

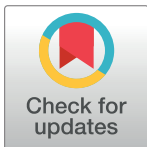
RESEARCH ARTICLE

Cover crops support the climate change mitigation potential of agroecosystems

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Abstract

Cover crops have the potential to mitigate climate change by reducing negative impacts of agriculture on ecosystems. This study is first to quantify the net climate change mitigation impact of cover crops including land-use effects. A systematic literature and data review was conducted to identify major drivers for climate benefits and costs of cover crops in maize (*Zea mays* L.) production systems. The results indicate that cover crops lead to a net climate change mitigation impact (NCCMI) of 3.30 Mg CO₂e ha⁻¹ a⁻¹. We created four scenarios with different impact weights of the drivers and all of them showing a positive NCCMI. Carbon land benefit, the carbon opportunity costs based on maize yield gains following cover crops, is the major contributor to the NCCMI (34.5% of all benefits). Carbon sequestration is the second largest contributor (33.8%). The climate costs of cover crops are mainly dominated by emissions from their seed production and foregone benefits due to land use for cover crops seeds. However, these two costs account for only 15.8% of the benefits. Extrapolating these results, planting cover crops before all maize acreage in the EU results in a climate change mitigation of 49.80 million Mg CO₂e a⁻¹, which is equivalent to 13.0% of the EU's agricultural emissions. This study highlights the importance of incorporating cover crops into sustainable cropping systems to minimize the agricultural impact to climate change.

1. Introduction

Mitigating climate change through measures in agriculture and food systems is essential for achieving the 1.50° and 2.00°C climate change targets of the Paris Agreement [1]. Worldwide, agriculture and food production systems are responsible for about one-third of global anthropogenic greenhouse gas (GHG) emissions, of which 40.0% are caused by agricultural production and 32.0% by land use and land use change [2]. However, agricultural systems also offer opportunities for climate change mitigation. Agroecosystems have significant potential to reduce global net emissions [3] and could even act as a net carbon sink [4]. To achieve these emission reduction and carbon sequestration opportunities, a transformation of agricultural systems is required. An essential component of climate-smart agricultural systems is planting cover crops. Cover crops are plants or plant mixtures that are not harvested for revenue, but

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are grown for the purpose of soil nutrient management, organic matter input, soil protection, and soil health improvement [5]. Cover crops are associated with multiple ecosystem services, such as closer nutrient cycling [5,6], activation of soil biology, biodiversity improvement [7], soil water management, and restoration of soil structures [8]. In addition, the mentioned effects of cover crops could mitigate climate change by soil carbon sequestration [9], biomass carbon storage, or reduced fertilizer losses to aquatic ecosystems. Recent studies show that these effects can lead to agronomic benefits that translate into higher yields and reduced agricultural input [10].

Despite these benefits, there exists a knowledge gap. The research problem addressed in this article is that there are no complete climate impact assessments of the cultivation of cover crops that also fully include land use effects. Cover crops reduces land use requirements by increasing yields of the subsequent crop. As land use change is still the largest carbon emissions source in the agri-food-system, yield increasing measures can be considered as a climate change mitigation option. According to Searchinger et al. [11], these carbon land benefits can be calculated as a "carbon opportunity cost," which is the foregone carbon storage potential from natural vegetation to produce a certain agricultural product in $\text{kg CO}_2\text{e kg}^{-1}$. When yields rise on one piece of land, this carbon storage potential can be maintained or restored on other locations since land use change is prevented or reverted. Kovak et al. [12] used this approach to quantify the climate change mitigation potential of a yield increase based on genetic modified crops. This is the first study to include carbon opportunity cost in the evaluation of the climate impact of cover cropping. As an additional climate benefit, cover crops remove carbon from the atmosphere during their growth while their residues and rhizodeposits are transformed to stable soil organic matter by retaining soil moisture. Further climate benefits of cover crops can be attributed to the supply of nutrients to the subsequent crop, which allows for fertilizer savings [13], reduced N_2O emissions due to less nitrogen leaching, reduced solar radiation due to plant growth [14], and reduced soil erosion [15]. We define all factors above as "climate benefits".

While cultivating cover crops can accrue these climate benefits, it can also generate GHG emissions that we refer as "climate costs". The cultivation of cover crops can increase N_2O emissions in periods of anaerobic microbial conversion of cover crop decomposition products [16]. Emissions are also generated in the production of cover crop seeds through a number of avenues, such as the land required for seed production and the production process of the seeds. In addition, produced seeds need to be packed and delivered, which also generates emissions [17]. Lastly, tilling, seeding, and termination of cover crops requires the use of GHG emitting machinery and resources [18]. Both climate benefits and climate costs of cover crops need to be carefully considered to calculate the NCCMI.

This article addresses the research problem by developing a comprehensive framework to quantify the NCCMI of cover crops including land use effects based on a systematic literature review. Using selected keywords, a systematic search was conducted in "Web of Science" and "Google Scholar" and resulted in 1269 publications. We define a list of relevant climate benefits and climate costs from which the NCCMI of cover crops is derived. We apply the framework to cover crops for maize in the European Union (EU-27, which is all EU Member States excluding the United Kingdom) to quantify its total NCCMI.

2. Methods

The following analyses are based on a typical Central European crop rotation, namely winter cover crops that are incorporated into the soil and maize as a cash crop following the cover crops in the spring. To quantify the impact of cover crop cultivation on the climate mitigation

Table 1. Calculation for mean land use for cover crops' seed production.

Species	Seed yield in kg ha ⁻¹	Seeding rate in kg ha ⁻¹	Seed land use in ha seed ha ⁻¹ for cover crops
Phacelia	350.00	10.50	0.03
Mustard	1,738.00	20.00	0.01
Clover	732.00	29.17	0.04
Oats	4,869.50	87.50	0.02
Mixture			0.03

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potential, a systematic literature review was conducted. The research platforms "Web of Science" and "Google Scholar" were used to explore the literature. Based on the initial research, we defined five factors that support climate change mitigation ("climate benefits") and five factors leading to additional GHG emissions ("climate costs") due to cover cropping (Table 1). The individual research terms of the individual impact factors are described below in detail.

To calculate the NCCMI of cover crops, the values of all impact factors were converted to the same unit, namely megagram of CO₂ equivalents per hectare and year (Mg CO₂e ha⁻¹ a⁻¹). From the values in the literature, a weighted average value that takes into account the number of measurements in the specific study was calculated. Only data from the literature that indicated the number of measurement points were considered in the calculation of the NCCMI. Thus, the climate benefits and climate costs could be added together in each case before subtracting the costs from the benefits. This resulted in a value for the NCCMI per hectare of cover crops given in Mg CO₂e ha⁻¹ a⁻¹. The 95% confidence interval was calculated from all study means and presents a range of estimates. To extrapolate the results to the EU-27 maize area the respective impact factors and the climate balances were subsequently multiplied with the maize acreage in the EU-27. The result was then divided by the total emissions from agriculture in the EU-27. This calculation resulted in the share of the NCCMI of cover crops before maize relative to all EU-27 agricultural emissions. The average maize acreage in 22 of the EU-27 countries was calculated as an average based on the years 2011 to 2022 (five of the EU-27 countries do not grow relevant quantities of maize and were thus not considered.)

