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Cereal yield, yield stability, and nitrous oxide release in European conservation agriculture: A meta-analysis

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ABSTRACT

Context: Conservation Agriculture (CA) aims to enhance the sustainability of agricultural production by minimizing soil disturbance, maintaining soil cover and implementing crop rotations. Despite its potential benefits, the effects of CA on cereal production and soil borne nitrous oxide (N_2O) emissions have not yet been investigated at a European scale.
Objective: We conducted a comprehensive meta-analysis on the effects of CA on cereal yield, yield stability, and N_2O emissions compared with conventional agriculture (CONV). Further, we performed a spatial-explicit analysis across different pedoclimatic conditions in Europe to identify regions more susceptible to negative impacts.
Methods: We compiled a dataset of 58 field experiments (a median duration of 7 years) examining the effect of CA on cereal yields (i.e., winter and spring wheat, barley, oats and maize). Additionally, a separate dataset of 11 field experiments (a median duration of 10 years) was assembled to evaluate CA effects on N_2O emissions. A

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weighted meta-analysis was conducted, and Cochran`s Q test was applied to evaluate heterogeneity in effect sizes associated with pedoclimatic conditions and agronomic management practices. Maps for Europe were created to evaluate the spatial patterns of yield changes under two tillage scenarios - minimum tillage (MT) and no tillage (NT) - both adhering to the core principles of CA.

Results: Overall, CA led to a statistically significant reduction in cereal yields by 3 % (95 % Confidence Interval (CI): 0.2 %–5 %, n = 58) and a decrease in yield stability by 9 % (95 % CI: 3 %–15 %, n = 50) when compared to CONV. A larger yield gap was linked to a higher topsoil clay content and a decreased tillage depth ($p < 0.001$). For soils with 30 % clay content, the estimated yield gap was 1 % under MT (15 cm depth) and 4.4 % under NT. N_2O emissions under CA did not differ from CONV overall (0 %, 95 % CI: –37 % to +67 %, n = 11), but increased significantly when clay content exceeded 30 % ($p < 0.0001$), though this result relies on the small dataset available.

Conclusions: Overall, this meta-analysis demonstrated a slight reduction in cereal yields under CA across Europe compared to CONV, coupled with a more pronounced decrease in yield stability, but no impact on N_2O emissions. Top soil clay content was a key moderator that amplified both the yield gap and N_2O emissions under CA. Consequently, cereal yields in Central and Southern Europe, where the soil clay content is generally higher, are more susceptible to tillage intensity. Thus, MT may offer greater benefits than NT in these regions, provided that the other principles of CA are met.

Implications: These findings demonstrate that a one-size-fits-all approach to CA is ineffective and highlights the importance of developing region-specific guidelines. This is particularly important regarding the tillage intensity in clay-rich soils. Recognizing the trade-offs associated with CA practices is critical for their effective and widespread adoption across varying pedoclimatic conditions in Europe.

1. Introduction

Conventional agriculture (CONV), characterized by intensive tillage, monocropping, and high external inputs, has historically ensured high crop yields. However, it has also contributed to soil erosion, nutrient losses, declining soil quality and biodiversity, leading to water and soil pollution (Calderini and Slafer, 1998; Gomiero et al., 2011; Stavi et al., 2016; Yang et al., 2020; Messéan et al., 2021). These impacts are particularly severe in Europe, where erosion-prone soils and climate change exacerbate degradation risks, leading to desertification in Mediterranean regions and topsoil loss in continental areas (Maetens et al., 2012; Panagos et al., 2020; Ali et al., 2022; Di Bene et al., 2022; Ferreira et al., 2022; Song et al., 2022; European Environment Agency, 2024). Additionally, the Boreal regions also face soil carbon losses linked to land-use changes (Heikkinen et al., 2013). Such vulnerabilities highlight the need to transition to practices that sustain soil fertility and agroecosystem health.

Conservation agriculture (CA) offers a sustainable alternative through three core principles: (1) minimal soil disturbance, such as no-tillage (NT) or minimum tillage (MT); (2) permanent soil cover, and (3) diversified crop rotations (FAO, 2011; Palm et al., 2014). Minimizing soil disturbance preserves soil structure and slows organic matter mineralization, thereby enhancing soil fertility, water retention, and microbial biomass and functional diversity (Kristensen et al., 2003; Palm et al., 2014; Kan et al., 2020; Tadiello et al., 2023; Wade et al., 2025). Simultaneously, maintaining soil cover through crop residue retention or cover crops protects against erosion and temperature extremes, while crop rotations improve nutrient cycling and pest control (Rusch et al., 2013; Zohry and Ouda, 2018).

The effect of CA on yields is complex. A global meta-analysis reported that NT alone reduced yields by 5.7 % compared to CONV, but this loss was mitigated when combined with residue retention and crop rotation; in rainfed dry climates, the full set of CA principles even increased yield by 7.3 % (Pittelkow et al., 2015a). Machine learning analyses on over 4000 paired yield observations worldwide confirmed high variability across crop types, climates and management practices (Su et al., 2021b).Yield stability, first introduced in plant breeding (Becker and Léon, 1988), is now central to agroecology for maintaining productivity under climate variability. It reflects the agroecosystem's ability to sustain yields despite stresses, such as drought or heavy rainfall, making it vital for planning, profitability, and food security. Evidence from long-term field experiments and a global meta-analysis indicates that yield variability in no-tillage systems is either lower than or comparable to CONV (Smith et al., 2007; Knapp and van der Heijden, 2018).

