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REVIEW ARTICLE

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Cover crops affect pool specific soil organic carbon in cropland – A meta-analysis

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Abstract

Cover crops (CC) offer numerous benefits to agroecosystems, particularly in the realm of soil organic carbon (SOC) accrual and loss mitigation. However, uncertainties persist regarding the extent to which CCs, in co-occurrence with environmental factors, influence SOC responses and associated C pools. We therefore performed a weighted meta-analysis on the effects of CCs on the mineral-associated organic carbon (MAOC), the particulate organic carbon (POC) and the microbial biomass carbon (MBC) pool compared to no CC cultivation in arable cropland. Our study summarized global research of comparable management, with a focus on climatic zones representative of Europe, such as arid, temperate and boreal climates. In this meta-analysis, we included 71 independent studies from 61 articles published between 1990 and June 2023 in several scientific and grey literature databases. Sensitivity analysis was conducted and did not identify any significant publication bias. The results revealed that CCs had an overall statistically significant positive effect on SOC pools, increasing MAOC by 4.8% (95% CI: 0.6%–9.4%, $n = 16$), POC by 23.2% (95% CI: 13.9%–34.4%, $n = 39$) and MBC by 20.2% (95% CI: 11.7%–30.7%, $n = 30$) in the top soil, compared to no CC cultivation. Thereby, CCs feed into the stable as well as the more labile C pools. The effect of CCs on MAOC was dependent on soil clay content and initial SOC concentration, whereas POC was influenced by moderators such as CC peak biomass and experiment duration. For MBC, for example, clay content, crop rotation duration and tillage depth were identified as important drivers. Based on our results on the effects of CCs on SOC pools and significant moderators, we identified several research needs. A pressing need for additional experiments exploring the effects of CCs on SOC pools was found, with a particular focus on MAOC and POC. Further, we emphasize the necessity for conducting European studies spanning the north–south gradient. In conclusion, our results show that CC cultivation is a

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key strategy to promote C accrual in different SOC pools. Additionally, this meta-analysis provides new insights into the state of knowledge regarding SOC pool changes influenced by CCs, offering quantitative summary results and shedding light on the sources of heterogeneity affecting these findings.

KEYWORDS

effect size, EJPSOIL, field experiments, MAOC, MBC, POC, review, SOC, synthesis

1 | INTRODUCTION

Cover crops (CCs), which are generally cultivated between cash crops, cover agricultural soils that would otherwise be left bare (Lal, 2015). They are able to provide multiple benefits to the agroecosystem, for example, reducing soil erosion (Kaye & Quemada, 2017) and nitrogen (N) losses (Ketterings et al., 2015; Valkama et al., 2015), increasing above- and belowground biodiversity (Lal, 2004), favouring soil temperature and heat flux (Lal, 2015) and improving overall soil quality and health (Chahal & Van Eerd, 2019). Further, it is evident that CCs also have a positive impact on soil organic carbon (SOC) sequestration (Kaye & Quemada, 2017; Poeplau & Don, 2015) and loss mitigation (Seitz et al., 2022). Among several agricultural practices, CCs were identified to be a very effective measure to increase C inputs (Xu et al., 2020). By now, there are numerous meta-analyses and reviews that quantitatively synthesized the effects of CCs on SOC globally (Bai et al., 2019; Crystal-Ornelas et al., 2021; Jian et al., 2020; McClelland et al., 2021; Poeplau & Don, 2015; Sun et al., 2020) and in the Mediterranean climate (Aguilera et al., 2013), all confirming the positive influence on SOC. However, there are still uncertainties about the magnitude by which CCs and environmental factors are driving SOC response and specific soil C pools (McClelland et al., 2021).

Total SOC is often not the most sensitive indicator to explain SOC accrual mechanisms or estimate SOC stock changes (Heckman et al., 2022; Rocci et al., 2021). By separating SOC into fractions, which are more sensitive to changes, better insights into C dynamics can be provided. In recent years, the idea of using two well-defined and operationally delineated fractions has gained increased acceptance. These are the mineral-associated organic matter (MAOM) and the particulate organic matter (POM) pools. Both have different properties when it comes to, for example, formation pathways, protection mechanisms, mean residence time and saturation (Lavallee et al., 2020). MAOM is smaller than POM, at less than 53 μm in size. Due to the adsorption to minerals and physical separation from microbes, it is well protected against decomposition and has a mean residence time between decades and centuries. Contrary, POM is sized between 53 μm–2000 μm and can be stabilized in soil from <10 years up to decades, being mainly protected by occlusion in aggregates (Lavallee et al., 2020).

> **Highlights**
>
> - First meta-analysis on the effects of cover crops (CCs) on soil organic carbon (SOC) pools in cropland relevant to European conditions.
> - CCs significantly increased mineral-associated organic carbon (MAOC), particulate organic carbon (POC) and microbial biomass carbon (MBC), but to different extents.
> - All pool changes due to CCs were influenced by moderators, while MBC response was impacted most.
> - We depict unresolved knowledge gaps of CC effects on SOC pools and long-term research needs.

Another C fraction, which is tightly linked to MAOM and POM, is the microbial biomass carbon (MBC) pool (Liang et al., 2017). It describes the living organisms in soil, measured by their carbon content (Ramesh et al., 2019). Soil microbes reduce SOC stocks by mineralizing organic matter, but also increase SOC stocks by transforming plant organic matter into microbial biomass and extracellular byproducts (e.g., carbohydrates, lipids, and peptides) and, finally, necromass. These components often form connections with mineral surfaces, so-called organo-mineral complexes, which foster stable organic matter (MAOM) production and therefore persistent SOC buildup (Cotrufo et al., 2013; Kästner & Miltner, 2018; Liang et al., 2017; Plaza et al., 2013). This process primarily takes place in microbial hotspots such as the rhizosphere through the in vivo microbial turnover pathway (Liang et al., 2017; Sokol, Sanderman, & Bradford, 2019).

SOC accrual under CCs is further dependent on a broad range of factors related to CC characteristics, environmental conditions and agricultural management (Lal, 2015; Wiesmeier et al., 2019). First, CC root-to-shoot

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ratio (Rasse et al., 2005) and biomass production (McClelland et al., 2021; Seitz et al., 2022) are examples of how SOC accrual success is built upon CC characteristics. These are also influenced by pedoclimatic factors such as mean annual temperature or soil texture, which were found to influence SOC change under CCs (Jian et al., 2020; Moukanni et al., 2022). Lastly, SOC is also dependent on additional agricultural management practices applied, for example, tillage, main crop residue management or crop rotation (Paustian et al., 1997).

Currently, there are several meta-analyses or quantitative synthesis available that study the effects of CCs on various SOC pools on a global (Hao et al., 2023; Hu et al., 2023; Kim et al., 2020; Muhammad et al., 2021; Wooliver & Jagadamma, 2023) and national level (Ma et al., 2021). However, a meta-analysis quantifying these effects for European agriculture, whilst following strict quality standards, is missing. A synthesis of available data studying the effects of CCs on SOC pools for agricultural management and climatic zones relevant to Europe would allow us to estimate the impact of this agricultural measure for this continent. This assessment holds significant importance, as it enables us to gauge the efficacy of this practice to foster SOC accrual and mitigate SOC losses. Consequently, it can significantly contribute to enhancing soil health, a matter of paramount concern in Europe's mission "A Soil Deal for Europe" (Commission et al., 2021). We therefore conducted the first global meta-analysis, investigating the effects of CCs on the mineral-associated organic carbon (MAOC), particulate organic carbon (POC) and MBC pool, that only included experimental studies conducted in climate zones that are relevant to Europe, whilst also following strict quality criteria (Borenstein et al., 2009; Fohrafellner, Zechmeister-Boltenstern, Murugan, & Valkama, 2023; Koricheva et al., 2013). This approach was chosen as not enough studies based on European experiments were available to conduct a meta-analysis. Throughout the adoption of this methodology, the relation to the European agricultural context and the comparability of studies was considered.

We hypothesized that the incorporation of CCs into an arable cropland system would affect MAOC, POC and MBC differently, with increasing POC and MBC through enhanced aggregation and assimilation of new C inputs, respectively, while only having a small but positive impact on MAOC. These changes would be affected by, for example, CC root systems and residue incorporation, hence, differ throughout the soil profile. Moreover, CC characteristics, agricultural management and other abiotic environmental factors would moderate these changes. Based on these hypotheses, the following research questions were addressed:

1. How does CC cultivation in arable cropland affect MAOC, POC and MBC?
2. How do CCs impact pool-specific SOC changes throughout the soil profile?
3. How do CC characteristics (e.g., sowing time, mixture) affect pool-specific SOC changes?
4. How do agricultural management practices (e.g., fertilization, residue management) impact pool-specific SOC changes in the presence of CCs?
5. How do pedo-climatic factors (e.g., climate zone, temperature, precipitation, soil texture) impact pool-specific SOC changes in the presence of CCs?

2 | MATERIALS AND METHODS

2.1 | Published protocol and information on primary data

A complete description of our materials and methods was previously published as a protocol (Fohrafellner, Zechmeister-Boltenstern, Murugan, Keiblinger, et al., 2023) in the open access journal MethodsX to make our research plans publicly available and allow fellow scientists to provide feedback and suggestions. The protocol contains information on the identification of the topic and the objective including description in the form of the PICO framework, where the population of scope was later extended to not only comprise crop rotations with mostly cereal crops but also soybean monocropping to allow the inclusion of additional experiments. Further, the complete literature search strategy and data management, screening strategy and developed eligibility criteria including a PRISMA flow diagram of the literature retrieval. Moreover, a list of moderators we planned to extract and analyse, as well as a short description of data extraction and synthesis, moderator and sensitivity analysis and data presentation, are available. There, we further describe that, as available data on the MAOC and POC pool was scarce, we also included organic matter data in our analysis, namely MAOM and POM. This was possible, as the effect size of choice (log response ratio) allows to summarize values with a large variation across studies (Fohrafellner, Zechmeister-Boltenstern, Murugan, & Valkama, 2023). Therefore, effect sizes, calculated from organic matter or organic carbon, can be compared with each other. To enhance the readability of this paper, we simplified our terminology by referring to both organic carbon and matter (MAOC, MAOM and POC, POM) as "MAOC" and "POC". Moreover, we completed the PRISMA 2020 Checklist (Page et al., 2021), which is attached to the Supplementary Material of this article. In the following, we describe the studies which were included in the meta-analyses.

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The final database (https://doi.org/10.5281/zenodo.10707812) consisted of 71 independent studies from 61 articles conducted globally since 1994 (Figure 1), studying the effects of CCs on the MAOC, POC and MBC pool. From each study, we extracted the means of response variables (SOC pools), the number of replicates (plots/blocks) and corresponding standard deviations for treatments (CC) and control (no CC). To allow moderator analysis, we further extracted an extensive number of possible explanatory variables and also provided descriptive information on, for example, CC species cultivated or use of herbicides or pesticides. In Table 1 the 71 studies including authors, publication year, country and site of experiment, soil texture class, Köppen-Geiger climate zone and SOC pools investigated are shown. All calculations regarding descriptive statistics (Section 3.1) were conducted in SigmaPlot Version 14.5.

2.2 | Moderators

After finishing the extraction of data and starting the moderator analysis, several explanatory variables were changed to descriptive variables, as the available data was not sufficient to do moderator analysis. For example, harvest time of CCs was rarely reported in articles, as most did not harvest CCs in the first place. Even though these moderators could not be assessed, descriptive information can be found in the database. Moreover, if initial moderator description from the protocol did not fit the available data in articles, we adapted them. For instance, inorganic N fertilization was changed from "type" to "applied or not". In Table 2 an updated list of moderators and their groups or ranges is presented. Moderator "Clay content class" (High >25%; medium 15%–25%; low <15%) was removed, as the results were in contradiction with the moderator "Clay content (%)" and therefore showed that this classification, based on soil texture classes as described in the articles, was not suitable to describe clay content. Further, the subgroups "Continent" and "Method used to analyze initial SOC content" were added.

2.3 | Meta-analysis and heterogeneity tests

The meta-analyses were conducted using MetaWin 2.1 software (Rosenberg et al., 2000) and IBM SPSS Statistics Version 27 and 29. For each SOC pool, we calculated an effect size (i.e., the magnitude of the treatment effect) that can be averaged across independent studies. For the response variables (the SOC pools), the response ratio (R) was computed as an index of the effect size:

$$R = \overline{X}_{CC} / \overline{X}_{C} \tag{1}$$

where $\overline{X}_{CC}$ and $\overline{X}_{C}$ represent the means for treatments (CC cultivation) and for controls (no CC cultivation), respectively, averaged for experimental replicates.