The following search terms were used in Web of Science:

Cover crop & albedo, Cover crop & C sequestration, Cover crop & Yield corn, Cover crop & Yield maize, Cover crop & life cycle assessment, Cover crop & N-fixation, Cover crop & N-leaching, Fertilizer & Greenhouse gas emissions, Greenhouse gas emissions & fertilizer production, Cover crop & N₂O, Catch crop & N₂O. To enable a phrase search, all search terms were used with quotation marks to obtain search results exactly in this word order.

A total of 883 publications were extracted and checked for their suitability. Criteria for the required data were an absolute value from the respective study and the number of measurements. Only 44 articles met these criteria and were finally included in the review. In addition, we used 31 publications from Google Scholar and data from 26 other Internet sources that were selected based on the above criteria. In selecting sources, cover crops were considered both consisting of individual components and mixtures, overwintering as well as freezing, and legumes as well as non-legumes. All data sources are presented in the supplemental material (S1 File) and sorted based on the subsections below.

2.1. Carbon land benefit based on yield gain

The relative yield gain of maize following cover crops is based on literature research. The absolute yield gain was calculated by multiplying the relative yield gain with the average maize yield in the EU-27. For this purpose, the harvest volume of silage and grain maize in Europe

was divided by the cultivated area. Since carbon opportunity costs factors published in Searchinger et al. [11] refer only to grain maize, the silage maize (SM) yields were transformed to grain maize (GM). It was assumed that 54% of the dry matter of silage maize is grain [19]. Thus, the fresh mass of silage corn was multiplied by a factor of 0.35 to calculate the dry matter and then multiplied by 0.54 [19] to generate the grain yield of SM (see the supplemental material for more detail). To obtain the grain yield based on the standard of 14% moisture, the result was divided by 0.86. The following formula shows the complete calculation to transfer SM to GM:

$$GM = \frac{SM \times 0.35 \times 0.54}{0.86}.$$

To quantify the effect of yield increases on climate change mitigation, we use the carbon land benefit approach of Searchinger et al. [11]. This approach quantifies the benefit of increasing yields on one piece of land through the carbon storage potential of native vegetation on other land that is not required to produce a certain quantity of product because of higher production on existing agricultural land. According to Searchinger et al. [11], the carbon land benefit carbon opportunity costs (COC_s) is defined as follows:

$$COC_s = Y \times COC,$$

where, COC_s is the carbon land benefit, Y is the grain and biomass yield of an agricultural product, and COC is the carbon opportunity cost factor for the agricultural product. COC quantifies the forgone carbon storage potential of the native vegetation of land, which is globally used to produce an agricultural commodity and given in kg CO₂e per kg of product. Searchinger et al. [11] use two methods to quantify the carbon opportunity cost. Here, we use the values of the so-called “loss-method.” To quantify the carbon land benefit caused by yield gains in maize through cover crops, the absolute yield increase of maize in kg ha⁻¹ is multiplied by 2.1 kg CO₂e kg⁻¹, which is the carbon opportunity cost factor of grain maize published in Searchinger et al. [11].

2.2. Carbon sequestration

Carbon sequestration through cover crops is usually provided in units of soil organic carbon. This value was multiplied by a factor of 3.667 (i.e., the ratio of molar masses of CO₂ and C) to obtain the value of CO₂ stored per ha land.

2.3. Nitrogen fertilizer savings

For nutrient savings, we considered only the main nutrient, namely nitrogen since its production is highly energy intensive. To quantify fertilizer savings, we only considered emissions of mineral fertilizers and not that of organic fertilizers. The overall nitrogen fertilizer savings were quantified as the sum of the mean literature values on nitrogen scavenging and the mean literature values of nitrogen fixation from cover crops.

2.4. Reduced indirect N₂O emissions due to less leaching

Reducing nitrogen leaching due to cover crops leads to lower indirect N₂O emissions since less nitrogen is deposited to rivers and other water bodies. To quantify this effect, we use the approach suggested in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: The amount of nitrogen leaching reduction is multiplied by the emission factor EF₅ of 0.0075 [20] to obtain the reduction in indirect N₂O emissions per hectare. This value is then converted from kg N₂O-N ha⁻¹ to kg CO₂-eq ha⁻¹ using the conversion factor 273 and divided by

1000 to obtain the unit $\text{Mg CO}_2\text{-eq ha}^{-1}$ [21].

$$\text{Reduced } N_2O - N = \frac{EF_5 * \text{Reduced } N_{\text{Leaching}} * 273}{1000}$$

2.5 Albedo change

The reduced adsorption and thus increased reflection of solar radiation by cover crops' plant cover compared to fallow land leads to a climate change mitigation effect. We found, however, only two studies evaluating the impact of albedo change from cover crops (Kaye and Quemada [22] and another by Carrer et al. [14]).

2.6. Nitrous oxide emissions

In the case of nitrous oxide emissions, the cumulative emissions that occur during the period of fallow or the period from sowing to incorporation of cover crops are considered. The values with the unit $\text{kg N}_2\text{O-N ha}^{-1}$ were multiplied by a factor of 273 and 1000 to obtain the unit in $\text{Mg CO}_2\text{e ha}^{-1}$.

2.7. Foregone benefits due to cover crop seed land use

The production of seeds for cover crops requires additional land that is not available for production of agricultural products. Land for these seeds cannot create the same carbon benefits [11] as alternative uses of this land. Therefore, this forgone carbon benefit needs to be added to the climate costs of cover crops. For this purpose, the yields of the four most common seed components of a cover crop mixture were determined in order to calculate the average land requirement for seed production of one hectare of cover crops' seed mixture based on typical seeding rates. The following four species were selected to determine the land use for cover crops' seed production: phacelia (*Phacelia tanacetifolia* Benth.), mustard (*Sinapis alba* L.), clover (*Trifolium alexandrinum* L.), and oats (*Avena strigosa* Schreb.). Each of these cover crops has a 25% share in the final mixture of cover crops. A literature search on seed yields and average seeding rates for these four species was conducted. The seed land use (SLU) for a specific cover crop was calculated per ha based on the following formula:

$$SLU = \frac{1}{n} \sum_{i=1}^n \left(\frac{Y_{cc}}{SR_{cc}} \right) i,$$

where Y_{cc} is the yield in kg ha^{-1} of a specific cover crop and SR_{cc} is the seeding ratio in kg ha^{-1} .

Table 2 shows the mean input values derived from the literature for the land use requirements for cover crop seeds.