CA also influences greenhouse gas (GHG) emissions, particularly N_2O, but effects are context-dependent. A global meta-analysis showed a 11 % reduction in N_2O emissions compared to CONV, particularly in humid regions and low-carbon soils (Li et al., 2023). While combining conservation tillage with cover crops can lower N_2O emissions (Qiu et al., 2024), yet, other meta-analyses reported a 10 % increase in N_2O emissions (Huang et al., 2018; Mei et al., 2018). Likewise, a recent review focusing on European agriculture observed increased N_2O emissions due to reduced tillage or leguminous cover crops (Maenhout et al., 2024).

While global and European meta-analyses have highlighted the impacts of CA on crop yields and N_2O emissions, they have limitations. Many studies a) overlook one or more of the CA principles, b) do not focus specifically on cereals – the dominant crop group in Europe, or c) rarely address trade-offs between productivity and environmental performance. Moreover, spatially explicit assessments across European pedoclimatic zones remain scarce. These gaps highlight the necessity for research specifically focused on Europe that assesses not only the performance of CA with respect to cereal yields but also with respect to yield stability and associated GHG emissions.

This meta-analysis synthesizes European field data from peer-reviewed studies to address significant knowledge gaps by identifying the conditions under which CA yields benefits or drawbacks compared to CONV. It also evaluates CA's potential to maintain yield stability and reduce N_2O emissions across various climatic and management contexts. This meta-analysis contributes to a more nuanced understanding of CA's performance across Europe, with the goal of informing policy tailored to regional agricultural challenges.

The following research questions were addressed:

1. What is the effect of CA on crop yields, yield stability, and N_2O emissions in cereal-based arable cropland when compared to CONV?
2. How do various agronomic management practices, such as tillage depth, mineral N fertilizers application, selection of cereal types, the number of crops in rotation, and inclusion of legumes in the rotation, affect crop yields, yield stability, and N_2O emissions within CA systems?
3. How do pedoclimatic factors, such as climate zone, temperature, precipitation, and soil texture affect crop yields, yield stability, and N_2O emissions in cereal-based CA systems?

Table 1
Keywords used for searching.

Population terms	Boolean operator	Intervention terms	Boolean operator	Outcome terms	Boolean operator	Exclusion terms
(soil* AND (agr* OR farm*) AND (Europe OR Name of European country))	AND	("conservation agriculture" OR "conservation till*" OR "reduced till*" OR "minimum till*" OR "direct drill" OR "no till*" OR "no-till*" OR "zero-till*" OR "direct seeding" OR "sod-seed*" OR "sod seed*")	AND	("yield" OR "crop production" OR "crop yield" OR "grain yield" OR N_2O OR "nitrous oxide")	NOT	(orchard OR forest OR fruit OR wood* OR vineyard OR pasture OR rice[a] OR olive OR wetland OR laboratory OR greenhouse)

[a] Rice was omitted because of its limited cultivation area in Europe.

2. Materials and methods

2.1. Studies collection and inclusion criteria

The research questions were structured according to the PICO framework (population, intervention, comparator and outcome):

Population: European arable land

Intervention: Conservation agriculture (CA)

Comparator: Conventional agriculture (CONV)

Outcome: Cereal yields, temporal yield variation (yield stability), cumulative N_2O emissions per unit land area for a period.

Articles were searched by using the keywords presented in Table 1 from a diverse set of Scholarly Databases and Journal Libraries, such as Web of Science (Core Collection), Scopus, Agricola (USDA National Agricultural Library), ScienceDirect, the AGRIS International System for Agricultural System and Technology, Oxford University Press, SpringerLink, Taylor & Francis Online Journal Library, Wiley Online Library, MDPI, Directory of Open Access Journals (DOAJ) and Google Scholar (Supplementary Material 1).

The subsequent screening was conducted in two stages:

1. The title of each study was examined for relevance. If at this stage no indications of presence of exclusion criteria were found (Table 2), the abstract was screened.
2. All studies that passed the abstract screening were checked for suitability in the form of a full text screening.

We also screened the references and databases of previously published global meta-analyses (Rusinamhodzi et al., 2011; Van Kessel et al., 2013; Pittelkow et al., 2015a, b; Knapp and van der Heijden, 2018; Huang et al., 2018; Feng et al., 2018; Mei et al., 2018; Sun et al., 2020; Su et al., 2021a; Allam et al., 2021, 2022; Li et al., 2023) and European meta-analyses (Sandén, et al., 2018; Achankeng and Cornelis, 2023). The article search was completed in June 2024. We have opted not to provide a PRISMA flow diagram due to time constraints to document each step systematically. To be included in the database, a study had to meet the inclusion criteria listed in Table 2.