Since the distribution of R is skewed, performing statistical analyses in the metric of the natural logarithm of R is preferable due to its more normal distribution in small samples compared to that of R (Hedges et al., 1999):

$$\ln(R) = \ln\left(\overline{X}_{CC} / \overline{X}_{C}\right) = \ln\left(\overline{X}_{CC}\right) - ln\left(\overline{X}_{C}\right) \tag{2}$$

normal distribution for ln(R) for each SOC pool was tested by Shapiro–Wilk test.

The variance of ln(R) was calculated as follows:

$$V_{\ln(R)} = \frac{(\mathrm{SD}_{CC})^2}{n_{CC}\left(\overline{X}_{CC}\right)^2} + \frac{(\mathrm{SD}_{C})^2}{n_{C}\left(\overline{X}_{C}\right)^2} \tag{3}$$

where SD_{CC} and SD_{C} are the corresponding standard deviations, and n is the sample size (number of replicates).

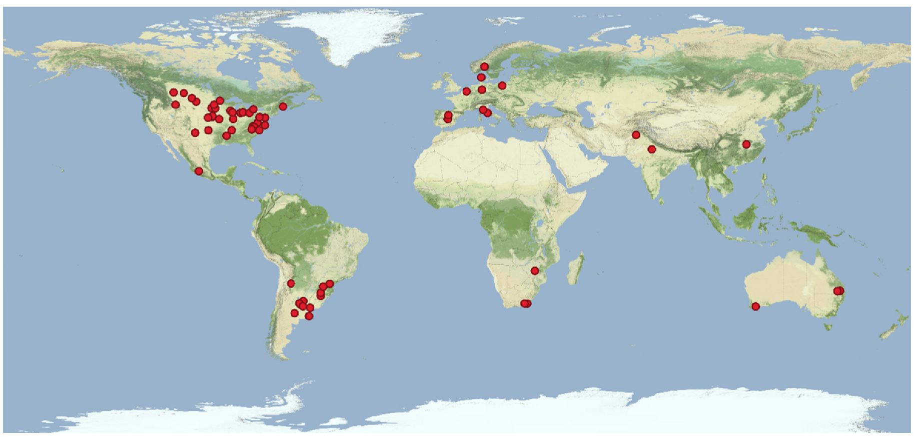

FIGURE 1 Experimental locations of the 71 included studies.

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TABLE 1 Meta-data describing the 71 included studies.

Nr.	ID*	Authors and year	Country	Site	Soil texture	Köppen-Geiger climate zone	Pools studied
1	717	Ali et al. (2023)	China	Hubei	Clay	Cfa	POC, MAOC
2	303a	Amado et al. (2006)	Brazil	Santa Maria	Loam	Cfa	POC
3	303c	Amado et al. (2006)	Brazil	Cruz Alta	Clay	Cfa	POC
4	610	Anuo et al. (2023)	USA	Clay Center	Loam	Dfa	POC, MAOM
5	420	Balota et al. (2014)	Brazil	Pato Branco	Clay	Cfa	MBC
6	217a	Beehler et al. (2017)	USA	Mason	Loam	Dfb	POC
7	183	Beltrán et al. (2018)	Argentina	Balcarce	n.s.	Cfb	POC, MAOC
8	716	Biederbeck et al. (2005)	Canada	Semiarid Prairie	Loam	Dfb	MBC
9	531	Bloszies et al. (2022)	USA	Goldsboro	Loam	Cfa	MBC
10	386	Brandan et al. (2017)	Argentina	Salta	Loam	Bsh	MBC
11	604	Bremer et al. (2008)	Canada	Brooks	Loam	Bsk	POC
12	219	Cates and Ruark (2017)	USA	Arlington	Loam	Dfb	POC, MAOC
13	351	Chahal and Van Eerd (2020)	Canada	Ridgetown	Loam	Dfb	MBC
14	742	Chen et al. (2020)	Norway	Gjoevik	Loam	Dfb	MBC
15	187	Córdoba et al. (2018)	Denmark	Foulum	Loam	Cfb	POC
16	73a	Crespo et al. (2021)	Argentina	Balcarce	Loam	Cfb	POC
17	73b	Crespo et al. (2021)	Argentina	Marcos Juárez	Loam	Cfa	POC
18	73c	Crespo et al. (2021)	Argentina	Paraná	Loam	Cfa	POC
19	807	Debosz et al. (1999)	Denmark	Foulum	Sand	Cfb	MBC
20	607	D'Hose (2015)	Belgium	Bottelare	Loam	Cfb	MBC
21	360	Feng et al. (2020)	USA	Dickinson	Loam	Bsk	MBC
22	298	Franzluebbers and Brock (2007)	USA	Iredell County	Loam	Cfa	MBC, POC
23	396	Frasier, Quiroga, and Noellemeyer (2016)	Argentina	Anguil	Loam	Cfa	MBC
24	359	Ghimire and Khanal (2020)	USA	Clovis	Loam	Bsk	MBC
25	309a	Griffin and Porter (2004)	USA	Clover	Loam	Dfb	MBC
26	4a	Gyawali et al. (2022)	USA	Blacksburg	Loam	Cfa	POC, MAOC
27	4b	Gyawali et al. (2022)	USA	Harrisonburg	Loam	Cfa	POC, MAOC
28	4c	Gyawali et al. (2022)	USA	Ferrum	Loam	Cfa	POC, MAOC
29	4e	Gyawali et al. (2022)	USA	Painter	Loam	Cfa	POC, MAOC
30	344	Hamer et al. (2021)	Germany	Göttingen	Loam	Cfb	MBC
31	371	Hontoria et al. (2019)	Spain	La Chimenea	Loam	Bsk	MBC
32	125a	Jilling et al. (2020)	USA	Champaign	Silt	Cfa	POM, MAOM
33	125b	Jilling et al. (2020)	USA	Mason	Sand	Dfa	POM, MAOM
34	125c	Jilling et al. (2020)	USA	Rock Spring	Silt	Cfa	POM, MAOM
35	214	King and Hofmockel (2017)	USA	Boone County	Loam	Dfa	MBC
36	918	Kumar et al. (2023)	India	New Delhi	Loam	Bsh	POC, MAOC
37	569	Landriscini et al. (2020)	Argentina	Córdoba	Loam	Cfa	POC, MAOC
38	605	Liebig et al. (2002)	USA	Mead	Loam	Dfa	POM
39	317a	Liebman (2018)	USA	Grand Rapids	Loam	Dfb	MBC, POC
40	317b	Liebman (2018)	USA	Lamberton	Loam	Dfa	MBC, POC
41	357	Malobane et al. (2020)	South Africa	Fort Hare	Loam	Bsk	MBC

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TABLE 1 (Continued)

Nr.	ID*	Authors and year	Country	Site	Soil texture	Köppen-Geiger climate zone	Pools studied
42	282	Marinari et al. (2010)	Italy	Viterbo	Loam	Csa	MBC
43	130a	Martinez et al. (2020)	Argentina	Arequito	Silt	Cfa	MAOC
44	606	Martín-Lammerding et al. (2015)	Spain	Miño de San Esteban	Loam	Bsk	MBC
45	423	Mohammad et al. (2014)	Pakistan	Peshawar	Loam	Cfb	MBC
46	295	Mtambanengwe and Mapfumo (2008)	Zimbabwe	Zimuto	Sand	Bsh	POM, MAOM
47	319	Mukumbareza (2014)	South Africa	Alice Jozini	n.s.	Cfa	MBC, POM
48	964	Murphy et al. (2011)	Australia	Gnowangerup	Loam	Csb	POC
49	226a	Novelli et al. (2017)	Argentina	Oro Verde	Loam	Cfa	POC
50	411	O'Dea et al. (2015)	USA	Montana	Loam	Dfb	MBC
51	256a	Osborne et al. (2014)	USA	Brookings	Loam	Dfa	POM, MAOM
52	779	Piotrowska-Dlugosz and Wilczewski (2015)	Poland	Bydgoszcz	Loam	Cfb	MBC
53	42	Restovich et al. (2022)	Argentina	Pergamino	n.s.	Cfa	POC
54	732	Roldán et al. (2003)	Mexico	Ajuno	Loam	Csb	MBC
55	205a	Ruis et al. (2018)	USA	Lincoln	Loam	Dfa	POM
56	205b	Ruis et al. (2018)	USA	Clay Center	Loam	Dfa	POM
57	967	Sainju and Lenssen (2011)	USA	Culbertson	Loam	Bsk	MBC
58	276	dos Santos et al. (2011)	Brazil	Ponta Grossa	Clay	Cfa	POC
59	450	Sapkota et al. (2012)	Italy	Enrico Avanzi	Loam	Csa	MBC
60	554	Sawchik et al. (2012)	Uruguay	Colonia del Sacramento	Clay	Cfa	POC
61	693	Semmartin et al. (2023)	Argentina	Don Eduardo	Loam	Cfa	POC
62	141	Singh et al. (2020)	USA	Jackson	Silt	Cfa	POC, MAOC
63	968	Somenahally et al. (2018)	USA	El Reno	Loam	Bsk	MBC
64	673	Tong et al. (2023)	Canada	Elora	Loam	Dfb	POC, MAOC
65	100	Tyler (2021)	USA	Stoneville	Silt	Cfa	MBC
66	314	Wander et al. (1994)	USA	Kutztown	Loam	Cfa	POC
67	302	Wander et al. (2007)	USA	Williams Bay	Loam	Dfa	POC
68	437	Weyers et al. (2013)	USA	Morris	Loam	Dfb	MBC
69	3	Williams et al. (2022)	Australia	Pampas	Clay	Bsh	POC, MAOC
70	525	Zhang et al. (2022)	USA	Ferguson	Loam	Cfb	POC, MAOC
71	683	Zhang, Ghahramani, et al. (2023)	Australia	Goondiwindi	Clay	Bsh	POC

Note: n.s. stands for "not stated" in studies/articles.
*Article ID (identification) according to article numbers in Database.

It was assumed that studies do not share the same effect size and consequently, a random effects model was used to combine estimates across studies. The random effects model accounts for experimental method differences between studies which may introduce heterogeneity (τ^2) among the true effects.

We calculated the weighted mean of $\ln(R)$ for all studies as follows:

$$\overline{\ln(R)} = \frac{\sum_{i=1}^{n} w_i \ln R_i}{\sum_{i=1}^{n} w_i} \quad (4)$$

where lnR_i is the log response ratio for study i, n is the number of studies and w_i is the weight for study i, defined as (Borenstein et al., 2009):

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TABLE 2 Updated list of explanatory variables (moderators) and their ranges or groups.

Explanatory variables (moderators)	Groups/ranges
Cover crop (CC) characteristics	
Type	Legumes; grasses; mixed
Species number	1–13
Single grown or in mix	Single; mixed
Sowing time (season)	Spring/summer; autumn/winter
Seed rate (kg ha^{-1} year^{-1})	13–3600
CC above ground peak biomass (Mg dry matter ha^{-1})	2–12
CC above ground average biomass (Mg dry matter ha^{-1} year^{-1})	1–8
Termination method	Herbicides; tillage; cut; none
Termination time (season)	Spring/summer; autumn/winter
Years in rotation with CC	1–10
Residue management	Left on field; incorporated; harvested/removed
Agricultural management	
Cropping system	Monocropping; crop rotation
Number of main crop species in rotation	1–6
Presence of leguminous main crops in rotation	Yes; no
Crop rotation duration (years)	1–9
Inorganic N fertilizer	Yes; no
Amount of inorganic N fertilizer (kg N ha^{-1} year^{-1})	0–700
Other inorganic fertilizer	Yes; no
Amount of other inorganic fertilizer (kg fertilizer ha^{-1} year^{-1})	0–130
Residue management of main crop	Left on field; incorporated; removed
Rate of residue incorporation of main crop (%)	0–100
Tillage system	Conventional tillage; reduced/minimum tillage; no-till
Maximum depth tilled (cm)	0–33
Pedo-climatic factors	
Initial SOC concentration (%)	0.5–5.5
Method used for to analyse initial SOC content	Wet oxidation, loss on ignition, dry combustion
Soil pH	4.5–8.5
Soil texture class	Clay; loam; silt; sand[a]
Clay (%)	6–72
Silt (%)	6–83
Sand (%)	4–85
Köppen-Geiger climatic zones in Europe	B (arid), C (warm temperate), D (boreal)
Mean annual rainfall (mm yr^{-1})	50–1930
Mean annual temperature (°C)	3.5–27
Continent	Africa, Asia, Australia and Oceania, Europe, North America, South America
SOC pools	
Duration of experiment (years)	1–38
Deepest point of soil sampling (cm)	0–60
Time of soil sampling (season)	Spring; summer; autumn; winter; several dates
Organic matter or carbon fraction	Organic matter; organic carbon

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TABLE 2 (Continued)

Explanatory variables (moderators)	Groups/ranges
MAOC size (µm)	< 20 µm; < 53 µm
Correction factor for MBC	None; 0.41–0.45; 0.33–0.38

[a]Texture classes according to IUSS Working group WRB (2022) and USDA (2019).

$$w_i = \frac{1}{V_i + \tau^2} \quad (5)$$

where V_i is the variance of the study i and τ^2 denotes the amount of residual heterogeneity (between-study variance). As the variance of an effect size is a function of its sample size, studies with a larger sample size have lower variances and therefore receive heavier weights.