The forgone carbon benefit of the land used for the production of cover crop seeds is determined as follows: We assume that seeds for cover crops are produced in the European Union on land that would otherwise be used for wheat production since wheat is the largest crop in the EU by acreage. The carbon benefit (CB) of wheat is defined by Searchinger et al. [11]. Here, we assume that the carbon stock of land is not changing between wheat and seed production for cover crops and that there are no carbon benefits from bioenergy. The equation for CB is as follows:

$$CB = (COC + PEM_{\text{avg}} - PEM_{EU}) \times Y$$

where COC is the global carbon opportunity cost factor of wheat, PEM_{avg} is the global average

Table 2. Calculation of the net climate change mitigation impact of cover crops during an annual cropping cycle.

	EU-27 average per hectare (ha)				EU-27 total			
	Unit	Mean	Low (-95% confidence level)	High (+95% confidence level)	Unit	Mean	Low (-95% confidence level)	High (+95% confidence level)
Area					1,000 ha	15,092.14	14,785.60	15,398.67
Average yield	Mg ha ⁻¹	7.88	7.46	8.31				
Relative yield gain	%	8.8%	2.9%	14.8%				
Absolute yield gain	Mg ha ⁻¹	0.70	0.21	1.23				
Carbon opportunity cost maize	kg CO ₂ e kg ⁻¹	2.10	2.10	2.10				
Carbon land benefit based on maize yield gain	Mg CO₂e ha⁻¹	1.46	0.45	2.59	1,000 Mg CO₂e	22,086.83	6,631.87	39,805.69
Carbon sequestration	Mg CO₂ ha⁻¹	1.43	0.86	2.01	1,000 Mg CO₂	21,632.51	12,701.51	30,915.61
Nitrogen fixation	kg N ha ⁻¹	52.49	32.06	72.92				
Reduced nitrogen leaching	kg N ha ⁻¹	38.82	19.13	58.51				
Total nitrogen fertilizer savings	kg N ha ⁻¹	91.32	51.19	131.44				
Nitrogen fertilizer emissions	kg CO ₂ e kg N ⁻¹	11.23	9.02	13.43				
Carbon benefit based on nitrogen fertilizer savings	Mg CO₂e ha⁻¹	1.03	0.46	1.77	1,000 Mg CO₂e	15,474.08	6,830.39	27,187.04
Reduced N₂O emissions due to less leaching	Mg CO₂e ha⁻¹	0.10	-0.15	0.35	1,000 Mg CO₂e	1,495.60	-2,218.43	5,362.37
Albedo change	Mg CO₂e ha⁻¹	0.20	-0.37	0.78	1,000 Mg CO₂e	3,087.10	-5,514.25	12,042.49
Total climate benefit	Mg CO₂e ha⁻¹	4.22	1.25	7.49	1,000 Mg CO₂e	63,776.11	18,431.09	115,313.18
N ₂ O emissions	Mg CO ₂ e ha ⁻¹	0.04	-0.02	0.09	1,000 Mg CO ₂ e	555.77	-306.57	1,453.41
Foregone benefits due to cover crop seed land use	Mg CO₂e ha⁻¹	0.28	0.27	0.29	1,000 Mg CO₂e	4,180.56	3,970.76	4,395.55
Production emissions cover crop seed	Mg CO₂e ha⁻¹	0.39	0.08	0.70	1,000 Mg CO₂e	5,920.55	1,194.38	10,837.69
Processing, packaging, and transport of cover crop seed	Mg CO₂e ha⁻¹	0.08	0.08	0.08	1,000 Mg CO₂e	1,182.71	1,158.69	1,206.74
Additional machinery operations	l Diesel ha ⁻¹	45.29	32.44	58.13				
Diesel emissions	kg CO ₂ l ⁻¹	3.13	3.13	3.13				
Additional machinery operations	Mg CO₂ ha⁻¹	0.14	0.10	0.18	1,000 Mg CO₂e	2,140.93	1,502.51	2,804.02
Total climate cost	Mg CO₂e ha⁻¹	0.93	0.51	1.34	1,000 Mg CO₂e	13,980.53	7,519.77	20,697.40

(Continued)

Table 2. (Continued)

	EU-27 average per hectare (ha)				EU-27 total			
	Unit	Mean	Low (-95% confidence level)	High (+95% confidence level)	Unit	Mean	Low (-95% confidence level)	High (+95% confidence level)
Net climate change mitigation impact of cover crops	Mg CO ₂ e ha ⁻¹	3.30	0.74	6.14	1,000 Mg CO ₂ e	49,795.58	10,911.32	94,615.78
Share of EU-27 agriculture emissions in 2020						13.0%	2.9%	24.7%

Note: Calculation, formulas and number of studies are provided as supplementary material (S1 File). ha is hectares. EU-27 is the 27 Member States of the European Union (all Member States excluding the United Kingdom).

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production emissions for wheat, PEM_{EU} is the European Union's production emissions for wheat, and Y is the average wheat yield in the European Union (based on data from 2011 to 2022 for the EU-27 [23]). COC , PEM_{avg} , and PEM_{EU} are from Searchinger et al. [11]. For PEM_{EU} , we used the production emissions for wheat in Sweden, since no European average values were available. The forgone carbon benefits due to seed land use can be calculated by multiplying SLU and CB .

2.8. Production emissions for cover crop seed production, dispatch and additional machinery costs

Product emissions for cover crop seed production are not available in literature and therefore derived from maize, rapeseed, and spring wheat seed production. This is a conservative assumption since the nitrogen input and machinery operations as key drivers of emissions are usually higher in these crops than in cover crops. Emissions data is collected from the literature in kg CO₂e kg⁻¹ of seed and is multiplied with the seeding rate of cover crops. This results in an emissions value per hectare.

Emissions for processing, packaging, and transporting cover crop seeds are also not available and derived from maize seed production emissions and are expressed in kg CO₂e kg⁻¹ of seed. This is again a conservative assumption since maize seed has to fulfill much higher quality standards than cover crop seed.

The emissions of additional machinery operations for tillage, seeding, and mechanical termination of cover crops were included only in terms of additional diesel fuel usage. Average diesel fuel consumption of all additional operations was calculated and multiplied by the average GHG emissions of diesel fuel.

3. Results

The impact of all analyzed factors on the NCCMI of cover crops is summarized in Table 3. The results refer to a typical European crop rotation using a winter cover crop and maize

Table 3. Impact factors of cover crops on climate change mitigation analyzed in this study, source: Own table.

Climate Benefits	Climate Costs
• Carbon land benefit based on yield gain	• N ₂ O emissions
• Carbon sequestration	• Foregone benefits due to cover crop seed land use
• Nitrogen fertilizer savings	• Production emissions for cover crop seed production
• Reduced indirect N ₂ O emissions due to less leaching	• Processing, packaging, and transport of cover crop seed
• Albedo change	• Additional machinery operations

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as the following crop in spring. Individual impact factors are described in the following sections.

3.1. Carbon land benefit based on yield gain

The literature review on the impact of winter cover crop on maize yields revealed that yield effects are highly dependent on the cover crop species or the composition of the cover crop mixture. The yield effect of cover crops on the following crop is also highly dependent on the type of land management. The lower the tillage intensity, the higher the yield increase [18]. The yield increase effect is also much higher in organic farming than in conventional systems. Marcillo and Miguez [24] find a yield increase of 8.0% for a conventional intensive tillage system, while for an organic reduced tillage system, yields increased by 61.0% when cover cropping was implemented. In summary, the considered studies showed a weighted mean maize yield gain due to cover cropping of 8.8% (95% CI, 2.9, 14.8).