2.2. Data extraction

The data extraction method is crucial for dealing with the non-independence of observations (Nakagawa et al., 2017). Statistical non-independence occurs when data points (in this case, effect sizes) are somewhat related to each other. For example, multiple effect sizes may be taken from a single study, making such effect sizes correlated. Independence may have had a larger effect than the other factors considered because repeated measurements of a similar effect size will tend to put greater emphasis on that particular study (and its effect) (Hungate et al., 2009). Failure to account for such dependencies may result in erroneous interpretations, particularly false positives in statistical significance.

To avoid problems with the non-independence of the effect sizes, only one pair of treatment-control comparisons corresponding to the longest period of yield or N_2O emissions measurements was extracted from each article. If an article reported results for several cereal species, tillage methods or rotations, only a single species, a specific tillage method, and a rotation were randomly selected, with the intention of ensuring roughly equal numbers for the different treatment groups. Doses of N mineral fertilizer were selected within the range used in the EU. If an article reported results from different experimental sites with different pedoclimatic characteristics or from the same site but with different soil characteristics, the observations at those sites were considered as independent and were included in the database. If several articles referred to the same experimental site with the same pedological characteristics and crop rotation, the article with the longest experimental duration was selected. The data were extracted from tables or digitized from figures using the ImageJ 1.37 program (Schneider et al., 2012). Standard errors (SE) and coefficient of variation (CV%) were converted to standard deviations (SD) where necessary ($SD = SE^{*}\sqrt{n}$, where n is the number of replicates; and $SD = CV\%^{*}\overline{X}/100\%$, where $\overline{X}$ is yield mean). When no measure of variability was provided, we extracted the SD from the ANOVA table using the EX-TRACT tool (Acutis et al., 2022).

2.3. Database creation

Comprehensive databases used for this meta-analysis are available at Zenodo (Valkama et al., 2026). Relevant data extracted from each study that met the inclusion criteria includes geospatial locations (latitudes, longitudes and altitude) of the experiments, pedoclimatic characteristics, the year of experiment establishment, CA duration, crop rotation practices, fertilization practices, tillage methods, crop residue management, as well as average yields or cumulative N_2O emissions in CONV and CA for a measured period, complete with standard deviations, sample sizes, effect sizes, variance, and upper and lower confidence intervals.

2.3.1. Yields and yield stability

The final dataset encompasses 58 field experiments conducted in 19 European countries, representing 10 distinct European environmental zones, ranging from Boreal (BOR) and Nordic Alpine (ALN) to Mediterranean South (MDS) (Fig. 1 and Table 3). A sample size ≥ 50 is considered as a larger body of primary study within the framework of meta-analysis (Hedges et al., 1999). The experiments cover a range of mean annual precipitation levels from 300 mm to 1800 mm and mean annual temperatures from 2.6 °C to 20 °C. The studies are distributed as follows: 8 from Switzerland, 7 from Spain, 6 from Germany, 5 each from Italy, Poland, and Norway, 4 from Croatia, 3 from Austria, 2 each from Sweden, France, the Netherlands, and the Czech Republic, and 1 from Lithuania, Türkiye, Romania, Denmark, Finland, Slovenia, and Serbia.

Among the CA farming systems studied, minimum tillage (MT) was implemented in 26 experiments, while no-till (NT) in 32 experiments. Crop residues were left on the soil surface in 48 studies or partly incorporated into soils in 10 studies. Increasing rotation diversity in CA compared to CONV was observed in 6 studies, while similar diversity in 52 studies. On average, crop rotations comprised three different species in both CONV and CA. Leguminous plants, such as faba bean, chickpea, soybean, pea, clover, and vetch, were included in the rotations of 24 studies. The dataset comprised 9 studies that incorporated cover crops,

Table 2
Inclusion and exclusion criteria for the literature screening process.

Criteria	Inclusion	Exclusion
Location of experiment	Europe, including non-EU, and Türkiye	Other parts of the world
Soil	Mineral	Organic
Experimental type	Field study	Laboratory, greenhouse, modelling studies (unless primary data from field studies are presented as well)
Land use	Arable land	Permanent crops (vineyard, fruit trees, berry plantation, olive grove); pastures, rice field; forests and semi-natural areas; wetlands; agroforestry; horticulture
Crop type	Cereals and cereals in rotation	Solely vegetables or grasses
Fertilization	- mineral N fertilizer or in combination with organic fertilizer; - doses of mineral N fertilizer within the range used in EU; - doses of mineral N fertilizer is similar in CONV and CA	- organic fertilization (animal or fish-based); - doses of mineral N fertilization higher or lower than used in EU; - zero fertilization; -doses of N fertilizer is different in CONV and CA
Control: CONV	-conventional tillage: inversion/mixing tillage (moldboard/disk plowing, disk harrow or chisel plowing; tillage depth > 20 cm) in spring, autumn or in both; -crop rotation, intercropping, monoculture;	- no-tillage, minimum tillage, reduced tillage
Treatment: CA	-no-tillage, minimum tillage, reduced tillage (all non-inversion); -tillage zone ≤ 20 cm; in strip tillage inversion is possible; -permanent soil organic cover (at least 30 % with crop residues and/or cover crops); -crop rotation, intercropping; ≥ 2 crops in rotation	-tillage involving soil inversion; -crop residues totally removed, and no cover crops were used; -less than 2 crops in rotation or monoculture
Means for crop yield over at least 3 years	-grain yield for cereals; -reported for treatment and control in text, tables and figures, or means can be calculated from annual yield	-vegetables, silage maize, bioenergy crops; -means are not reported and cannot be calculated; -means reported only for one year
Means for N_2O emissions	Reported cumulative N_2O emissions for a period for treatment and control in text, tables, and figures, or means can be calculated	Not reported and cannot be calculated, or results expressed as a daily flux
Standard deviation or standard error	Reported for treatment and control or can be calculated by using EX-TRACT tool (Acutis et al., 2022)	Not reported and cannot be calculated by using EX-TRACT tool (not available statistics or experimental design)
Sample size (number of years for yield and number of replicates for N_2O emissions)	Reported in tables, figures or methods	Not reported
Years of experiment	≥ 3 (for yield studies)	Less than 3 years
Replicates (plots)	≥ 2	Less than 2 replicates Pseudo-replicates