The bootstrap statistical method to generate bias-corrected 95% CIs around the log response ratios from 4999 iterations was applied (Efron & Tibshirani, 1986). To test whether response ratios differed between the groups of categorical moderators, we used the χ^2 test to examine the between-group heterogeneity (Q_B) as well as to check for possible inter-correlation between the variables. To study the effect of continuous moderators, we ran weighted meta-regressions. The χ^2 test was used to examine model heterogeneity (Q_M), which describes the amount of heterogeneity explained by the regression models. The significant level of Q_M indicates that an independent variable (a moderator) explains a significant amount of variability in effect sizes ln(R).

Results for the overall effects of CCs on SOC pools and subgroup analysis were back-transformed and reported in the text and figures, respectively, as percentage changes from the controls:

$$\text{SOC pool change}\,(\%) = [EXP(\ln(R)) - 1] * 100\% \quad (6)$$

The CC cultivation effects on the SOC pools were considered significantly different from the controls if the 95% confidence interval (CI) did not overlap with zero.

2.4 | Sensitivity analysis

To assess potential publication bias, funnel plot asymmetry was investigated by plotting the natural logarithm of R (*lnR*) against its corresponding standard error, following the approach outlined by Sterne and Egger (2001). Additionally, we employed Egger's regression-based test to detect any signs of funnel plot asymmetry. A non-significant p-value from Egger's test indicates the absence of publication bias. To address the potential impact of missing studies and create a more symmetric funnel plot, we conducted a Trim-and-Fill analysis (Duval & Tweedie, 2000). This analysis involves adding values for missing studies, enabling us to estimate a new mean effect size. To gauge the magnitude of the file-drawer problem, we calculated the Rosenthal Fail-Safe Number (Nfs). The Nfs represents the number of unpublished, non-significant, or missing studies that would need to be included in the meta-analysis to alter the results from significant to non-significant (Borenstein et al., 2009). Lastly, rank correlation analysis using Kendall's τ was conducted to check the relationship between the effect size and variance. These analyses were done in MetaWin 2.1 and 3 software.

3 | RESULTS

3.1 | Review descriptive statistics

In order to get an overview of the available data studying the effects of CCs on SOC pools, we analysed the included studies regarding type of pools studied, publication year, experiment location, climate zone and maximum soil sampling depth. Moreover, the normal distribution of included studies for the pools was assessed.

The number of times each pool was studied in the 71 studies varied greatly (Figure 2a). Best studied was the POC pool (43 studies), followed by the MBC pool (32 studies) and the MAOC pool (20 studies). The number of articles on this topic has been increasing steadily in the last decades (exponential regression, $y = 1.0598e^{-71} \times \exp^{(0.0817*x)}$, $R^2 = 0.577$, $p < 0.001$, $n = 61$) (Figure 2b). Starting our search from 1990 onwards, the first article identified was published in 1994 (Wander et al., 1994). Over 36% of the included articles have been published in the last 3 years (from 2020 until June 2023, when the search for literature ended). The duration of the experiments ranged from 1 (minimum requirement for study inclusion) to 38 years. The majority of studies had a duration of less than 10 years. Studies were conducted mostly in the USA ($n = 31$), followed by Argentina ($n = 11$) (Table 3). All other countries, with counts of maximum four studies, were less represented. Regarding counts per continent, North America (36 studies), South America (16 studies) and Europe (10 studies) were represented best.

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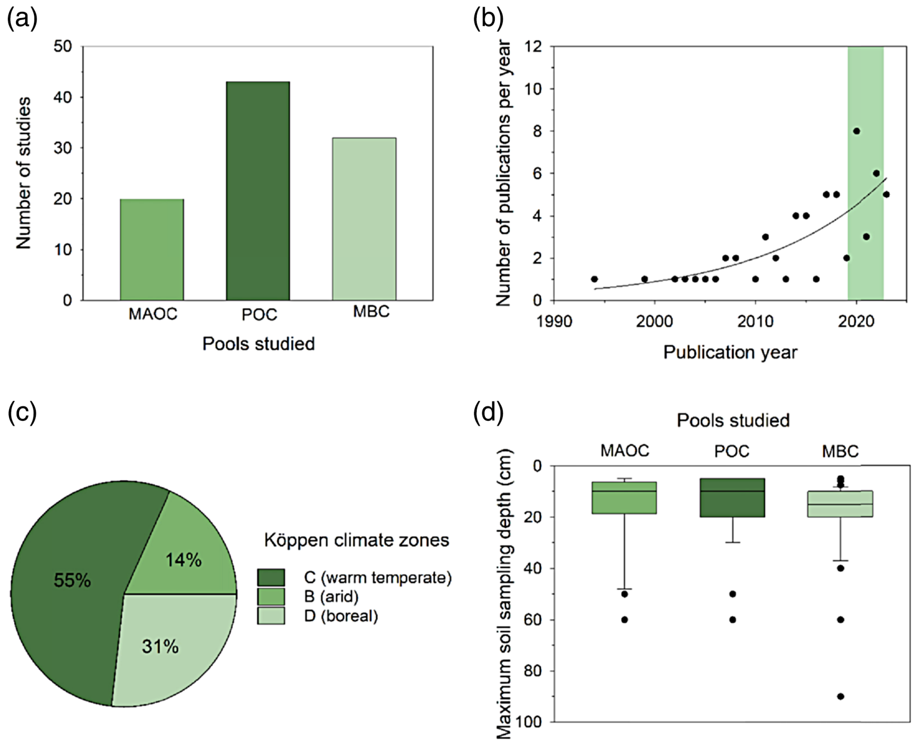

FIGURE 2 (a) Number of times each SOC pool was studied among the 71 studies and (b) publication year of included articles. The line represents the exponential regression line. The green-shaded area highlights studies published since 2020. Number of publications for 2023 only includes articles published until June of that year. (c) Percentage of studies located in climatic zones according to Köppen-Geiger. (d) Box plot for maximum soil sampling depth (cm) for SOC pools extracted from included studies.

According to Köppen-Geiger (Kottek et al., 2006) (Figure 2c), the majority of included experiments were conducted in the warm temperate and a substantial share in the boreal climate. The maximum soil sampling depth for SOC pool samples was in the top 20 cm for most extracted data (Figure 2d). Therefore, the analysed data-set is representative of the top soil only. When taking a closer look at the included articles, we found that the majority studied winter-hardy CCs, which were usually terminated in spring, before sowing the main crop, and were rarely harvested. Overall, 116 CCs were investigated in the 71 studies, of which vetch (*Vicia*) species ($n = 16$) were studied most often, followed by rye (*Secale cereale*) ($n = 15$), clover (*Trifolium*) species ($n = 14$), oat (*Avena sativa*) ($n = 11$) and radish (*Raphanus*) species ($n = 9$). The main crops most represented throughout the data-base were maize (*Zea mays*) ($n = 42$), followed by winter wheat (*Triticum aestivum*) ($n = 17$). Besides cereals, soybean (*Glycine max*) was frequently part of the rotations ($n = 34$). The number of main crop species in treatment and control were mostly equal. The predominant farming system was conventional agriculture, with no irrigation and no additional organic matter input. Overall, the included studies were comparable in regards to crops and management methods applied. Other variabilities between studies (e.g., climate zones, temperature, precipitation, tillage type and tillage depth) were addressed through moderator analysis. Regarding POC analysis in these studies, most authors chose to investigate total POC (50–2000 μm) compared to smaller sub-fractions. Over 80% of studies measured MAOC and/or POC by dry combustion with elemental analysers. MBC was almost in all cases analysed by chloroform fumigation extraction. A complete description of each included study can be found in the database.

In Figure 3, we show the normal distribution of effect sizes for the MAOC pool, the POC pool and the MBC pool after exclusion of outliers. For the MAOC and POC pool we identified four outliers each (ID 141, 918, 219, 256a and 295, 141, 303a, 319, respectively). Each pool had two outliers where *lnR* was too small (−0.84 [−57%], −0.55 [−42%] for MAOC and −1.05 [−65%], −0.92 [−60%] for POC) and two where *lnR* was too high (0.46 [58%] and 0.86 [136%] for MAOC and 1.00 [172%], 1.21 [235%] for POC). The effect sizes for the MBC pool were normally distributed after removing two outliers (ID 968 and 420) with large *lnR* (0.84 [132%] and 0.86 [136%]). The effect sizes of the outliers and other extracted data can be found in the database. Finally, we had 16, 39 and 30 independent studies examining the effects of CCs cultivation on MAOC, POC and MBC pool, respectively.

3.2 | Mineral-associated organic carbon

MAOC can persist long-term in soils before turning over, as the organic compounds within this pool generally exhibit spatial separation from microbes and strong physio-chemical sorption to mineral surfaces

TABLE 3 Number of studies per continent and country.

Continents and countries	Number of studies
North America	**36**
USA	31
Canada	4
Mexico	1
South America	**16**
Argentina	11
Brazil	4
Uruguay	1
Europe	**10**
Denmark	2
Italy	2
Spain	2
Germany	1
Belgium	1
Norway	1
Poland	1
Africa	**3**
South Africa	2
Zimbabwe	1
Asia	**3**
China	1
India	1
Pakistan	1
Australia & Oceania	**3**
Australia	3

(Dungait et al., 2012; Sokol, Sanderman, & Bradford, 2019; von Lützow et al., 2006). To answer how CCs impact MAOC in arable cropland, influenced by moderating factors, we calculated an overall effect size and co-variate impacts.

In our analysis, a total of 11 studies out of 16 investigated the effects of CCs on the mineral-associated fraction in the form of organic carbon, whereas five studies looked at the whole organic matter. We combined these parameters and reported them as "MAOC", as their response to CCs did not show significant differences ($Q_B = 0.247$, df = 1,15, $p = 0.642$). All included studies were conducted outside of Europe. Effect sizes of MAOC ranged from −10.3% ($lnR = -0.11$) to +25.5% ($lnR = 0.23$) across all studies (Figure 4). The weighted summary effect size showed that MAOC increased slightly, by 4.76% ($lnR = 0.047$), under CC cultivation compared to no CC cultivation. The result was significant, as the 95% CI (0.6%–9.4% or *lnR* 0.01–0.09) did not overlap with zero (control).

None of the studied moderators of categories "CC characteristics", "Agricultural management" or "SOC pools" were significant for MAOC (Table S1). With respect to the category "Pedo-climatic factors", meta-regression indicated that MAOC responses to CCs were significantly dependent on the clay content of soils ($p < 0.005$) (Figure 5a). When clay contents were low (e.g., 10%), CC cultivation reduced MAOC (−28% or $lnR = -0.33$), while with rising clay contents to, for example, 30%, it became positive (5% or $lnR = 0.05$). Moreover, the effect of CCs on MAOC depended on initial SOC concentration (Figure 5b). For example, we found that CCs increased MAOC by about 6% ($lnR = 0.06$) in soils

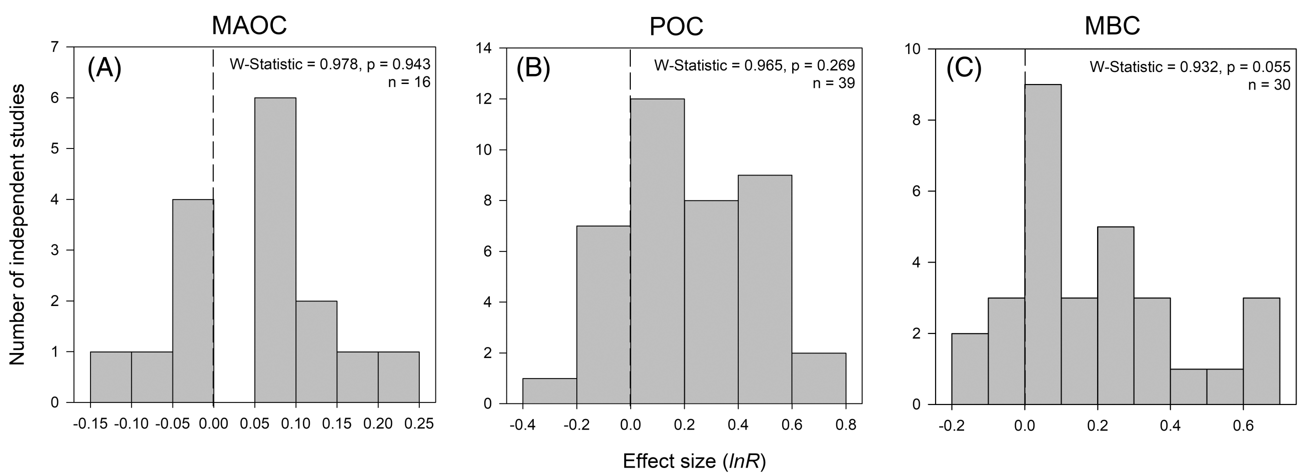

FIGURE 3 The distribution of effect sizes examining the effect of CCs on (a) MAOC, (b) POC and (c) MBC after exclusion of outliers. The dashed line indicates no CC cultivation (control). The W-Statistic (Shapiro–Wilk test), *p*-values of normal distribution tests and number of studies (*n*) for each pool are shown.