Fig 1 shows the included yield effect results, confidence intervals and the pooled effect. If more than one result is shown from one study in Fig 1 this literature showed results from multiple experiments.

Multiplying the weighted mean yield gain with the average EU-27 maize yield and the carbon opportunity cost factor for maize (2.10 kg CO₂e kg⁻¹ maize [11]) results in a mean carbon land benefit increase of 1.46 Mg CO₂e ha⁻¹.

3.2. Carbon sequestration

Cover crops have a positive impact on soil organic carbon sequestration in arable soils. The literature research revealed two meta-analyses with 139 and 1195 studies included. In addition, 26 studies that were not included in the above-mentioned meta-analyses were also included in our calculations. Up to 12.0% of carbon from cover crop biomass can be sequestered as soil organic carbon [13]. Similar to the crop yield effects shown above, the potential of soil organic

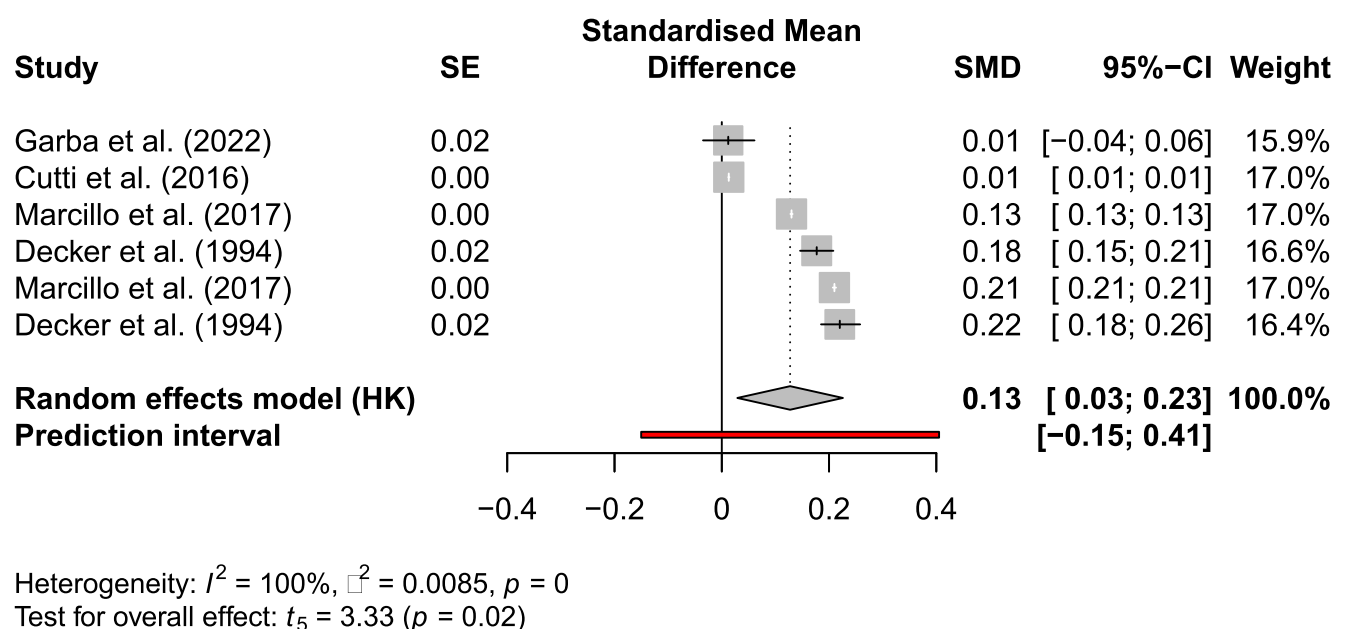


Fig 1. Forest plot of included literature on yield effects.

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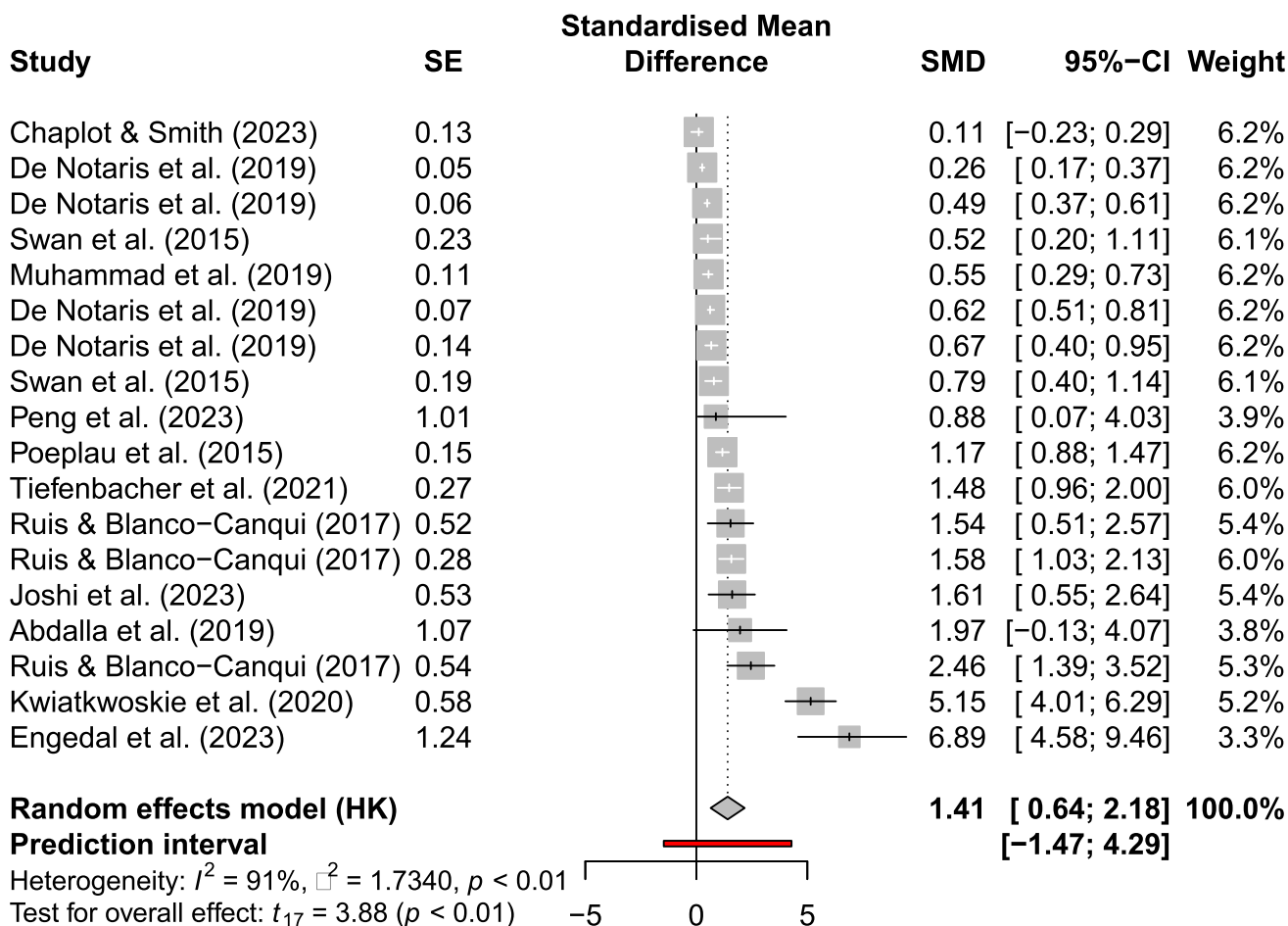


Fig 2. Forest plot of included literature on carbon sequestration effects.

