero. GHG emissions are lower than for other soil amendments for 5- and 10-year durations. The costs of a 10-year duration are higher than those of gypsum. Structure lime contains agricultural lime the application of which to the soil causes emissions. For a 5-year duration, the share of agricultural lime is 2.4 t ha^{-1} with soil emissions of 1056 kgCO$_2$e ha^{-1}. For a 10-year duration, the share of agricultural lime is 16.5 t ha^{-1} with soil emissions of 4840 kgCO$_2$e ha^{-1}. These emissions are largely displayed since conventional agricultural lime is not applied for fields treated with structure lime.

Table A3. Emissions and costs from using recycled structure lime

	Structure lime, recycled materials, 5 y		Structure lime, recycled materials, 10 y	
	Emissions, kgCO$_2$e ha^{-1}	Costs, € ha^{-1}	Emissions, kgCO$_2$e ha^{-1}	Costs, € ha^{-1}
Production/Price	13.1	124	60.2	569
Transport	7.05	16.7	7.05	76.6
Spreading	19.6	26.0	16.9	26.0
Harrowing	39.2	70.6	39.2	70.6
Total	79.0	238	126	742

Cost-effectiveness and social net benefits

The cost-effectiveness ratio in Table A4 is better than that of structure lime from pristine materials but falls short of that of gypsum when only the P load or both P load and GHG emissions are considered. In the case of 5- year duration, it gives the highest private profits of all soil amendments and the second highest social welfare after gypsum when only the P load or both the P load and GHG emissions are considered. When targeted to 10-year duration, it performs weakly but still outperforms structure lime from pristine materials.

Table A4. Cost-effectiveness (€ kg^{-1} P reduction) of recycled structure lime based on treatment cost

	Reduction in totP load, kg ha^{-1} y^{-1}	Cost-effectiveness (€ kg^{-1} P)	
		I	I + GHG
Structure lime, recycled (5 y)	0.53	65.1	60.1
Structure lime, recycled (10 y)	0.53	129	177

Table A5. NPV of private profits and social net benefits over 5 or 10 years with a 3% discount rate (€ ha^{-1})

	Private profits (NPV)	Social net benefits (NPV)		
		P	GHG	P + GHG
Structure lime, recycled, effective 5 y, € ha^{-1} 5 y^{-1})	1404	898	758	252
Structure lime, recycled, effective 10 y (€ ha^{-1} 10 y^{-1})	2044	1102	563	-379

Appendix 4. Sensitivity results for the cost-effectiveness ratios

Table A6. Cost-effectiveness (€ kg^{-1} P reduction) of gypsum and structure lime amendments based on annual treatment costs only (I) and annual treatment costs and increased climate costs (I+GHG)

	Reduction in totP load, kg ha^{-1} y^{-1}	Cost-effectiveness (€ kg^{-1} P)	
		I	I + GHG
Baseline			
Gypsum	0.78	58.2	59.0
Structure lime	0.53	86.0	121.7
Gypsum, lower P reduction (PP 34%, DRP 0%)			
Gypsum	0.45	101.8	103.2
Gypsum, higher P reduction (PP 72%, DRP 25%)			
Gypsum	1.07	42.5	43.1
Structure lime: 30% PP reduction			
Structure lime	0.39	114.7	162.3
Structure lime: 50% PP reduction			
Structure lime	0.66	68.8	97.4
Lower erosion (875 kg ha^{-1})			
Gypsum	0.65	70.3	71.3
Structure lime	0.42	108.1	153.0
Higher erosion (1375 kg ha^{-1})			
Gypsum	0.94	48.1	48.8
Structure lime	0.66	68.8	97.4
Lower soil P status (8 mg l^{-1})			
Gypsum	0.51	88.7	89.9
Structure lime	0.36	125.6	177.8
Higher soil P status (25 mg l^{-1})			
Gypsum	0.99	46.0	46.6
Structure lime	0.63	71.2	100.8
Higher climate damage (50 € t^{-1}CO2e)			
Gypsum	0.78	58.2	59.4
Structure lime	0.53	86.0	137.0

Appendix 5. Reducing PP runoff using buffer strips

The PP runoff function with buffer strip is based on Saarela et al. (1995) and Uusitalo and Jansson (2002):

$$\frac{(1-b^{\alpha})\Delta[\zeta\{250\,ln(\sigma+0.01)\,(1-b)P-150\}]}{10^{6}}$$

where *b* is the share of the buffer strip from a 1 ha field, and *α* (based on Lankoski et al. (2006)) denotes the ability of the buffer strip to capture PP. Setting *P* = 5 and *b* = 0 gives the baseline PP runoff of 1.31 kg ha^{-1}. To reduce PP runoff by 40%, i.e., to 0.788 kg ha^{-1}, and keeping P fertilization at 5 kg ha^{-1}, the value of *b* has to increase to 0.10. This means a 10-meter buffer strip on one side of a 1 ha square field. To reduce PP loading by 50%, i.e., to 0.656 kg ha^{-1}, *b* needs to be 0.18, i.e., 18 meters.

To evaluate the cost-effectiveness, private profits in the baseline and with the increased buffer strips are needed. In the baseline, private profits without the use of agricultural lime are 348 € ha^{-1} (see Table 5). The additional costs from buffer strip are the establishment and maintenance cost of 10 € ha^{-1} (Lankoski and Ollikainen 2006) and the reduced revenue from crop yield. Profits with a 10-meter buffer strip are 287 € ha^{-1}, which gives a 61 € ha $^{-1}$ reduction in profits and further a cost-effectiveness of $\frac{348-287}{1.31-0.788}\approx 116$ € kg^{-1}P. Profits with an 18-meter buffer strip are 242 € ha^{-1}, which gives a 106 € ha^{-1} reduction in profits and further a cost-effectiveness of $\frac{314-42}{1.13-0.656}\approx 161$ € kg^{-1}P.