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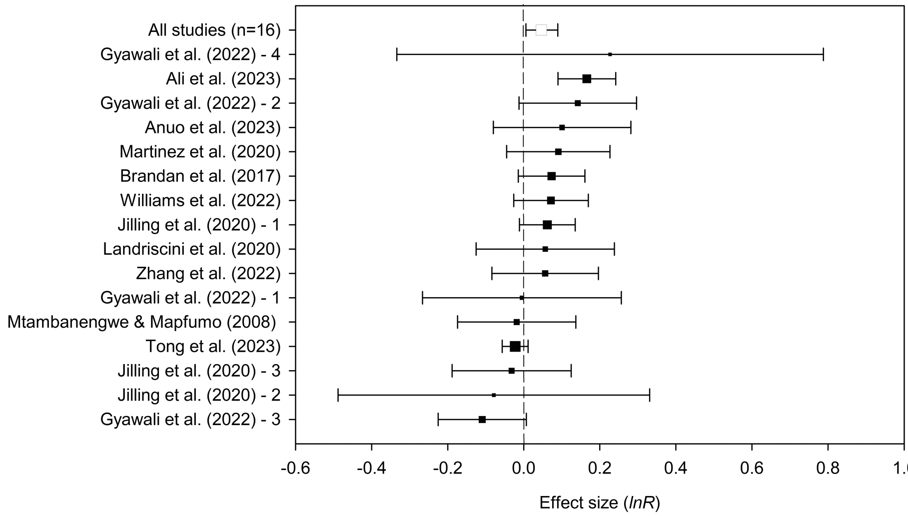

FIGURE 4 Forest plot showing effect sizes for 16 independent studies examining the effect of cover crop (CC) cultivation on the MAOC pool compared to no CC cultivation (control). Black squares are the effect estimates for each study with lower and upper 95% CIs. Square size corresponds to study weight. White square indicates weighted average with 95% CIs across all studies. The dashed vertical line indicates the control. When a number is shown after the publication year, this indicates that several independent studies (different sites) have been extracted from this article.

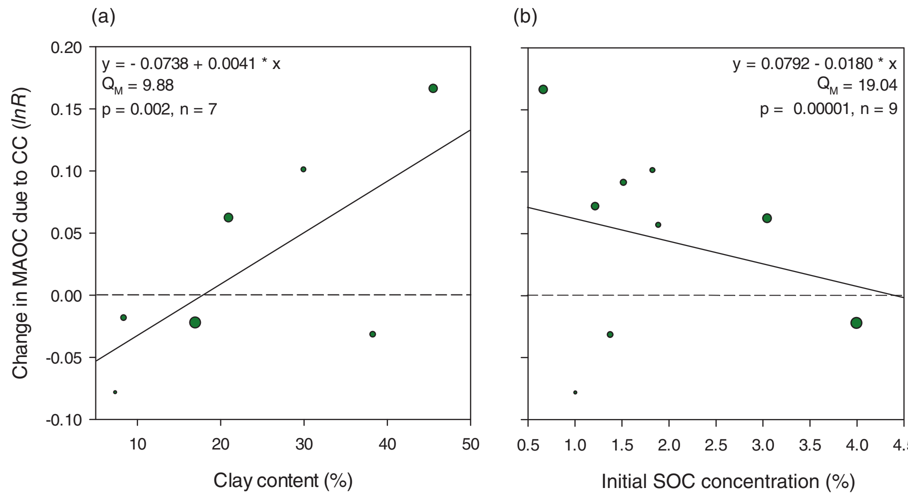

FIGURE 5 Weighted linear regression between changes in mineral-associated organic carbon (MAOC) due to cover crops (*lnR*) and (a) clay content (%) and (b) initial soil organic carbon (SOC) concentration (%). The solid line shows the linear regression, the striped line the control and the size of the dots indicates the study weight. In the top corner, the equation for the linear regression and values for Q_M (model heterogeneity), *p*-value and number of independent studies are stated.

with initial SOC concentrations of 1%, while the effect was only 3% ($lnR = 0.03$) in soils with 3% SOC. Nevertheless, the overall effect was always positive.

All other studied moderators could not explain any variability in effect sizes for MAOC (Table S1). For some of these non-significant categorical moderators, imbalances in the number of studies within sub-groups need to be acknowledged. Moreover, various moderators were excluded from the heterogeneity analysis due to an insufficient number of distinct groups (<2) or studies (<5) (see Supplementary Material Section 1.1.).

3.3 | Particulate organic carbon

Being of predominantly plant origin, POM consists of many structural C compounds with low N content, and can be available freely in soil or protected through occlusion in aggregates (Cotrufo et al., 2019; Golchin et al., 1994; Lavallee et al., 2020). To answer the research question of how CCs will impact POC under various conditions, we synthesized primary research results and calculated moderator effects.

32 studies described CC effects on the particulate organic fraction as organic carbon (POC), whereas seven studies investigated the whole organic matter (POM). For further analysis, we combined both parameters and reported them as "POC", since there was no statistically significant difference between their response to CCs ($Q_B = 1.85$, $df = 1{,}38$, $p = 0.196$). One of the included studies was conducted in Europe (Córdoba et al., 2018). The effect sizes ranged from −23.1% ($lnR = -0.26$) to +154.3% ($lnR = 0.93$) across all studies (Figure 6), with the overall effect of +23.2% ($lnR = 0.21$) compared to control. Since its 95% CI did not overlap with zero (13.9%–34.4% or lnR 0.13–0.30), the results were statistically significant.

Regarding heterogeneity analysis, moderator "CC seed rate" demonstrated a strong impact on POC change (Figure 7a). Meta-regression showed a decline in POC

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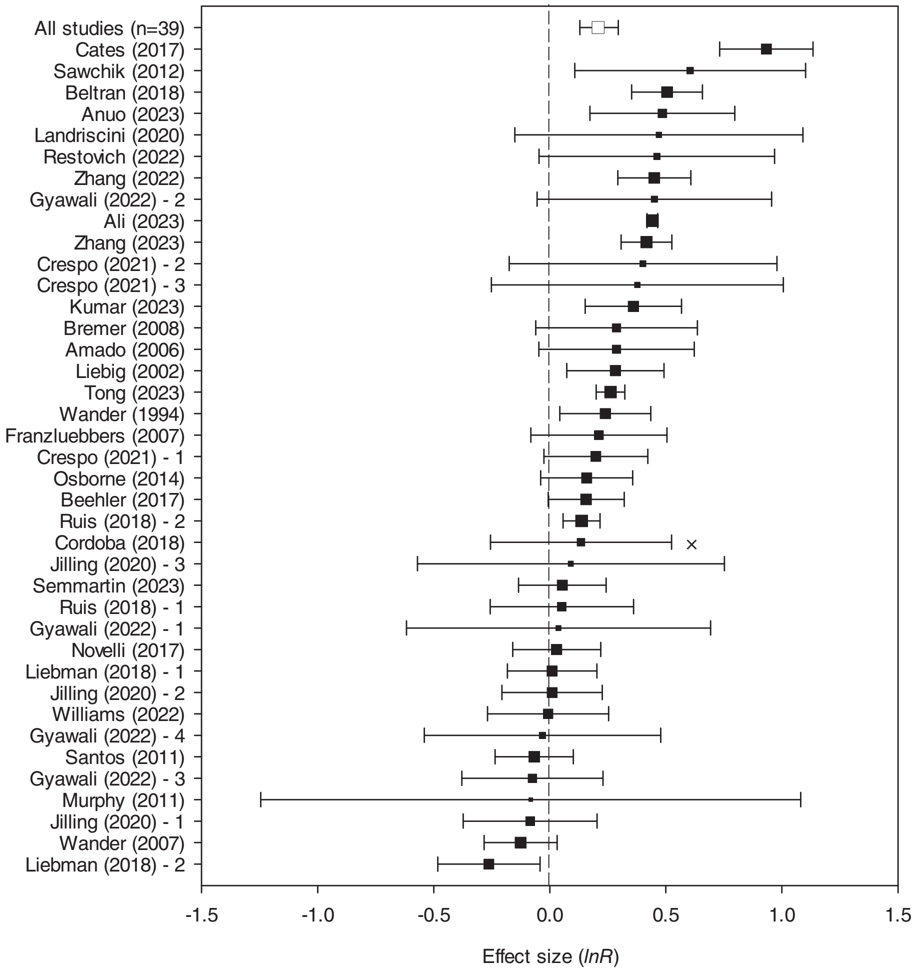

FIGURE 6 Forest plot showing the effect sizes for 39 independent studies examining the effect of cover crop (CC) cultivation on the particulate organic carbon (POC) pool compared to no CC cultivation (control). Black squares are effect estimates for each study with lower and upper 95% confidence intervals (CIs). Square size corresponds to study weight. White square indicates weighted average with 95% CIs across all studies. The dashed vertical line indicates control. When a number is shown after the publication year, this indicates that several independent studies (different sites) have been extracted from this article. Cross indicates European study.

with increasing seed rate, for example, a seed rate of 20 kg ha^{-1} showed stronger effects on POC ($lnR = 0.35$ or 42%) compared to 120 kg ha^{-1} ($lnR = 0.11$ or 12%). Further, moderator "CC above ground peak biomass", where "peak" describes the highest biomass (Mg ha^{-1}) measured during the experiment, also was highly significant (Figure 7b). A low peak CC biomass production up to 3.4 Mg ha^{-1} led to a decrease in POC compared to control, while with increasing peak biomass from 3.4 Mg ha^{-1} upwards, a positive impact was observed. Further, no significant inter-correlation was found between seed rates and peak biomass ($R^2 = 0.102$, $p = 0.37$, $n = 10$) or average biomass ($R^2 = 0.012$, $p = 0.77$, $n = 10$).

In the category "SOC pools", experiment duration was an important factor influencing POC change (Figure 7c). With increasing experiment duration, an increase in POC due to CCs can be observed. For example, after 5 years of experiment establishment, a POC change of +20% ($lnR = 0.18$) compared to the control was found, whereas after 20 years a change of +46% ($lnR = 0.38$) was visible. It is worth noting that only two studies out of 39 evaluated CC effects over 20 years. Lastly, the time of soil sampling had a significant influence on the effect size (Figure 7d). Early sampling of soil (i.e., in spring) under CC cultivation resulted in the highest POC response levels (46% or $lnR = 0.38$). Soil sampling in the autumn months still indicated significantly higher POC contents (20% or $lnR = 0.19$), whereas sampling in summer showed a tendency for POC reduction (−3% or $lnR = -0.03$). When soil was sampled on several dates (e.g., three times in 1 year), a change in POC of 28% ($lnR = 0.25$) was observed.

None of the other examined moderators, including all moderators in category "Agricultural management", did account for any variations in effect sizes for POC ($p > 0.05$, Table S2). As for MAOC, several moderators had to be excluded from the heterogeneity analysis because there were imbalances within sub-groups or insufficient studies available (n < 5) (see Supplementary Material Section 1.2.).