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carbon stock increases depending on the type of cover crop. For example, a soil organic carbon increase of $0.26 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ has been found for a winter vetch cover crop [13]. A much larger increase in soil carbon of $5.12 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ was found by Abdalla et al. [25] for non-legume cover crops. The weighted mean of all studies investigated shows an average sequestration of $1.43 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ (95% CI, 0.86, 2.01). Based on the included studies, grass cover crops lead to a 2.3-times higher soil organic carbon sequestration than legume cover crops. Cover crop mixtures of grasses, legumes, and various other species are in the middle of the field in sequestration performance [26].

Fig 2 shows the included carbon sequestration results, confidence intervals and the pooled effect. If more than one result is shown from one study in Fig 2 this literature showed results from multiple experiments.

3.3. Nitrogen fixation

Legume cover crops are able to fix atmospheric nitrogen and transfer it to the rhizosphere or utilize it for their own biomass. The decay of nitrogen-rich legume litter or rhizosphere products contribute to soil nitrogen fertilization and plant nutrition of the crop following the cover crop [13]. The amount of nitrogen fixed depends on the legume species and/or the companion

crop species in the mixture. For example, red clover fixes 29.00 kg N ha⁻¹ as a single species cover crop, but 52.00 kg N ha⁻¹ in a mixture with ryegrass [13]. The same was observed with winter vetch, which fixes 85.00 kg N ha⁻¹ as single species and 113.00 kg N ha⁻¹ in a mixture with winter rye [27]. A much wider range from 50.00 kg N ha⁻¹ to 300.00 kg N ha⁻¹ was found by Kaye and Quemada [22]. Wittwer et al. [18] showed that legumes as a single species cover crop can increase nitrogen uptake of maize by 32.00 kg N ha⁻¹ and as part of cover crop mixtures by 28.00 kg N ha⁻¹. The summarized literature resulted in a weighted mean of 52.49 kg N ha⁻¹ (95% CI, 32.06, 72.92) that can be contributed by legumes from nitrogen fixation.

3.4. Reduced nitrogen leaching

Cover crops prevent nutrient leaching over winter, especially of mineral nitrogen (N_{min}) that otherwise would be leached from the soil profile. However, this leaching reduction strongly depends on the timing of when cover crop are planted and type of cover crop. Early sown oil radish reduces leaching in the fall and winter months [28]. Rye as an over-wintering cover crop can better protect nitrogen from leaching in the spring [28]. Non-legume cover crops and mixtures can protect up to 100.00 kg N ha⁻¹ from leaching, while pure legumes can protect between 60.00 to 70.00 kg N ha⁻¹ [6,22]. Abdalla et al. [25] show that legume cover crops prevent 18.00 kg N ha⁻¹ from leaching, non-legume cover crops 38.00 kg N ha⁻¹, and cover crop mixtures 19.00 kg N ha⁻¹. A study by McCracken et al. [29] resulted in an average leaching reduction of 35.80 kg N ha⁻¹. The amount of scavenged nitrogen depends heavily on water availability and soil type. Early sowing and sufficient precipitation enable cover crops to develop faster, establish more biomass, and absorb more nitrogen in the fall. The tillage system also affects the amount of scavenged nitrogen. The faster mineralization in conventional tillage systems in autumn resulted in higher N_{min} stocks and higher nitrogen uptake from cover crops than in no-till systems [30]. Literature research resulted in a weighted mean value of 38.82 kg N ha⁻¹ (95% CI, 19.13, 58.51) of scavenged nitrogen available to the crop following the cover crop.

3.5. Fertilizer emissions

Nitrogen fertilizer emissions are caused by different factors and vary between fertilizer types. About half of the CO₂e emissions of nitrogen fertilizer is N₂O emissions from soil after application and about one-third of all emissions occur during the production process of fertilizer itself. The remaining emissions are divided into N₂O emissions from NH₄⁺ and NO₃⁻ losses and CO₂ from lime [31]. Total emissions per kg of nitrogen also vary between fertilizer types and the literature. For example, Hasler et al. [32] reported 8.69 kg CO₂e kg⁻¹ N for urea fertilizer to 11.64 kg CO₂e kg⁻¹ N for CaH₄N₄O₉ fertilizer. A much higher emission factor of 15.00 to 31.00 kg CO₂e kg⁻¹ N is used by Kahrl et al. [33]. The mean value of all studies considered was 11.23 kg CO₂e kg⁻¹ N (95% CI, 9.02, 13.43). Emissions from organic fertilizers were not considered.

3.6. Reduced indirect N₂O emissions due to less leaching

Leached nitrogen is deposited into aquatic ecosystems and represents a globally significant source of N₂O through indirect emissions. These emissions can be calculated using the IPCC emission factor EF₅, which incorporates three components: EF_{5g} (groundwater and surface drainage), EF_{5r} (rivers) and EF_{5e} (estuaries) [34].

The IPCC emission factor EF₅ amounts to 0.0075 and is the sum of EF_{5g}, EF_{5r} and EF_{5e} with a value of 0.0025 each. Tian et al. [34] suggest a higher emission factor for EF_{5g} of 0.0060, the other two factors are almost the same as those suggested by IPCC in 2006. Here, we use the

mean of two results: One using the IPPC factor which results in $0.08 \text{ Mg CO}_2\text{-eq ha}^{-1}$ and the other one using the factor of Tian et al. [34] which results in $0.12 \text{ Mg CO}_2\text{-eq ha}^{-1}$. The mean of both values leads to an average climate benefit caused by reduced indirect N_2O emissions due to less leaching of $0.10 \text{ Mg CO}_2\text{-eq ha}^{-1}$ (95% CI, -0.15, 0.35).