in contrast to 49 studies that did not utilize them. The duration of the conservation practices ranged from 3 to 44 years, a median duration of 7 years. Most fields, 53 out of 58, were rainfed, with only 9 studies applying organic fertilization alongside mineral fertilization. Yield measurements for cereals mainly including winter and spring wheat, spring and winter barley, and maize were recorded over periods of 3–22 years. Annual yields in conventionally managed farming systems ranged from 1.88 t ha^{-1} to 11.40 t ha^{-1} , with a median value of 5.25 t ha^{-1} across all studies. In conservation farming systems, annual yields ranged from 1.87 t ha^{-1} to 10.90 t ha^{-1} , with a median yield of 5.39 t ha^{-1} .

To account for the variations in yields and the stability of yield responses to conservation farming practices, we selected 15 explanatory variables from the database (Valkama et al., 2026) and categorized them into three groups: climate, soil, and agronomic management (Table 4). A Spearman rank order correlation (r_s) was run between the topsoil clay content, the amount of N fertilizer and tillage depth in CA to assess their intercorrelation. To investigate the potential link between the geographical locations of the experimental setups and the application rates of N fertilizer, r_s was performed to assess the relationship between the average annual temperature or annual precipitation and the rates of N fertilizer used.

2.3.2. N_2O emissions

The database on N_2O emissions consists of 11 field experiments with mostly loamy soil texture across 8 European countries, covering 5 European environmental zones, from Boreal (BOR) to Mediterranean South (MDS) (Fig. 1; Table 5). Among the 11 studies, a total of 3 studies were located in Spain, 2 in Denmark, and 1 Belgium, Italy, Germany, Finland, Switzerland and the UK, respectively. In 9 studies NT was applied, while in 2 studies MT was adopted. The duration of the conservation practices ranged from 1 to 38 years, with a median duration of 10 years. A sample size of less than 20 is considered small within the framework of meta-analysis (Hedges et al., 1999). However, we performed the meta-analysis to gain insights into the current state of the art and to identify significant factors that warrant future investigations.

To analyze the variation in N_2O emissions change due to CA, we included the following moderators: pedoclimatic factors (annual precipitation, annual average temperature, clay content, and soil texture), mineral N fertilization, CA duration, and monitoring period (Table 6).

2.4. Meta-analysis

Meta-analysis was conducted by using MetaWin 3.0 statistical software (Rosenberg, 2024), the R environment for statistical computing (version 4.3.1, R Core Team, 2021) and IBM SPSS Statistics for Windows, Version 29 (IBM Corp., 2023).

2.4.1. Effect size on yield

As an index of effect size, we used relative yield, ln(R) (Hedges et al., 1999):

$$\ln(R) = \ln(\overline{X}_{CA}/\overline{X}_{CONV}) \quad = \quad \ln(\overline{X}_{CA}) - \ln(\overline{X}_{CONV}) \tag{1}$$

where $\overline{X}_{CA}$ and $\overline{X}_{CONV}$ represent the means for crop yields (kg ha^{-1}) in CA and CONV respectively, averaged for experimental duration.

We calculated the variance of ln(R) (Hedges et al., 1999):

$$V_{\ln(R)} = \frac{SD_{CA}^2}{n_{CA}\overline{X}_{CA}^2} + \frac{SD_{CONV}^2}{n_{CONV}\overline{X}_{CONV}^2}, \tag{2}$$

where SD_{CA} and SD_{CONV} are the corresponding standard deviations, and n is the sample size (number of years).