3.4 | Microbial biomass carbon pool

Soil microbes, responsible for the formation and turnover of SOC, convert organic matter into microbial biomass

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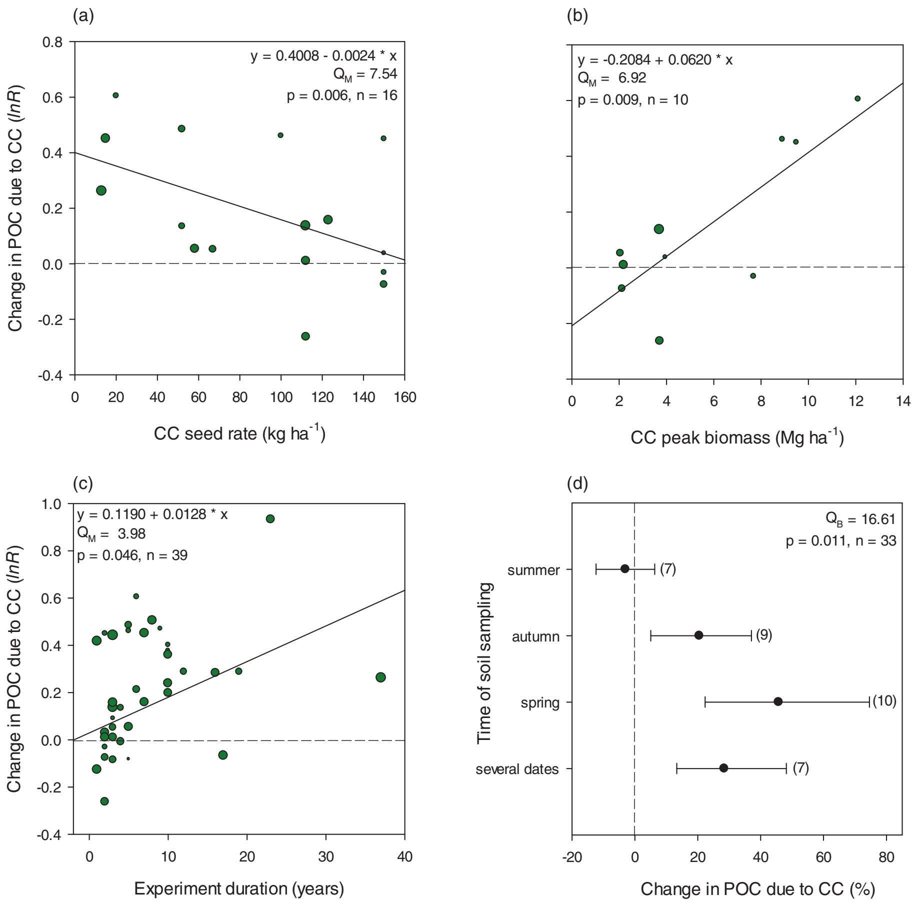

FIGURE 7 Weighted linear regression between changes in particulate organic carbon (POC) due to cover crops (CCs) (*lnR*) and (a) CC seed rate (kg ha^{-1}), (b) CC peak biomass (Mg ha^{-1}), (c) experiment duration (years) and (d) sub-group analysis (%) for time of soil sampling. The striped line indicates the control. In the top corner, the values for Q_M (model heterogeneity) or Q_B (between-group heterogeneity), *p*-value and number of independent studies are stated. For the regression analysis, the solid line shows the linear regression and the size of the dots indicates the study weight. In the top corner, the equation for the linear regression is shown.

and byproducts (Liang et al., 2011, 2015), making MBC a rapidly reacting C pool. In regards to the research question on how CCs affect these processes and therefore MBC, we included 30 studies in this meta-analysis and calculated effect sizes. They ranged from −15.1% ($lnR = -0.16$) to +100% ($lnR = 0.69$) across all studies (Figure 8). The overall effect estimate was +20.2% ($lnR = 0.184$) and statistically significant, with its 95% CIs not crossing zero (11.7%–30.7 or *lnR* 0.11–0.27). For this pool, 9 of the 30 studies were conducted in Europe. We ran an additional analysis for the European studies and found that the summary effect of +22.40% ($lnR = 0.20$) and 95% CIs (4.82%–31.77% or *lnR* 0.05–0.28) were close to the one of all 30 studies (Figure 8). The effect sizes for European studies ranged from −15.1% ($lnR = -0.16$) to 38.3% ($lnR = 0.32$), and were well distributed throughout the full dataset.

Heterogeneity analysis identified several moderators that significantly affected MBC under CC cultivation (Figure 9), others showed non-significant trends. First, regarding category “CC characteristics”, changes in MBC were significantly influenced by the sowing time of CCs ($p < 0.05$). When CCs were cultivated in spring and summer, MBC was 36% ($lnR = 0.31$) higher compared to control, while autumn and winter cultivation resulted in a 9% increase in MBC response under CCs ($lnR = 0.09$) (Figure 9a). The number of years in a rotation cultivated with CC had a positive, but non-significant impact ($p < 0.1$, Figure 9b). Moreover, concerning category “Pedo-climatic factors”, MBC change due to CCs was highly dependent on clay content in soil ($p < 0.01$) and decreased with increasing percentages of clay (Figure 9c). For example, in soil with 5% clay, a 26% ($lnR = 0.23$) increase in MBC response was found, whereas this change declined to 5% ($lnR = 0.05$) in soils with 30% clay content.

For the category “Agricultural management”, two moderators showed significant impacts on MBC. First, the duration of the crop rotation was linked to MBC change. Rotations with longer durations had a positive impact on MBC change due to CCs ($p < 0.05$, Figure 9d). Second, responses of MBC due to CCs were significantly influenced by maximum tillage depth ($p < 0.05$, Figure 9e). When no-till was applied, effects of CCs on MBC were stronger (24% or $lnR = 0.22$) than with maximum tillage depths of, for example, 20 cm (11% or $lnR = 0.10$). As a great variation of effect sizes for no-till studies was found (−2% to +88% or $lnR = -0.02$ to 0.63), we did a separate heterogeneity analysis for no-till studies only. This analysis, however, did not find a significant

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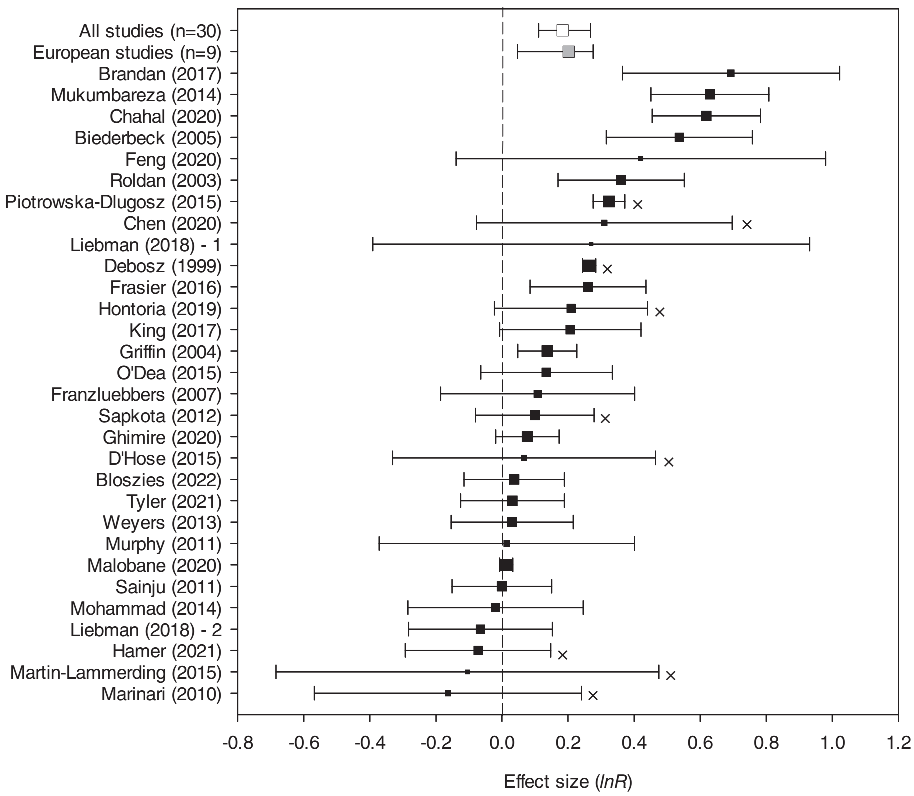

FIGURE 8 Forest plot showing effect sizes for 30 independent studies examining the effect of cover crop (CC) cultivation on the MBC pool compared to no CC cultivation (control). Black squares are effect estimates for each study with lower and upper 95% confidence intervals (CIs). Square size corresponds to study weight. White square indicates weighted average for all studies with 95% CIs across all studies. Grey square indicates weighted average for European studies only. The dashed vertical line indicates control. When a number is shown after the publication year, this indicates that several independent studies (different sites) have been extracted from this article. Crosses indicate European studies.

moderator or trend impacting the effect size for MBC under no-till. Lastly, with increased numbers of main crop species used in the rotation, hence increased diversity, MBC change showed a positive trend ($p < 0.1$, Figure 9f). Interestingly, monocropping (growing a single crop year after year on the same land) showed a large variation of effect sizes across studies (−48% to +99% or $lnR = -0.65$ to 0.69). Therefore, as done for studies under no-till, we analysed whether other moderators impacted CC effects on MBC under monocropping. We found that the type of CC (grass, legume, mixed) showed a trend ($Q_B = 8.64$, df = 2,14, $p = 0.063$) with grasses having the most positive impact (68% or $lnR = 0.52$) followed by legumes (19% or $lnR = 0.17$) and mixes (7% or $lnR = 0.07$). Moreover, increased experiment duration had a significant and positive impact on MBC under CC cultivation in monocropping systems ($Q_M = 5.09$, df = 1,14, $p = 0.024$).

All other considered moderators could not explain any variability in effect sizes for MBC ($p > 0.05$), including all moderators in category "SOC pools" (Table S3). Regarding experiment duration, it is crucial to acknowledge that only two studies exceeded durations beyond 12 years. As for the other pools, several moderators had to be excluded from heterogeneity analysis because there were imbalances within sub-groups or insufficient studies available (n < 5) (see Supplementary Material Section 1.3.).

3.4.1 | Sensitivity analysis

Sensitivity analysis, comprising of several tests, is necessary to determine the robustness of meta-analytical results. When testing included studies on MAOC for publication bias, we did not observe any evidence of funnel plot asymmetry. Furthermore, Trim-and-fill analysis did not identify any missing studies, as depicted in Figure S1. Additionally, examination using Egger's regression did not reveal any indication of publication bias ($p = 0.51$). The rank correlation analysis using Kendall's τ yielded non-significant results ($\tau = -0.20$, $p = 0.31$), indicating no relationship between effect sizes and variances. However, the Rosenthal Fail-safe-N (Nfs) value of 6 indicates the moderate robustness of our findings. Adding six unpublished, non-significant, or missing studies would need to be included in the meta-analysis to alter the results for MAOC from significant to non-significant.

Regarding the investigation of POC, the sensitivity analysis similarly indicated the absence of publication bias. Funnel plot asymmetry was not detected, and Trim-and-fill analysis could not identify any missing studies, as illustrated in Figure S2. Moreover, Egger's regression results were not statistically significant ($p = 0.51$), further supporting the absence of publication bias. The high Rosenthal Nfs of 343 provides strong evidence of the robustness of our findings, suggesting that they are

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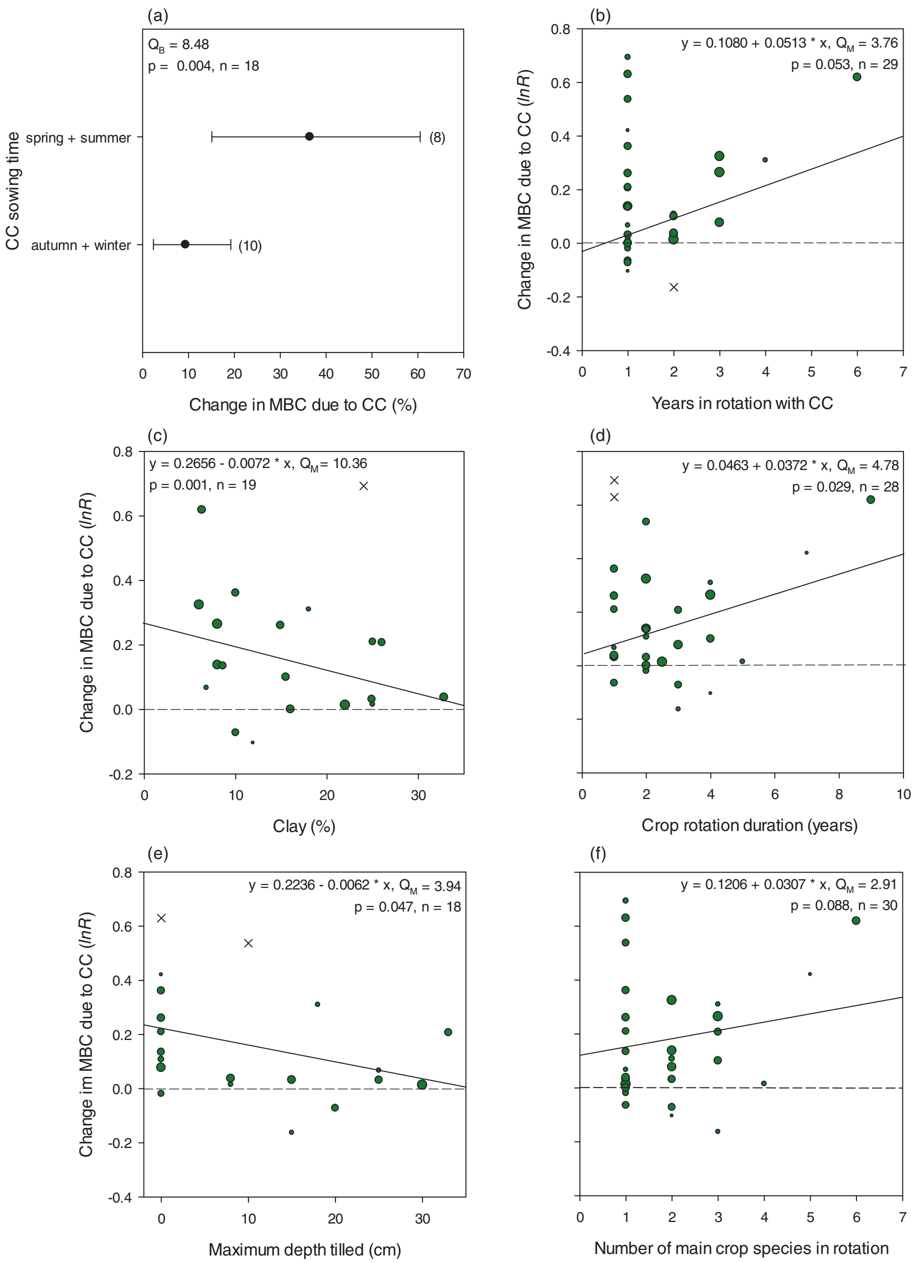