3.7. Albedo change

When soil is covered with cover crops, less solar radiation reaches the soil surface compared to fallow land. Thus, the albedo value of plants is higher than that of fallow soil. Due to this reduced net radiation, there is a cooling effect that impacts the global climate. However, the albedo value of fallow soil strongly depends on soil type and condition. In particular, the color and moisture content of the soil play important roles. Dark and moist soils have a lower albedo than light dry soils, so there is a wide variation in the albedo value of fallow land. Since there is often a high soil moisture level during the growth period of cover crops (in fall and winter) the albedo effect of covering the soil with cover crops is stronger than for the yearly average [14]. Unfortunately, research on albedo effects of cover crops is in its infancy and only two adequate publications were found. The albedo effect of cover crops ranges from -4.00 to 10.00 W m^{-2} was calculated by Kaye and Quemada [22]. Converted to CO_2e , this corresponds to a climate benefit of $0.25 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$. Carrer et al. [14] show that three months of cover cropping in Europe results in a climate benefit of $0.16 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$. Similarly, this study found that longer time periods with cover cropping would increase the mitigation potential by 27.0%. Overall, a mean climate benefit of $0.20 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ (95% CI, -0.37, 0.78) was identified in the considered literature for the albedo change of cover crops.

3.8. Nitrous oxide emissions

Cover cropping can increase N_2O emissions under certain weather conditions compared to fallow land depending on the fertilizer N rate, soil incorporation, and the period of measurement and rainfall [35]. There are many factors that influence the level of N_2O emissions which leads to high variability from this GHG emission source. A prerequisite for cover crops is high soil moisture and water saturation, or at least water saturation of the upper soil layers. Another factor is the C/N ratio of the cover crop, which influences how fast cover crop residues decompose. Cover crops with low C/N ratios emit more N_2O than cover crops with high C/N ratios [36,37]. Another factor influencing N_2O emissions is the treatment of cover crop residues. Incorporating residues into the soil leads to higher N_2O emissions as compared to leaving cover crop residues decaying on the soil surface [36]. Air temperature also effects N_2O emissions. As temperatures increase, N_2O emissions from cover crops also increase. Overall, air temperature accounts for 22.0% of the variability in N_2O emissions [38]. In a meta-analysis, Basche et al. [35] found that N_2O emissions increased in 60.0% and decreased in 40.0% of the publications when cover cropping was practiced. The overall conclusion of the meta-analysis is that cover cropping increases N_2O emissions only to a very small extent and that the variability is very large. For example, compared to a chemical fallow system, Olofsson and Ernfors [39] identified the highest value with $1.80 \text{ kg N}_2\text{O-N ha}^{-1}$ for oilseed radish, whereas Preza-Fontes et al. [40] identified the lowest emissions with $-0.54 \text{ kg N}_2\text{O-N ha}^{-1}$ for a sorghum-sudan-grass-mixture. The result of our calculation based on a systematic literature search also shows only a very small increase in N_2O emissions from cover cropping. The determined weighted mean value of emissions, as displayed in Table 2, is $0.13 \text{ kg N}_2\text{O-N ha}^{-1}$, which is equivalent to $0.04 \text{ Mg CO}_2\text{e ha}^{-1}$ (95% CI, -0.02, 0.09).

3.9. Foregone benefits due to cover crop seed land use

Land use for producing seeds for cover crops was calculated for the species phacelia, mustard, clover, and oat as representatives of the most important plant families used as cover crops. Their average was used for further calculations. The average land use requirement to produce one ha of cover crop seeds was calculated as 0.02 ha (95% CI, 0.00, 0.04).

We assume that the land used for the production of cover crop seeds would otherwise be used for wheat production. Wheat production on land in the EU offers a carbon benefit that consists of: (1) the opportunity that the wheat output enables storing carbon elsewhere (yield $\times$ carbon opportunity cost); and (2) savings in global production emissions due to lower production emissions in the EU compared to the global average (here, the difference between Swedish and global wheat production emissions is based on Searchinger et al. [11]). Other factors, like changes in soil organic carbon or bioenergy benefits are not considered here. The climate benefit of wheat consisting of factors (1) and (2) is forgone due to land requirements for cover crops' seed requirements and can be quantified accordingly to a mean value of 0.28 Mg CO₂e ha⁻¹ (95% CI, 0.27, 0.29).

3.10. Production emissions for cover crop seed production

Since no specific literature sources for seed production emissions could be found for typical cover crop species, emissions from corn, spring wheat, and canola seed production are used in this study. Hybrid corn seed production in China leads to emissions of 1,459.00 kg CO₂e Mg⁻¹, whereas in the U.S. it causes 2,250.50 kg CO₂e Mg⁻¹ [17,41] of emissions. Seed production of rapeseed in Poland causes slightly lower emissions of 1,014.00 kg CO₂e Mg⁻¹ [42]. In contrast, for spring wheat, it is only 580.00 kg CO₂e Mg⁻¹ in Southwest Finland and 680.00 kg CO₂e Mg⁻¹ in Northern Savonia (Finland) [43]. These emissions mostly depend on the amount of fertilizer used since fertilization is responsible for the majority of production emissions, especially the production and application of nitrogen fertilizers [17]. The weighted average value used for our calculation is 1,066.26 kg CO₂e Mg⁻¹ (95% CI, 219.56, 1912.95). For the emissions of processing, packaging, and transporting cover crop seeds, only one literature source for corn seed could be found. The emissions here are 213.00 kg CO₂e Mg⁻¹ [44].

3.11. Additional machinery operations for cover crop establishment

We assume that cover crop establishment requires either tillage with a plow or cultivator followed by seeding. In addition, it is assumed that the only relevant emission from these machinery operations is from burning fossil diesel fuel. Based on data of an internet database from KTBL [45], plowing plus seeding is estimated at 55.00 liter diesel fuel ha⁻¹, while cultivator tillage and seeding is estimated at 45.00 liter diesel fuel ha⁻¹. The variability of the machinery operation intensity and corresponding fuel consumption was analyzed by Wittwer et al. [18]. In this study, diesel fuel consumption ranges from 22.00 l ha⁻¹ for no-till systems to 61.00 l ha⁻¹ for conventional intensive tillage systems. In organic farming, diesel fuel consumption ranges from 32.00 l ha⁻¹ for reduced tillage to 55.00 l ha⁻¹ for intensive tillage. The average diesel fuel consumption used in this study was calculated as 45.29 l ha⁻¹ (95% CI, 32.43, 58.13).

The emission factor per liter of diesel fuel ranges from 3.00 kg CO₂e l⁻¹ [44] to 3.31 kg CO₂e l⁻¹ [46]. The average emissions were calculated as 3.13 kg CO₂e l⁻¹ (95% CI, 2.92, 3.34) diesel fuel. The additional machinery operations thus cause emissions of 0.14 Mg CO₂e ha⁻¹ (95% CI, 0.10, 0.18).

3.12. A factor not considered: Erosion reduction

According to Lugato et al. [47], soil erosion can lead to a loss of soil carbon, lowering the carbon sink capacity of soils. Additionally, soil erosion can disturb the soil structure and reduce soil fertility, which disconnects soil element cycles and further contributes to GHG emissions. However, the extent to which soil erosion leads to higher carbon fluxes out of the system depends on the specific context and interplay of many factors [48].