2.4.2. Effect size on yield stability

As inverse measure of yield stability, we calculated the relative coefficient of temporal yield variation, ln(CVR), Nakagawa et al. (2015):

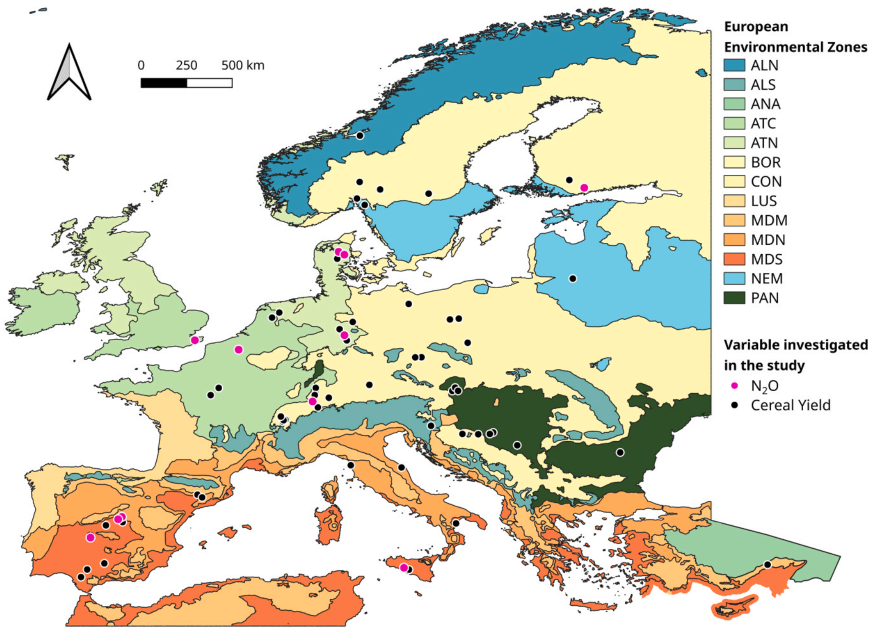

Fig. 1. The geographical positions of the 58 field experiments on cereal yields and 11 field experiments on N_2O emissions included in the meta-analysis, mapped onto the environmental zones of Europe as defined by Metzger et al. (2005). Abbreviations for environmental zones: ALN, Alpine North; ALS, Alpine South; ANA, Anatolian; ATC, Atlantic Central; ATN, Atlantic North; BOR, Boreal; CON, Continental; LUS, Lusitanian; MDM, Mediterranean Mountains; MDN, Mediterranean North; MDS, Mediterranean South; NEM, Nemoral; PAN, Pannonian.

$$\ln(CVR) = \ln(CV_{CA}/CV_{CONV}) \quad = \quad \ln(CV_{CA}) - \ln(CV_{CONV}) \tag{3}$$

where CV_{CA} and CV_{CONV} represent the coefficient of temporal yield variation for CA and CONV, respectively, calculated as:

$$CV_{CA} = \quad SD_{CA}/\overline{X}_{CA}$$

and

$$CV_{CONV} = \quad SD_{CONV}/\overline{X}_{CONV}$$

We calculated the variance of $\ln(CVR)$ according to Nakagawa et al. (2015):

$$V_{\ln(CVR)} = \frac{SD_{CA}^2}{n_{CA}\overline{X}_{CA}^2} + \frac{1}{2(n_{CA}-1)} - 2p_{CA}\sqrt{\frac{SD_{CA}^2}{n_{CA}\overline{X}_{CA}^2}\frac{1}{2(n_{CA}-1)}} + \frac{SD_{CONV}^2}{n_{CONV}\overline{X}_{CONV}^2} + \frac{1}{2(n_{CONV}-1)} - 2p_{CONV}\sqrt{\frac{SD_{CONV}^2}{n_{CONV}\overline{X}_{CONV}^2}\frac{1}{2(n_{CONV}-1)}} \tag{4}$$

Where p_{CA} and p_{CONV} are the correlations between $\overline{X}_{CA}$ and SD_{CA}, and between $\overline{X}_{CONV}$ and SD_{CONV}.

2.4.3. Effect size on N_2O emissions

As an index of effect size, we used relative N_2O emissions, ln (R_{N2O}):

$$\ln(R_{N2O}) = \ln(\overline{X}_{CA}/\overline{X}_{CONV}) \quad = \quad \ln(\overline{X}_{CA}) - \ln(\overline{X}_{CONV}) \tag{5}$$

where $\overline{X}_{CA}$ and $\overline{X}_{CONV}$ represent the means for cumulative N_2O emissions (kg N_2O-N ha^{-1}) for a growing period or year in CA and in CONV respectively, averaged for experimental replicates.

We calculated the variance of $\ln(R_{N2O})$ as in Eq. (2), taking into consideration that in this case the sample size n is the number of replicates.

2.4.4. Summarized effect sizes

Normality of the distribution for effect sizes ($\ln(R)$, $\ln(CVR)$, and ln (R_{N2O})) was assessed by Shapiro-Wilk test in R.

We assumed that studies did not share the same effect sizes, and we therefore used a random effect model to combine estimates ($\ln(R)$, ln (R_{N2O})) across the studies. The application of this kind of model accounts for differences in experimental methods between studies (that are considered only a random sample of possible effect sizes) which may introduce variability ("heterogeneity", τ^2) among the true effects.

We calculated the weighted mean of the log response ratios $\ln(R)$ and $\ln(R_{N2O})$ for all studies as:

$$\overline{\ln(R)} = \frac{\sum_{i=1}^{n} w_i \ln R_i}{\sum_{i=1}^{n} w_i} \tag{6}$$

Where $\ln R_i$ 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):

$$w_i = \frac{1}{V_i + \tau^2}, \tag{7}$$

where V_i is the variance of the study i, and τ^2 denotes the amount of residual heterogeneity (between-study variance). Because the variance of the effect sizes is a function of the sample size (Eq. 2), studies with a larger sample size had lower variances and received heavier weights.