FIGURE 9 Sub-group analysis between changes in microbial biomass carbon (MBC) due to cover crops (CCs) (%) and (a) CC sowing time and weighted linear regression (*lnR*) for (b) years in rotation with CC (outlier: ID 282), (c) clay content (outlier: ID 386), (d) crop rotation duration (outliers: ID 319, 386), (e) maximum depth tilled (outliers: ID 319, 716) and (f) number of main crop species in rotation. The striped line indicates the control. In the top corner, the values for Q_M (model heterogeneity) or Q_B (between-group heterogeneity), *p*-value and number of independent studies are stated. For the regression analysis, the solid line shows the linear regression and the size of the dots indicates the study weight. In the top corner, the equation for the linear regression is shown.

unlikely to be influenced by unpublished studies. Kendall's τ also showed non-significant results ($\tau = 0.20$, $p = 0.07$).

In the case of MBC, our Trim-and-fill analysis detected two missing studies, as shown in Figure S3. These two imputed studies caused a slight shift in the *lnR* value, from 0.184 (20%) to 0.194 (21%). However, the adjusted estimate remains very close to the original. Egger's regression results were not statistically significant ($p = 0.34$), supporting the absence of publication bias. The high Nfs of 226 indicates the robustness of our findings and suggests that they are unlikely to be significantly influenced by unpublished studies. Additionally, Kendall's τ yielded non-significant results ($\tau = -0.01$, $p = 0.96$).

4 | DISCUSSION

This meta-analysis is the first of its kind summarizing effects of CCs on SOC pools in cropland under conditions relevant to European arable farming. It considers three different soil C pools differing largely in their turnover times. The underlying studies cover a publication period of almost 30 years and focus on the top layer of arable cropland soils. Moreover, a wide range of moderators was considered to explain the heterogeneity of the outcomes across these studies. There are several published meta-analyses and quantitative syntheses, which studied the impact of CC cultivation on several SOC pools on a global level (Hao et al., 2023; Hu et al., 2023; Kim et al., 2020; Muhammad et al., 2021;

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Wooliver & Jagadamma, 2023). Our meta-analysis synthesized global data on CC effects on SOC pools, focusing on agricultural management and climatic zones which are also found in Europe. At the same time, we followed strict quality criteria for conducting agricultural meta-analyses (Borenstein et al., 2009; Fohrafellner, Zechmeister-Boltenstern, Murugan, & Valkama, 2023; Koricheva et al., 2013). Therefore, our meta-analysis provides novel information and high-quality data on the responses of SOC pools to CCs, cultivated under conditions representative of Europe.

4.1 | Overall effects of CCs on SOC pools

Our analysis reveals a significant positive impact of CCs on MAOC, POC and MBC when compared to non-CC cultivation. The most pronounced response was observed in POC with an increase of 23.2%, followed by MBC with a 20.2% increase and MAOC with a 4.8% increase. These changes can be attributed to various soil processes. First, living microbial organisms play a fundamental role in SOC storage, as they transform plant residues, as provided by CCs, through the ex vivo and in vivo microbial pathways. In the ex vivo pathway, plant residues are enzymatically converted into plant-derived carbon deposits, which are not readily assimilated by microbes, whereas in the in vivo pathway, microbes incorporate plant-derived carbon into their biomass, forming microbial-derived carbon (Liang et al., 2017; Sokol, Sanderman, & Bradford, 2019). Although microbial biomass makes up less than 5% of SOM (Dalal, 1998), the structures generated by microbial activities can become associated with mineral surfaces, incorporated into organo-mineral complexes, and occluded to aggregates, therefore forming primarily MAOC (Cotrufo et al., 2013; Liang et al., 2017; Sollins et al., 1996; von Lützow et al., 2007). This highlights the indispensable role of microbes in stable SOC, hence MAOC formation. POC on the other hand is mainly fed by physical transfer of fragmented and depolymerized plant litter to the mineral soil. There, it facilitates aggregation, providing protection to the C in the litter by spatial inaccessibility and formation of occluded POC (Cotrufo et al., 2015; Lavallee et al., 2020). All these processes are reliant on plants, their biomass and root exudates. Introducing CCs into agricultural systems can accelerate these processes and enhance C inputs into soil where it can be readily used or stored short- and long-term.

When comparing our findings with other meta-analyses on this topic, both similarities and differences emerge. A meta-analysis by Hu et al. (2023) reported a 15% increase in POC (CI: 12%–17%, $n = 255$), a 33% increase in MBC (CI: 28%–39%, $n = 141$) and a 7% increase in MAOC (CI: 5%–9%, $n = 120$). Their conclusions differed from ours, as they found CCs to most strongly affect MBC, while we observed a greater impact on POC. Despite following most meta-analytical quality criteria, the authors extracted SD only for some studies (Fohrafellner, Zechmeister-Boltenstern, Murugan, & Valkama, 2023) and did not extract studies independently, thereby causing overrepresentation of these observations (Hungate et al., 2009). According to another meta-analysis by Wooliver and Jagadamma (2023), who examined CC effects on several agricultural systems (e.g., cereals, vineyards and cotton) and reported combined effects, POC increased by 15% (CI: 9%–22%, $n = 404$), which is approximately 8% lower than our results. For MAOC they reported an increase by 6% (CI: 2%–9%, $n = 178$) which is similar to our findings. It is important to note that they included effect sizes for MAOC in their meta-analysis which were estimated by subtracting POC from total SOC and not directly measured (Fohrafellner, Zechmeister-Boltenstern, Murugan, & Valkama, 2023).

Lastly, the research question on how CCs affect SOC pools throughout the soil profile could not be answered, as most extracted data was representative for the upper 20 cm (Figure 2d). Thus, future experimental studies and quantitative reviews should aim to sample deeper soil layers, up to 100 cm, and analyse these results in a meta-analytical manner to generate knowledge on how C accrual is distributed in soil.

To summarize, our research suggests that CCs positively impact MAOC, POC, and MBC through a set of fundamental processes involved in SOC formation. However, the strength of this impact varies among the pools, as supported by other meta-analyses. While the effect sizes for MAOC are consistent throughout meta-analyses, differences in POC and MBC effects can be attributed to variations in statistical methodologies and the inclusion of studies from diverse pedo-climatic zones and agricultural systems. It is essential to consider these factors when comparing and interpreting the results of different meta-analyses. Table 4 provides a comprehensive summary of the findings concerning the impact of CCs on SOC pools, major moderators and supporting evidence gathered through our meta-analysis and pertinent literature. These conclusions are further elaborated in Sections 4.2 and 4.3 of this study.

4.2 | Sources of variation across studies

The distribution of effect sizes in this study described a wide range of SOC pool changes in response to CCs. For MAOC, effect sizes ranged from −10.3% to +25.5%, for POC from −23.1% to +154.3% and for MBC from

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TABLE 4 Summary table on the effects of cover crops (CCs) on soil organic carbon (SOC) pools and major moderators impacting outcomes.

Conclusions	SOC pools	Confirmed by other meta-analyses, reviews and original articles	Supported/not supported by this meta-analysis
CCs have an overall positive effect	MAOC	Hu et al. (2023); Wooliver and Jagadamma (2023)	Supported, Figure 4
	POC	Hao et al. (2023); Hu et al. (2023); Wooliver and Jagadamma (2023)	Supported, Figure 6
	MBC	Hao et al. (2023); Hu et al. (2023)	Supported, Figure 8
Important CC characteristics			
CC type	MAOC	Wooliver and Jagadamma (2023)	Not supported, Table S1
CC seed rate	POC	–	Supported, Figure 7a
CC peak above ground biomass	POC	Liang et al. (2023)	Supported, Figure 7b
CC sowing time	MBC	McClelland et al. (2021); Moukanni et al. (2022)	Supported, Figure 9a
Number of years in rotation with CCs	MBC	Brennan and Acosta-Martinez (2017); White et al. (2020)	Supported, Figure 9b
Important agricultural management practices			
Tillage type	POC	Wooliver and Jagadamma (2023)	Not supported, Table S2
	MBC	Kim et al. (2020)	Not supported, Table S3
Maximum tillage depth	MBC	Kandeler et al. (1999); Zuber and Villamil (2016)	Supported, Figure 9e
Crop rotation duration	MBC	Feng et al. (2020); Liu et al. (2023)	Supported, Figure 9d
Number of main crop species in rotation	MBC	Motta et al. (2007)	Supported, Figure 9f
Important pedo-climatic factors			
Mean annual temperature	POC	Hu et al. (2023); Wooliver and Jagadamma (2023)	Not supported, Table S2
Clay content	MAOC	–	Supported, Figure 5a
	MBC	Franzluebbers et al. (1996); Muhammad et al. (2021)	Supported, Figure 9c
Initial total SOC concentrations	MAOC	Cotrufo et al. (2019)	Supported, Figure 5b
Important SOC pool-related factors			
Experiment duration	POC	Moukanni et al. (2022); Wu et al. (2023)	Supported, Figure 7c
	MAOC	Hu et al. (2023); Wooliver and Jagadamma (2023)	Not supported, Table S1
Soil sampling time	POC	–	Supported, Figure 7d

+15.1% to +100%. Therefore, moderator analysis was conducted to assess where these differences in effects arise from. In the following sections, we will discuss these results and possible underlying mechanisms of the observed effects, structured according to the predefined moderator categories (i.e., "CC characteristics", "Agricultural management", "Pedo-climatic factors" and "SOC pools").

4.2.1 | Impact of CC characteristics

We hypothesized that CC characteristics would impact the response of SOC pools to CCs. After conducting moderator analysis and discussing the results, several conclusions could be drawn. Starting with POC, a significant negative relation between CC seed rate and response ratio was observed (Figure 7a). As no significant

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inter-correlation between seed rate and CC above-ground biomass (both average and peak) was found, potential effects of root biomass were considered. Due to a lack of root data in the studies, no statistical testing was possible. Despite the acknowledged significance of roots in SOC accrual, their measurement is often neglected in experimental studies due to labour-intensive efforts. Nevertheless, it is evident that both the rhizodeposits of living roots and the decomposition of dead roots contribute substantially to both MAOC and POC (Huang et al., 2021; Sokol, Kuebbing, et al., 2019; Yang et al., 2023). The predominant impact of living root inputs on the net formation of MAOC aligns with expectations from the 'dissolved organic C (DOC)-microbial pathway' theory (Cotrufo et al., 2015). This theory posits that labile DOC compounds are efficiently anabolized by microbes, undergo turnover, and are subsequently deposited into the MAOC pool (Sokol, Kuebbing, et al., 2019). In contrast, structural litter inputs are believed to preferentially contribute to POC (Cotrufo et al., 2015). These underlying processes are species-dependent, influenced by factors such as the root-to-shoot ratio (Huang et al., 2021) and root morphology, which exerts a stronger impact on the accrual of root carbon into the MAOC and POC pools than root quality (C:N ratio) (Engedal et al., 2023). This influence extends beyond the described C allocated in the form of rhizodeposition to include the provision of root surface area for in vivo and ex vivo transformation of fresh C. Additionally, CC functional groups exhibit varying qualitative traits, such as root length, that significantly impact SOC pool accrual (Engedal et al., 2023). These findings underscore the indispensable role of CC roots and associated plant traits when studying the effects of CCs on SOC.