Cover crops protect soil erosion during the fall and winter and also after the establishment of the following crop, such as maize, due to remaining cover crop residues [49]. According to Laloy and Biolders [49] and Gentsch et al. [6], Cover crops increase the infiltration rate and improve soil structure, allowing the soil to absorb more water without eroding. According to Panagos et al. [15], cover crops reduce soil erosion by at least 20.0% in Europe and the United Kingdom. Machiwal et al. [50] found a reduction in soil loss of 33.0% to 77.0%, depending on the cover crop type for India. The reduction in soil erosion is highly dependent on the slope and management of the land. In addition, the soil type also plays a major role.

Given the uncertainty between soil erosion and fluxes from the soil system as well as the varying factors leading to soil erosion, we have not included climate benefits of soil erosion prevention from cover crops in our calculations.

3.13. Net climate change mitigation impact (NCCMI) of cover crops

We calculate the summary of all climate benefits from cover crops as $4.23 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ (95%CI, 1.25, 7.49) and all climate costs from cover crops as $0.93 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ a}^{-1}$ (95% CI 0.51, 1.34). The NCCMI of cover crops was calculated as $3.30 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ (Table 3). The NCCMI was then extrapolated to the maize harvest area for all EU-27 countries. Here, we assume a scenario in which cover crops are grown before maize on all of the EU-27's harvested maize areas, which is $15,092 \times 10^6 \text{ ha}$, on average [23]. Based on this calculation, planting cover crops before maize in the EU-27 results in a climate change mitigation potential of 49.80 million $\text{Mg CO}_2\text{e a}^{-1}$. This is equivalent to 13.0% of the EU-27's agricultural GHG emissions [51].

3.14 Sensitivity analysis based NCCMI scenarios

The impact factors “carbon land benefit based on yield gain” and “carbon sequestration” have a high impact on NCCMI but also show a high uncertainty. To address this uncertainty, we use four scenarios for NCCMI to analyze the sensitivity of the results:

- A) Base scenario as shown in section 3.13
- B) Base scenario less carbon land benefit based on yield gain
- C) Base scenario less carbon sequestration
- D) Base scenario less carbon land benefit based on yield gain and less carbon sequestration

4. Discussion

4.1. Review of results

The results of this study indicate that the climate benefits of cover crops significantly exceed their climate costs. This resulted in a positive NCCMI of $3.30 \text{ Mg CO}_2\text{e ha}^{-1} \text{ a}^{-1}$ that can be achieved if cover crops were incorporated in crop rotations of maize production. The major contributor to climate benefits is through carbon land benefits based on yield gain for maize following a cover crop, which alone contributed to 33.8% of all climate benefits. Several meta studies [9,10] showed that cover crops increase soil organic carbon stocks, with an average organic carbon sequestration rate of $1.43 \text{ Mg ha}^{-1} \text{ a}^{-1}$. The most important mechanism behind this is the stimulation of microbial activity from cover crops' organic matter input. Litter from

shoots and roots, rhizodeposits, and the transport of photoassimilate to the rhizosphere during the growth of cover crops results in a higher and more active microbial biomass [52]. These processes resulted in microbial derived organic substances that are key to build up mineral associated organic matter fractions with prolonged turnover times [53]. The activation of microbial cycling that derived from higher organic matter input rates is therefore a strong indirect factor of the climate benefits from cover crops. Carbon sequestration was the second largest contributor (34.5%) to climate benefits. The results indicate a maize yield increase of 8.8% by following a cover crop. Since maize yield gains are higher following legume cover crops and in organic systems, it can be assumed that increased nutrient availability is one of the key factors driving crop yield gains from cover crops. Cover crops might help in closing the yield gap between organic and conventional systems, as well as in improving the resilience of arable production under climate change. However, yield benefits depend on the quality of cover crop residues and reach its maximum at litter C/N ratios <25 [54]. Closer nutrient cycling and reduction of leaching losses resulted in another 24.3% of cover crops' climate benefits, including nitrogen fixation of legume cover crops. The highest maize yield gains were found for legume-based cover crops while graminoid cover crops showed only minor effects. For example, Marcillo and Miguez [24] found that a grass cover crop has no influence on maize yield. In the same study, a legume-only mixture shows up to a 21.0% yield gain in the maize crop following the cover crop. Wittwer et al. [18] confirmed that a legume-free cover crop mixture leads to only a 3.0% increase in maize yield. Mixtures of legumes and grasses as cover crops enable yield gains from 1.3% [55] to 21.0% [56], respectively. However, cover crops can also have negative effects on the subsequent maize yield. Hunter et al. [57] showed that a high carbon to nitrogen (C/N) ratio in spring cover crops resulted in a lower yield of silage maize. Nutrient use efficiency has been demonstrated to increase through cover crops that are in crop rotations for several crops, including maize [58–60]. The inclusion of legumes increases cover crops' litter quality and crop yield benefits; however, pure legume stands are less effective to prevent nitrogen leaching over the winter [6]. The inclusion of cover crops in crop rotations, therefore, requires a high degree of management by selection of suitable cover crop species or mixtures to maximize their green manure and environmental benefits.

Cover crops are able to change the amount of incoming shortwave radiation that is reflected back to the atmosphere and thereby mitigate warming [22]. Albedo change through cover crops' land cover has the smallest contribution (4.5%) to the climate benefits from cover crops. The systematic literature search resulted in only two publications that analyze albedo change through cover crops. Both found a slight climate change mitigating effect through radiative forcing changes induced by an increase in surface albedo.

Climate costs of cover crops were nearly six times lower than climate benefits and are mainly dominated by cover crops' seed production emissions and foregone benefits due to cover crops' seed land use (accounting for 41.9% and 30.1%, respectively, of the total climate costs of cover crops). Interestingly, additional machinery operations and N₂O emissions from cover crops' decomposition contributed minorly to climate costs (15.0% and 4.3%, respectively). Emissions of N₂O have a 280 times higher global warming potential compared to CO₂. Therefore, the latest studies were alarmed about the emission potential that can appear from decomposition of cover crop residues [35]. However, N₂O emissions are of episodic nature and depend on extended precipitation events. Despite this, N₂O emissions from cover crops' decomposition can be further reduced if cover crop residues were not incorporated into the soil [35]. With this respect, no-till operations would further reduce the N₂O emissions factor.

We created four scenarios where we assumed that not all positive impacts of cover cropping might be present at the same time. We removed the major contributors: C sequestration (B) and yield gain (C) or both together (D). All scenarios kept a positive NCCMI (Fig 3).