The τ^2 parameter is considered the variance of the true effect size. As it is impossible to compute it from the entire population of the effect size, τ^2 is an estimation of the observed effect by using DerSimonian and Laird method (Borenstein et al., 2009):

$$\tau^2 \quad = \quad \frac{(Q - df)}{C}, \tag{8}$$

where:

$Q \quad = \quad \sum_{i=1}^{k} w_i(Y_i - \quad M)^2; \; df = n-1; \; C \quad = \sum w_i \quad - \quad \frac{\sum W_i^2}{\sum W_i},$

with w_i as study weight, Y_i as study effect size, M as summary effect, n as the number of studies, Q as the total variance and C as a scaling factor.

For temporal yield variation, the estimate of the pool variance was

Table 3
Studies included in the meta-analysis on yield and yield stability.

ID	Authors	Country	Site	Environmental zone[a]	Soil texture	Experiment establishment	CA duration (years)
1	Ali et al. (2019)	Italy	Policoro	MDS	Loam	2009	3
2	Amato et al. (2013)	Italy	Pietranera	MDS	Clay	1991	18
3	Anken et al. (2004)	Switzerland	Tänikon	CON	Sandy loam	1987	14
4.1	Arvidsson (2010)	Sweden	Ultuna	BOR	Clay	2003	5
4.2	Arvidsson (2010)	Sweden	Säby	BOR	Silt loam	2003	5
5	Avižienyte et al. (2013)	Lithuania	Kaunas	NEM	Silt loam	2010	3
6.1	Büchi et al. (2017)	Switzerland	Changins	ATC	Clay	1969	44
6.2	Büchi et al. (2017)	Switzerland	Changins	ATC	Loam	1969	44
7	Carbonell-Bojollo et al. (2019)	Spain	Seville	MDS	Clay	2009	4
8	Carof et al. (2007)	France	Grignon	ATC	Loam	2002	3
9	Celik et al. (2011)	Türkiye	Adana	MDS	Clay	1976	3
10	Cociu and Alionte (2011)	Romania	Fundulea	PAN	Clay loam	2007	3
11	de Cárcer et al. (2019)	Switzerland	Changins	ATC	Sandy clay loam	1967	34
12	Dimassi et al. (2014)	France	Boigneville	ATC	Silt loam	2003	8
13	Dorado et al. (1998)	Spain	La Higueruela	MDS	Loamy sand	1992	3
14	Gruber et al. (2012)	Germany	Meiereihof	CON	Silt loam	2002	9
15	Hansen et al. (2011)	Denmark	Foulum	ATN	Loamy sand	2002	3
16	Jalli et al. (2021)	Finland	Jokioinen	BOR	Sandy clay	2007	10
17	Jug et al. (2011)	Croatia	Kneževo	PAN	–	2001	4
18	Kisić et al. (2010)	Croatia	Daruvar	CON	Sandy loam	1995	10
19	Krauss et al. (2020)	Switzerland	Frick	ALS	Clay loam	2002	15
20	Küstermann et al. (2013)	Germany	Scheyern	CON	Loamy to sand	1994	12
21.1	Lampurlanés et al. (2016)	Spain	Agramunt	MDN	Clay silt loamy	2000	14
21.2	Lampurlanés et al. (2016)	Spain	Selvanera	MDN	Loam	1996	18
22	Lebbink et al. (1994)	Netherlands	Lovinkhoeve	ATN	Silt loam	1986	6
23	López-Bellido et al. (2000, 1996, 2012)	Spain	Cordoba	MDS	Clay	1988	14
24.1	Ludwig et al. (2011)	Germany	Garte Süd	ATN	Silty clay	1970	5
24.2	Ludwig et al. (2011)	Germany	Hohes Feld	ATN	Silty clay	1967	5
25.1	Małecka et al. (2012)	Poland	Poznan	CON	Loamy sand	1999	4
25.2	Małecka et al. (2012)	Poland	Poznan	CON	Loamy sand	1999	4
26	Maltas et al. (2013)	Switzerland	Changins	ATC	Loam	1997	12
27	Martínez et al. (2016)	Switzerland	Zollikofen	CON	Sandy loam	1995	20
28	Martin-Rueda et al. (2007)	Spain	Alcala de Henares	MDS	Loamy sand	1996	4
29	Mazzoncini et al. (2008)	Italy	Pisa	MDN	Silt loam	1990	16
30	Mihelič et al. (2024)	Slovenia	Moškanjci	ALS	Loam	1999	11
31	Mikanová et al. (2012)	Czech Republic	Prague	CON	Clay loam	1995	7
32	Moitzi et al. (2019)	Austria	Raasdorf	PAN	Silt loam	1996	12
33	Mühlbachová et al. (2015)	Czech Republic	Prague-Ruzyně	CON	Clay loam	1995	8
34	Neugschwandtner et al. (2015)	Austria	Raasdorf	PAN	Silty caly loam	1996	14
35	Ordóñez Fernández et al. (2007)	Spain	Seville	MDS	Clay	1982	21
36.1	Pabin et al. (2006)	Poland	Laskowice	CON	Loamy sand	1999	3
36.2	Pabin et al. (2006)	Poland	Laskowice	CON	Sandy loam	1999	3
37	Panasiewicz et al. (2020)	Poland	Złotniki	CON	Sandy loam	2012	4
38	Rieger et al. (2008)	Switzerland	Schafisheim	CON	–	1996	5
39	Ruisi et al. (2014)	Italy	Santo Stefano Quisquina	MDS	Clay	1991	18
40	Seddaiu et al. (2016)	Italy	Agugliano	MDN	Silty clay	1994	20
41	Spiegel et al. (2007)	Austria	Fuchsenbigl	PAN	Fine sandy loam	1998	8
42.1	Tørresen et al. (1999)	Norway	Wikmark, Stjordal	ALN	Silty caly loam	1994	4
42.2	Tørresen et al. (1999)	Norway	Brandval prestegard, Roverud	BOR	Silt	1994	4
42.3	Tørresen et al. (1999)	Norway	Norderas, As	NEM	Clay loam	1994	4
42.4	Tørresen et al. (1999)	Norway	Hauer, Drobak	NEM	Silt loam	1994	4
43	Van Balen et al. (2023)	Netherlands	Lelystad	ATC	Sandy loam	2009	10
44	Verch et al. (2009)	Germany	Dedelow	CON	Sandy loam	2002	4
45	Videnović et al. (2011)	Serbia	Zemun Polje	PAN	Silty caly	1999	10
46	Vogeler et al. (2009)	Germany	Braunschweig	CON	Silt loam	1998	8
47.1	Zugec (1986)	Croatia	Osijek	CON	–	1979	4
47.2	Zugec (1986)	Croatia	Fericanci	PAN	–	1979	3
48	Korsaeth (2012)[b]	Norway	Kapp	BOR	Loam	1989	35