When connecting these findings with the significant results for moderator "Peak CC biomass", we can observe that aboveground (and potentially belowground) biomass production is an important driver in POC accrual under CCs. Interestingly, a negative impact on POC is seen when peak biomass is below 3.4 Mg ha^{-1} which increases with rising peak biomass (Figure 7b). This could be explained by rhizosphere C inputs which can cause a rhizosphere priming effect of native C (Kuzyakov, 2010), especially when C pulses are large and infrequent (Moukanni et al., 2022). C priming can be defined as "an extra decomposition of organic C after addition of easily-decomposable organic substances to the soil" (Dalenberg & Jager, 1989). This is dependent on the increased activity and/or amount of microbial biomass causing either acceleration or retardation of SOC turnover (Kuzyakov et al., 2000). Our results confirm the findings by Liang et al. (2023), who concluded that SOC buildup is constrained by low CC biomass production (hence C input rates) and positive priming effects. In order to achieve net SOC accrual, C inputs need to exceed losses from priming. Common factors contributing to low CC biomass production in temperate and cold climates include late seeding within the cropping season. This delay, often accompanied by reduced daylight hours and cold temperatures, hampers the optimal growth conditions for CCs. On the other hand, arid climates pose challenges to CC growth due to water limitations, which can significantly stress their development. An alternative strategy to address these challenges involves undersowing CCs in the main crop. However, this practice is not yet widely established across Europe (Smit et al., 2019). While undersowing offers potential solutions to the issues of late seeding and related environmental constraints, it comes with its own set of limitations. For instance, it may not be compatible with all main crops, and special machinery may be required to effectively implement this practice (Smit et al., 2019).

In the case of MBC, our heterogeneity analysis identified a significant influence of sowing time of CCs on the outcomes. Specifically, CCs sown during the spring and summer seasons exhibited a more pronounced positive effect on MBC change compared to CCs sown in the autumn and winter seasons (Figure 9a). This suggests a season-dependent variation in the impact of CCs on MBC levels in the soil. Nevertheless, it needs to be acknowledged that more than half of the included studies in this meta-analysis were conducted in warm temperate climates, possibly causing a bias towards this climate zone. CC growing period throughout Europe differs greatly, from short durations in Romania to the Netherlands with long periods, keeping CCs until the early spring (Smit et al., 2019). Overall, CC growth duration is an important predictor of SOC responses to CC cultivation (McClelland et al., 2021; Moukanni et al., 2022) along with plant establishment, biomass and residue quality. Therefore, adjusting CC growth duration by selecting CC planting and termination times is an intrinsic consideration when managing CCs (Alonso-Ayuso et al., 2014).

Regarding the impact of the number of years in a crop rotation cultivated with CCs, our analysis detected a positive trend on MBC change (Figure 9b). Continued incorporation of CCs promotes plant-derived C inputs, for example, litter (Lal, 2004), root biomass and exudates (Dijkstra et al., 2021; Schmidt et al., 2011), which support growth and accumulation of microbial biomass (Brennan & Acosta-Martinez, 2017; White et al., 2020). Other experimental studies revealed a rapid and substantial response in soil microbial biomass size and community composition in response to the introduction of CCs. This change is attributed to ongoing residue inputs and a consistently active rhizosphere throughout the year (Frasier, Noellemeyer, et al., 2016; Lehman et al., 2012).

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Lastly, for MAOC, our analysis did not reveal any significant moderators or trends within the category "CC characteristics" (Table S1). This might be because MAOC is a slow cycling pool and its C accrual is most dependent on prevalent soil characteristics (see Section 4.2.3) rather than CC features. These findings align with the observations made by Hu et al. (2023), who likewise found no significant influence of CC type or termination method on MAOC change under CCs. In contrast, Wooliver and Jagadamma (2023) reported that MAOC change was significantly related to CC type and growing season.

In regards to our research question on how CC characteristics impact SOC pool responses to CCs, we can conclude that POC change was significantly negative and positive affected by CC seed rate and peak biomass, respectively, whereas MBC change showed a significant relation to CC sowing time and a positive trend regarding years in rotation with CCs (Table 4). Effects on MAOC responses could not be identified, which is not consistent with the findings of Wooliver and Jagadamma (2023).

4.2.2 | Impact of agricultural management

As initially hypothesized that other additional agricultural management practices will impact SOC pool changes under CCs, we obtained a significant negative impact of maximum tillage depth on MBC in response to CCs in our study (Figure 9e). A deeper tillage depth corresponds to a higher degree of soil disruption (Zhang, Wang, et al., 2023), which, in turn, has the potential to interfere with microorganisms and associated processes (Babujia et al., 2010; Sae-Tun et al., 2022). However, our findings, in contrast to Kim et al. (2020), did not reveal any apparent impact of tillage type on changes in MBC under CCs.

Moreover, our analysis found that the duration of studied crop rotations was significantly and positively correlated with MBC change. Longer rotation durations allow the inclusion of more CCs (number as well as species) and provide the necessary time for effective CC establishment, which as mentioned before, is crucial regarding above- and belowground biomass production. Further, the moderator "number of main crop species in the rotation", which can be seen as a proxy for main crop diversity, followed a positive trend (Figure 9d,f, respectively). Diverse crop rotations, in comparison to monocropping, provide abundant plant biomass inputs and rhizodeposits, which are known to stimulate microbial growth and, hence can promote MBC accrual (Feng et al., 2020; Motta et al., 2007). Additionally, crop rotations are recognized for their capacity to enhance soil structure, providing an environment favourable to microbial development (Kennedy, 1999) and hence MBC accrual.

No significant results or trends were observed for the MAOC or POC change under CCs (Tables S1 and S2) for moderators in this category. When comparing these findings with the agricultural management moderators studied in other meta-analyses, outcomes are inconsistent. For instance, Hu et al. (2023) also found no significant impact of tillage effects on the POC or MAOC response to CCs, whereas Wooliver and Jagadamma (2023) reported that tillage type affected POC, but not MAOC response.

Concerning the research question on how agricultural management practices influence SOC pools under CCs, we can conclude that MBC response was significantly positively related to crop rotation duration and significantly negatively related to maximum tillage depth (Table 4). For the number of main crop species in rotation on MBC change a positive trend was observed. Contrary, MAOC and POC responses under CCs were not impacted by other agricultural management practices in our study, which is not consistent with the results of others (Wooliver & Jagadamma, 2023). Hence, the research question on how agricultural management practices impact SOC pool change under CCs is not clearly answered and supplementary research on the effects of this management practice on MAOC and POC is advisable.

4.2.3 | Impact of pedo-climatic factors

Pedo-climatic factors were hypothesized to significantly impact SOC pool change under CC cultivation. Starting with the moderator clay content, interesting observations could be drawn from heterogeneity analysis. For both MAOC and MBC, highly significant impacts were found, but calculated meta-regressions followed opposite directions, being positive for MAOC and negative for MBC (Figure 5a and 9c, respectively). Attempting to first explain the results for MAOC, we followed the prevailing hypothesis that higher clay contents mean higher surface areas and therefore higher binding capacities for C (Cotrufo et al., 2019; Lavallee et al., 2020). Nevertheless, MAOC under CCs was negatively impacted by clay to a content of about 20%. In an experiment by Jilling et al. (2021), the authors observed that common root exudates (i.e., glucose and oxalic acid) caused a significant increase in turnover and potential release of C from MAOM through direct (e.g., mobilization of metal oxides) and indirect (e.g., enzyme induction) mechanisms. Similar effects were found in another field experiment by Huang et al. (2021), who showed that about 70% of rhizosphere

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priming occurred in MAOC, which differed between species. The interspecific variations in the priming effects were explained by the differences in specific root length and root N concentration. Considering this, in soils with low clay contents and therefore less binding site capacities, CCs may cause a net decline in MAOC through priming, desorption and ultimately, mineralization.

Regarding the negative relationship between clay and CC effects on MBC (Figure 9c), it can be hypothesized that the abundance and distribution of bacterial and fungal communities are highly influenced by soil texture and pores (Bodner et al., 2023). When clay contents are low (as in coarse-textured soils), it appears that more C from CCs is stored in the MBC rather than the MAOC pool. This might be caused by enhanced anaerobic conditions in fine-textured soils and limitation of aerobic microorganisms (Drury et al., 1991). Medium-textured soils were found to increase MBC, phospholipid fatty acid (PLFA), fungi-to-bacteria ratio and actinomycetes (Muhammad et al., 2021). Moreover, in a lab experiment by Franzluebbers et al. (1996) the authors reported that the amount of mineralizable C per unit MBC decreased with increasing clay content, thereby indicating that MBC was more active in coarse-textured soils compared to fine-textured soils. At the same time, we found that low clay contents influenced C stabilization negatively in the MAOC pool under CCs, possibly by causing priming of initial C. To conclude, when clay contents are higher, it seems that more C is stabilized in MAOC, and MBC is less influenced by CCs.

Moreover, we found a highly significant negative relation between the response of MAOC under CCs and initial total SOC concentrations, where the positive impact of CCs on MAOC decreased with greater initial SOC (Figure 5b). This result can be explained mathematically by considering the diminished likelihood of C increase when the total SOC content is already high. For instance, soils with a coarse texture and low initial SOC levels may undergo more pronounced changes as a result of sustainable soil management practices, in contrast to fine-textured soils with already abundant SOC content (Schweizer et al., 2019). Contrary to our findings, which partially correspond to statements by Cotrufo et al. (2019), Liang et al. (2023) observed opposite effects. They studied the C sequestration potential of CCs based on a long-term field experiment and found that C storage in MAOC showed a strong positive correlation to total SOC. Moreover, the meta-analysis by Li et al. (2023), who studied the effects of legume incorporation on SOC pools, summarized that initial SOC concentrations did not significantly influence MAOC. Also, a recent paper by Begill et al. (2023) challenged the prevalent hypothesis of MAOC saturation by Cotrufo et al. (2019). They report no upper limit of MAOC was observed within 189 samples from the German Agricultural Soil Inventory. In conclusion, there is an ongoing debate on the relationship between total SOC concentrations and MAOC, and possible saturation effects. Opposing results are reported in different syntheses efforts and the underlying mechanisms are still under discussion. Another aspect that might impact the response of MAOC under CCs, influenced by initial total SOC concentrations, is the method with which initial SOC was measured. As only 2 out of 9 studies provided information on the method applied for analysing initial SOC in MAOC studies, we were not able to study this moderator. Nevertheless, methods like wet oxidation or loss on ignition are dependent on correction factors, which can potentially introduce bias. This and other limitations of analytical methods applied to measure SOC in total soil or fractions are discussed below in Section 4.2.4.

Lastly, regarding POC, heterogeneity analysis did not determine any significant moderators or trends for this category (Table S2). Contrary, both Hu et al. (2023) and Wooliver and Jagadamma (2023) observed a significant impact of mean annual temperature on POC changes under CCs in their global studies without limitations to certain climatic zones. Our meta-analysis only collected studies from arid, temperate and cold climates and more than half of the studies included belong to the warm temperate climate (Figure 2c), causing an overrepresentation of this zone. This overrepresentation may be partially attributed to the challenges posed by arid and boreal climates when it comes to implementing CC cultivation. These regions are characterized by water limitations (Mitchell et al., 2015) and a scarcity of warm days suitable for crop growth (Mela, 1996), respectively, which can make the implementation of CCs more challenging. Moreover, as climate change continues to unfold and climatic zones shift across Europe, these challenges are expected to become more pronounced in the southern regions (Lavalle et al., 2009), while boreal areas may experience an increase in warm days hence prolonged growing season (Peltonen-Sainio et al., 2018). To conclude, more experimental results conducted in arid and boreal climates, preferably set up in Europe, are needed to provide a more balanced analysis. Lastly, our moderator analysis regarding continents, climate zones, precipitation and temperature did not reveal any significant impacts on the studied effects of CCs on SOC pools, thereby indicating that the results of the meta-analysis are applicable globally for the investigated climatic zones, such as arid, temperate and boreal climates.

In addressing our research question regarding the impact of pedo-climatic factors on SOC pools under CCs (Table 4), our analysis revealed that the initial SOC

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concentration had a significant negative effect on the response of MAOC, which contrasts with the results reported by others (Li et al., 2023; Liang et al., 2023). Moreover, clay content in soils exhibited a significant positive influence on MAOC responses, while MBC demonstrated a significant but negative change. Lastly, our research did not identify a significant impact on POC responses, in contrast to findings from Wooliver and Jagadamma (2023) and Hu et al. (2023), who suggested a relationship with mean annual temperature.