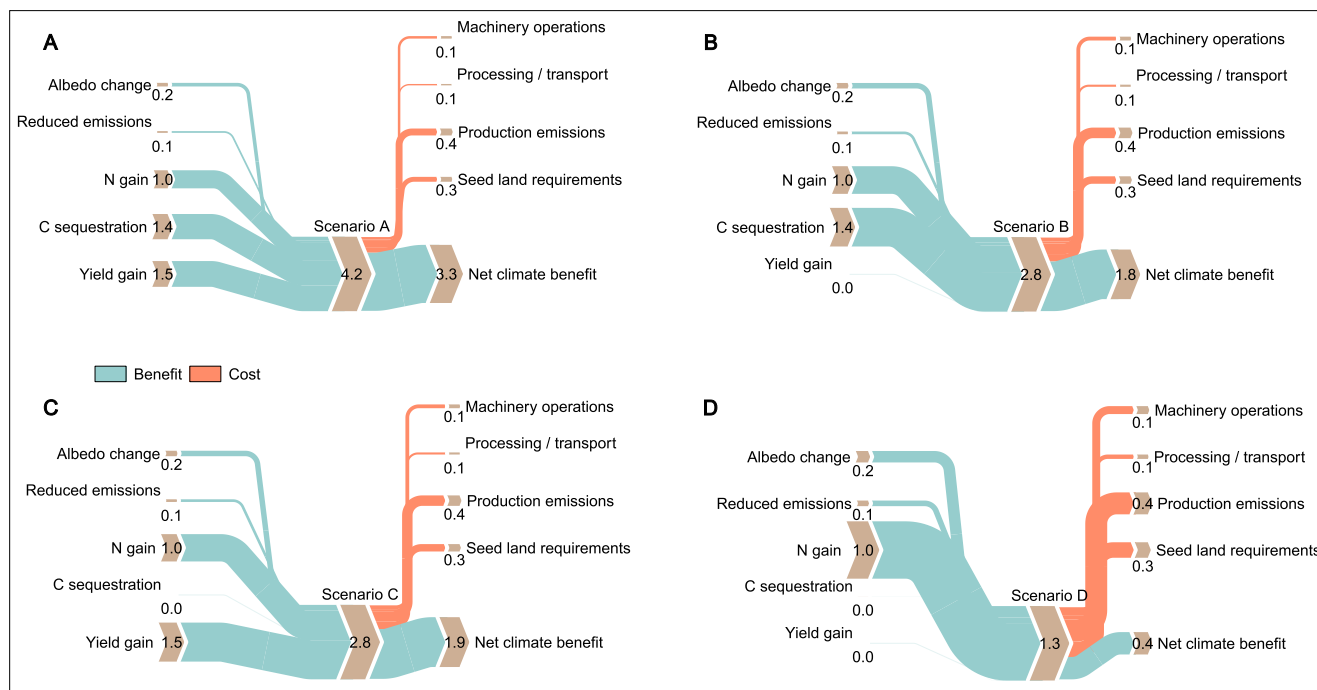


Fig 3. Sankey plots describing gains and losses of different scenarios for the NCCMI. Numbers are given as Mg CO₂e ha⁻¹.

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Therefore, we conclude that positive aspects of cover cropping always superimpose the negative impacts.

All scenarios show a positive NCCMI.

4.2. Comparing overall results to existing literature

In contrast to Kaye and Quemada [22], this study is first to include land use effects based on the yield gain caused by cover crops. Furthermore, our study uses a systematic literature review and quantifies the climate change mitigation impact for all of EU-27, which demonstrates the magnitude of climate change mitigation opportunities of cover crops. So far no other literature has extrapolated the climate change mitigation impact of cover crops to a country or region. Overall, Kaye and Quemada [22] found a climate change mitigation effect of 1.16–1.35 Mg CO₂e ha⁻¹ a⁻¹ from cover crops, which is lower than that calculated in this study. This discrepancy is a result of different analyzed literature and the inclusion of land use effects in our research. In addition, Abdalla et al. [25] showed a slightly lower climate change mitigation impact from cover crops compared to our results of 2.06 Mg CO₂e ha⁻¹ a⁻¹ (95% CI -0.04, 4.16). The study, however, does not consider land use change effects (1.51 Mg CO₂e ha⁻¹ a⁻¹ in our study), albedo change, emissions for cover crop seed production, and additional machinery operations. If the study would have considered these factors, their results would be more comparable to those in our study.

4.3. Limitations

A limitation of this study is that we did not include erosion reduction of cover crops as a climate benefit due to the high data variability and uncertainty of its climate impact. Furthermore, the use of carbon opportunity cost as suggested by Searchinger et al. [11] is criticized by

some authors for separating supply and demand side efficiencies and including supply and demand side interactions [61,62]. Despite this criticism, carbon opportunity cost is a widely used approach to quantify changes in efficiency of land use for mitigating climate change. Given that land use change is still the highest source of emissions in the global agri-food sector [2], carbon opportunity cost based on Searchinger et al. [11] is an adequate land use change quantification approach for changes in maize yield.

For the climate impact of land use for cover crop seed production, we use the forgone climate benefit of wheat based on Searchinger et al. [11]. Here, the same arguments discussed above for using carbon opportunity costs are relevant. We assume wheat as the displaced crop when cover crop seeds are produced since wheat is the crop with the largest acreage in the European Union [23]. For additional machinery operations to establish cover crops, we only consider diesel fuel emissions. There are also emissions for producing, maintaining, and repairing agricultural machinery, but in the majority of cases, existing machinery is used for cover crop establishment, i.e., no additional machinery is produced to establish cover crops. In this study, we only evaluated maize as the crop to follow cover crops. Maize is the largest spring crop by acreage in the European Union [23] and the most investigated crop in the scientific literature with a good data base. Despite this, other spring crops like oats, spring barley, sunflower, or sugar beet are investigated for the benefits of winter cover crops in the European Union. More data is needed to complete the view on climate benefits of cover crops based on different main crops.

4.4. Conclusion and policy recommendations

This is the first study to include all relevant climate change impacting effects of cover crops in a comprehensive calculation and to extrapolate the NCCMI of cover crops to the whole maize cropping area of the EU-27. We show that cover crops are powerful tools to mitigate climate change impacts from European agriculture, which make our findings very relevant for political decisions in the EU. If all maize cropping acreage in the EU-27 were to include cover crops, GHG emissions from EU-27 agriculture could be reduced by 13.0%. Based on this result, we recommend that the Common Agricultural Policy (CAP) of the European Union should continue to accelerate the integration of cover crops into farming. The current CAP (2023–2027) does not include regulations that make cover crops before spring crops mandatory or provide incentives so the area devoted to cover crops in the EU is maximized. There are conditionality requirements, such as obligatory soil cover in the winter for 80% of a farm's arable land. Therefore, if a farm has 80% winter crops and 20% spring crops in its rotation, there is no requirement to grow cover crops under the current CAP for this farm [63].

Our results recommend a stronger commitment from the EU's agricultural policy to make cover crops before spring crops a common practice on all farms. This will not only help to achieve the EU's climate protection goals, but also global targets in the Paris Agreement.

5. Statistics

The weighted mean was calculated from study values using the number of observations as the weighting factor. Mean values are followed by the 95% confidence intervals (CI) and are shown in brackets (lower CI limit, upper CI limit). All data collected from the literature as well as the calculations shown in Table 3 are provided as supplementary material (S1 File).

Forest plots were produced with the R package [64] with R version 4.3.2 [65]. Detailed description of the statistic parameters are outlined in [66].

Supporting information

S1 File. Calculations.

(XLSX)

S2 File. Included literature.

(XLSX)

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