[a] For Abbreviation see Fig. 1
[b] Published data collected for the period of 2001–2010, whereas data for the years 2011–2019 obtained from LTE staff.

Table 4
Categorical and continuous explanatory variables (moderators) included in the meta-analysis on yield and yield stability.

Variable Category	Explanatory Variables	Group or range (median)
Climate	Annual precipitation (mm)	304–1818 (649)
	Annual average temperature (°C)	2.6–20 (10.20)
	European Environmental Zone	ALS; ATC; ATN; BOR; CON; MDM; MDN; MDS; NEM; PAN[a]
Topsoil	Clay (%)	5–77.1 (21)
	Silt (%)	0–90 (35)
	Sand (%)	1–80 (30.10)
	Soil pH	4.21–8.50 (7.10)
	Soil organic carbon (%)	0.70–10.50 (1.45)
Agronomic management	Tillage depth in CA (cm)	0–19 (4.5)
	Type of cereals	Maize; winter wheat; spring wheat; spring and winter barley
	Number of crops in rotation in CA	2–6 (3)
	Legumes in rotation	Yes; No
	Cover crops	Yes; No
	Mineral N fertilizer (kg ha^{-1})	55–300 (120)[b]
	CA duration (year)	3–44 (7)

[a] For Abbreviation see Fig. 1
[b] The doses of mineral N fertilizer are similar in CONV and CA within a study.

equal to zero, therefore, the data was analyzed using a fixed effects model. We calculated the weighted mean of the log response ratios (ln(*CVR*)) for all studies as in Eq. (6), with $w_i = 1/v_i$.

Because meta-analytic data often have small sample sizes and may violate basic distributional assumptions (such as normality), resampling techniques can be important to accurately determine the significance of meta-analytic metrics (Rosenberg et al., 2000). We used a bootstrap statistical method (Efron and Tibshirani, 1986) to generate bias-corrected 95 % Confidence Intervals (CIs) around the log response ratios from 4999 iterations.

2.4.5. The relations between explanatory and response variables

To test whether the effect sizes differed between the groups of categorical explanatory variables (moderators) listed in Tables 4 and 6, we used the χ^2 test (Cochran`s *Q* test) to examine the between-group heterogeneity (Q_b). To study the effect of continuous explanatory variables, we ran linear weighted meta-regressions, with the effect sizes as the dependent variable, and the continuous variables (moderators) listed in Tables 4 and 6) as independent ones. We also used the χ^2 test to examine the 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*), ln(*CVR*) or ln(R_{N2O})).

Generalized Linear Models (GLMs) were employed to capture more complex patterns and accommodate the variability of effect sizes by including in the model structure two moderators, such as tillage depth and topsoil clay content or mineral nitrogen fertilization within the range of observed data. GLM is a flexible extension of traditional linear regression that allows for the modeling of response variables with distributions beyond the normal, such as binomial, Poisson, or gamma distributions. GLMs consist of three main components: the link function, which defines the relationship between predictors and the response variable; the random component, which specifies the distribution of the response variable; and the systematic component, which describes the linear predictor as a weighted sum of input variables (Dobson and Barnett, 2018) This versatility makes GLMs well-suited for analyzing data where response variables may not adhere to linear assumptions.