4.2.4 | Impact of SOC pool-related factors

Lastly, for moderator category "SOC pool-related factors", we hypothesized to see a significant effect on SOC pool change. Nonetheless, concerning MAOC and MBC, no significant moderators or trends were found for this category (Tables S1 and S3). Against initial expectations based on the hypothesis that the mean-residence time of MAOC reaches from decades to centuries (Lavallee et al., 2020), we did not observe a significant impact of experiment duration on MAOC response to CCs. A possible explanation is that only one included study investigated CC effects on MAOC for more than 10 years (ID 673, 37 years), which made it difficult to analyse long experiment duration effects for this pool. On the other hand, we found that experiment duration was positively related to POC response to CCs. CCs promote aggregate formation and physical protection and therefore stabilization of occluded POM (Moukanni et al., 2022), which can lead to an accumulation of POC over time. The meta-analysis by Wu et al. (2023), studying nitrogen fertilization on SOC pools, found that POC change was also positively and significantly impacted by experiment length. Contrary to these results, Hu et al. (2023) and Wooliver and Jagadamma (2023) did not observe a significant impact on the duration of CC cultivation on POC, but on MAOC in their meta-analyses. It is noteworthy that the studies included by Wooliver and Jagadamma (2023) were mostly less than 15 years long.

In regards to methods applied to measure SOC pools in the primary studies and their potential impact on CC effects on SOC pool, we considered the analysis method and correction factor for MBC and sieve size, density separation and analysis method for MAOC and POC. Firstly, for MBC, the majority of studies used chloroform fumigation extraction, hence, no moderator analysis of the analysis method applied was possible. Further, the sub-group analysis revealed that correction factors did not impact CC effects on MBC significantly. Regarding MAOC, we found that the impact of sieve size on CC effects on MAOC was not significant. As the majority of studies applied the sieve size separation method for MAOC and POC (in contrast to density separation) and sieve sizes used for POC were mostly uniform (50–2000 μm for total POC), we were not able to perform the complete moderator analysis as initially planned. Nevertheless, this illustrates that the dataset was relatively homogeneous, and no strong effects of SOC pool analysis methodologies were expected. Moreover, the analytical method used to measure organic matter or carbon content of MAOC and POC fractions may introduce additional bias, as they differ in methodology. Methods used frequently are wet oxidation, weight loss on ignition and dry combustion. Wet oxidation, a method that requires little laboratory infrastructure, was applied to measure MAOC and/or POC only in 3 of 42 studies. The recovery of C with this method varies, but is typically ranging from 60%–95%, and therefore requires a correction factor (Nelson & Sommers, 1996), which might induce bias. Moreover, wet oxidation is believed to recover the most active SOC pools (Kamara et al., 2007) and is texture-dependent (Lettens et al., 2007) and hence could overestimate POC and underestimate MAOC. Loss on ignition (used in 2 of 42 studies) also requires the application of a correction factor or regression analysis to convert weight loss into SOC contents. It was found that the standard conversion factor of 0.58 overestimated SOC, particularly with increasing contents of clay and fine particles <20 μm. Also, the application of regression models under- and overestimated SOC stocks, which was dependent on clay contents (Jensen et al., 2018). Lastly, of the 42 studies, 3 expressed MAOM and POM dry weight as a percentage of the initial soil mass, which we named "mass fraction" (see database). This method can only yield an estimated value of organic matter, as C/N ratios differ in various mass fractions (Mikha & Marake, 2023), therefore each mass fraction is not directly proportional to its organic C content, and inorganic C is not accounted for. As the majority of included studies in our analysis used dry combustion to measure SOC contents in MAOC and POC (over 80%), we were not able to study the impact of fraction analysis on MAOC and POC change under CCs. Overall, differences in sampling procedures, sample preparation and analysis of MAOC and POC between studies are to be expected, as there is a multitude of methods available to conduct fractionation (Just et al., 2021; Poeplau et al., 2018) as well as organic carbon and matter measurement (Johns et al., 2015; Kögel-Knabner &-Rumpel, 2018; Nelson & Sommers, 1996). Nevertheless, similarly to fractionation sizes used, the dataset is mostly homogeneous in this regard and no strong effects of this moderator were expected. To conclude, these differences and pitfalls in fractionation and carbon analysis methodology might introduce additional bias into syntheses,

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which, compared to the impacts of other moderators are small, but still should be acknowledged.

Lastly, soil sampling time was found to impact POC change due to CCs significantly in the present study. When sampled in spring, changes in POC were largest under CCs, followed by sampling on several dates throughout the year, in autumn and in summer months. An explanation could be that most included studies that reported sampling in spring and summer were investigating winter-hardy CCs that were cultivated in autumn and terminated in spring, thereby maximizing their growing period, C inputs and potential to support aggregate formation (Blanco-Canqui et al., 2011; Calonego et al., 2017), hence POC acceleration (Moukanni et al., 2022). When sampled in summer, growth period of most studied CCs was already over and beneficial effects might be less pronounced than during CC cultivation.

In regards to our research question on how SOC pool-related factors influence SOC pool change under CCs, we can summarize that experiment duration and time of soil sampling had a significant impact on POC response, whereas for MAOC and MBC change no significant moderators were identified (Table 4).

4.3 | Implications and perspectives

Our findings show that CC cultivation has positive effects on SOC pools in arable cropland under European conditions. Nevertheless, cultivation of CCs throughout Europe is still limited. A 2019 survey collecting data from over 600 farmers in Spain, France, Netherlands and Romania, found that the average adoption rate of CC across arable farms was 11.6 %, varying greatly between countries. Based on these adoption rates, potential adoption area and C-sequestration were calculated which ranged from 2,592,700 t^{-1} CO_2 equivalent to 2,399,490 ha in Spain to 79,300 t^{-1} CO_2 equivalent to 47,170 ha in the Netherlands (Smit et al., 2019). A modelling study found that the recent CC area in Germany could be tripled to 30% of arable cropland, thereby enhancing total C inputs by 12% and facilitating an annual increase of 2.5 Tg CO_2 in the top 30 cm (Seitz et al., 2022). It is evident that policies are the strongest external determinant of adoption rates of CC (Kathage et al., 2022) and that they are shaping CC application in the European Union to different extents. For example, Switzerland's agriculture is highly regulated and offers substantial financial incentives to implement CC cultivation (Garland et al., 2021). The Nitrates Directive and the Common Agricultural Policy's greening requirements impact CC adoption patterns strongest (Kathage et al., 2022). These findings stress not only the diversity of European agricultural systems but also varying potentials within countries and their dependency on policies and incentives.

Besides the potential of CC cultivation for Europe, we identified five crucial research needs regarding CC effects on SOC pools relevant to European agricultural conditions. First, a necessity for additional experiments studying the effects of CCs on SOC pools was found, specifically regarding MAOC. After screening almost 1000 articles, we were able to retrieve 20 studies that investigated MAOC under CCs, showing that this parameter is measured rarely in experimental studies, especially when compared to POC ($n = 43$). Often, as each additional fraction analysed increases the workload significantly (Poeplau et al., 2018), measurement of MAOC is neglected. Researchers also tend to calculate MAOC by subtracting POC from total SOC, thereby estimating parameters that cannot be used in high-quality meta-analysis, which only include measured response variables (Fohrafellner, Zechmeister-Boltenstern, Murugan, & Valkama, 2023). We therefore encourage scientists to assess the stable fraction analytically in their experiments, as there are still uncertainties on how CCs and related moderators impact MAOC. This can also be done in ongoing experiments, where SOC pools have not been analysed so far, in order to increase the amount of information on this topic.

This brings us to the second point, which is about contradictory and missing results regarding moderator analysis. First, differences between our and other available meta-analyses were encountered. Experiment duration (>10 years) was found to impact MAOC and POC contrastingly in different meta-analyses. Similarly, conflicting results for the moderators "mean annual temperature" on POC responses, "tillage type" on POC and MBC responses and "CC type" on MAOC responses under CCs were observed. Second, the impact of irrigation, organic agriculture and organic matter input under CCs on MAOC, POC and MBC changes are unknown, as a lack of experimental studies including these management practices was identified. Hence, moderator analysis was not possible for these parameters. Therefore, more experiments, preferably longer than 10 years, that address comprehensive sets of parameters regarding soil and agricultural management, are needed (Chaplot & Smith, 2023). This is specifically true for organic farming, as these systems are dependent on nutrient inputs from CCs and organic matter. These new studies also should provide a detailed description of all agricultural practices applied (e.g., fertilization types and rates, irrigation amounts, crop residue management) so meta-analytical analysis is possible.

In relation to these research needs, we found that the number of European experiments studying the response of

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SOC pools to CCs is low. Only 10 articles, of which 9 studied MBC, 1 POC and none MAOC were identified. This shows why a meta-analysis only including European experiments is, up to date, not possible. By communicating this knowledge gap, we hope to inspire fellow researchers to tackle this issue. Increasing not only the number but also the spatial distribution of European studies would allow the analysis of European pedoclimatic impacts in more detail. The planned development of numerous living labs, as implemented by the EU Mission "A Soil Deal for Europe", constitutes a key opportunity to address these knowledge gaps (European Commission, 2021).

Fourth, our meta-analysis encountered limitations in addressing the research question regarding the impact of CCs on SOC pools throughout the soil profile, as the majority of extracted effect sizes from included studies were sampled within the first 20 cm of the soil. We anticipate that future experimental studies should expand their sampling to encompass SOC pools in deeper soil layers. Additionally, we encourage future meta-analyses to place a particular emphasis on including data from sampling depths beyond the top layer to provide a more comprehensive understanding of SOC dynamics throughout the soil profile.

Lastly, meta-analysts are dependent on primary literature to produce synthesis results. Unfortunately, we often find promising articles which fit our scope perfectly, but then encounter hurdles when it comes to including these articles in our meta-analysis. The reporting of standard deviation (SD) or standard error (SE) of means for SOC pools is crucial to allow the calculation of weights (see Equation 3). Nevertheless, many authors fail to provide this basic information, thereby forcing meta-analysts to either neglect their articles or search for possible ways to obtain SD another way. Often, this leads to estimating SD by various measures, which are highly imprecise, if not fabricated. A recently developed tool by Acutis et al. (2022) allows to compute SD from ANOVA and multiple comparison test outcomes, thereby offering a highly useful way to combat this issue. Nevertheless, we encourage authors to provide information on SD in their article, as no tool can exceed complete statistical reporting. Moreover, a definite lack in presentation of basic soil parameters, such as soil texture, pH or initial SOC concentrations was observed, causing difficulties in moderator analysis. Also, in this regard, we urge authors to improve their reporting of valuable information, preferably in the form of databases uploaded to online repositories.

5 | CONCLUSION

The present meta-analysis evaluated the response of MAOC, POC and MBC to CC cultivation. By synthesizing the results of 71 independent studies whilst following meta-analytical quality criteria, we were able to generate high-quality outputs, relevant to European conditions. Therefore, we provided a novel contribution to the understanding on how CCs affect SOC on a pool level.

Our findings demonstrate that CCs had a positive and significant effect on all three studied pools, with POC and MBC presenting the highest sensitivity (+23.2% and + 20.2%, respectively) whereas MAOC exhibited a modest increase (+4.8%). Among these pools, it was MBC change that was most influenced by moderators. Specifically, CC characteristics and other agricultural practices demonstrated substantial impacts on MBC responses. This highlights the considerable role that agricultural management choices play in shaping the positive effects of CCs on MBC accrual.

Apart from this, analysis was not possible for the moderators "irrigation", "organic agriculture" and "organic matter input", as a lack of experimental studies including these management practices was identified. Further, more studies on the dynamics of SOC pools throughout the soil profile are necessary. Lastly, a pressing need for additional experiments exploring the effects of CCs on SOC pools, specifically for Europe, was identified, with a particular focus on MAOC, POC and long-term experiments. The establishment of living labs, as integral components of the European Soil Mission, presents a crucial opportunity to address these research needs.

AUTHOR CONTRIBUTIONS

Julia Fohrafellner: Methodology; investigation; data curation; visualization; writing – original draft; writing – review and editing; software; formal analysis; validation; resources. **Katharina Keiblinger:** Writing – review and editing; supervision; conceptualization; methodology. **Sophie Zechmeister-Boltenstern:** Writing – review and editing; supervision; funding acquisition; methodology. **Rajasekaran Murugan:** Writing – review and editing; supervision; methodology. **Heide Spiegel:** Methodology; writing – review and editing. **Elena Valkama:** Conceptualization; methodology; writing – review and editing; project administration; funding acquisition; supervision; software; formal analysis; validation.

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conducted as a part of the EJP SOIL project MIXROOT-C and CarboSeq.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo.org at https://doi.org/10.5281/zenodo.10707812.

PROTOCOL AND REGISTRATION

This meta-analysis was not registered. The corresponding protocol to this meta-analysis can be accessed online: Fohrafellner, J., Zechmeister-Boltenstern, S., Murugan, R., Keiblinger, K., Spiegel, H. & Valkama, E. 2023. Meta-analysis protocol on the effects of cover crops on pool-specific soil organic carbon. MethodsX, 11, 102,411, https://doi.org/10.1016/j.mex.2023.102411.

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