Results were back transformed, except for meta-regressions, and reported in the text and figures as percentage changes from CONV (conventional agriculture):

$$Yield\ change\ (\%) = [EXP(\ln(R)) - 1\,] \times 100\% \quad (9)$$

$$Temporal\ yield\ variation\ (\%) = [EXP(\ln(CVR)) - 1\,] \times 100\% \quad (10)$$

$$N_2O\ \ change\ (\%) = [EXP(\ln(R_{N2O})) - 1\,] \times 100\% \quad (11)$$

The CA effects on yields, temporal yield variation and N_2O emissions were considered to be significantly different from CONV, if the 95 % CIs did not overlap with zero. It should be emphasized that the increase in temporal yield variability due to CA signifies a reduction in the stability of yields.

2.5. Geospatial analysis

Effect sizes from the GLM ($\ln(R) = 0.0023 \times tillage\ \ depth - 0.0015 \times clay\ \ content$) were spatialized to provide geographically explicit insights, with a spatial resolution of 100 m. The continuous variable "*tillage depth*" was set at zero cm or 15 cm to represent two different management scenarios: (1) NT maintaining undisturbed soil surface,

Table 6
Categorical and continuous explanatory variables (moderators) included in the meta-analysis on N_2O emissions.

Category	Explanatory variable	Group or range (Median)
Climate	Annual precipitation (mm)	400–970 (704)
	Annual average temperature (°C)	4.5–17.1 (10.9)
Soil	Clay in topsoil (%)	8–52.5 (14.3)
	Texture group	clay/silt loam; sandy loam/ loamy sand
Agronomic management	Mineral N fertilizer (kg ha^{-1})[a]	56–200 (116)
	CA duration (year)	1–38 (10)
Experiment	Duration of monitoring period (days)	79–365 (297)

[a] The doses of mineral N fertilizer are similar in CONV and CA.

Table 5
Studies included in the meta-analysis on N_2O emissions.

ID	Authors	Country	Site	Environmental zone[a]	Soil texture	CA duration (years)
1	Badagliacca et al. (2018)	Italy	Pietranera Farm (Agrigento province)	MDS	Clay	22
2	Baggs et al. (2003)	UK	Wye Estate	ATC	Silt loam	1
3	Boeckx et al. (2011)	Belgium	Maulde	ATC	Sandy loam	2
4	Chatskikh and Olesen, (2007)	Denmark	Foulum	ATN	Loamy sand	2
5	García-Marco et al. (2016)	Spain	Raña of Cañamero	MDS	Sandy loam	7
6	Guardia et al. (2016)	Spain	La Canaleja (near Madrid)	MDS	Sandy loam	18
7	Krauss et al. (2017)	Switzerland	Frick	CON	Clay	11
8	Ludwig et al. (2011)	Germany	Garte, near Göttingen	ATN	Silt loam	38
9	Mutegi et al. (2010)	Denmark	Foulum	ATN	Sandy loam	5
10	Sheehy et al. (2013)	Finland	Vihti	BOR	Clay	10
11	Tellez-Rio et al. (2015)	Spain	La Canaleja (near Madrid)	MDS	Sandy loam	16

[a] For Abbreviation see Fig. 1

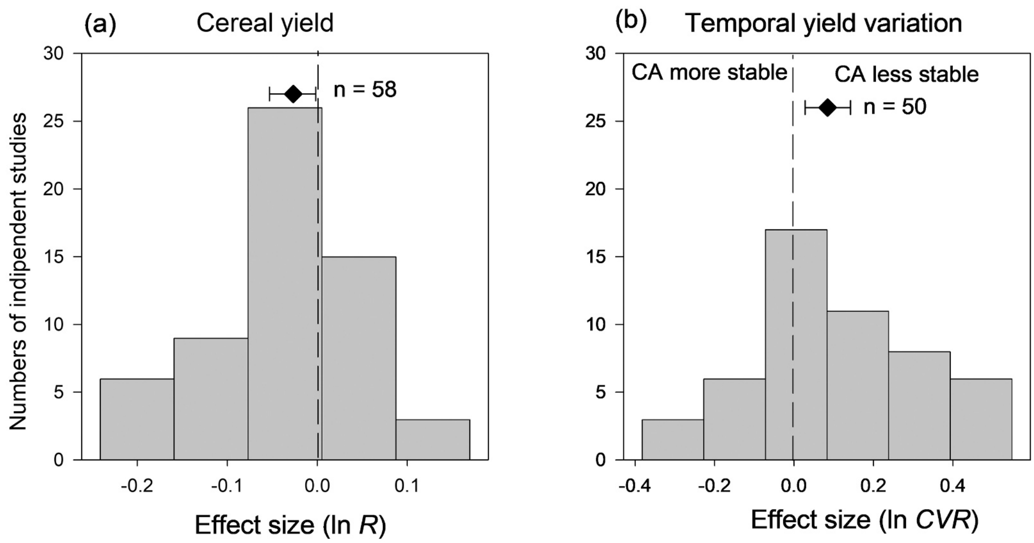

Fig. 2. The distribution of (a) the relative yield, ln (*R*), and (b) the relative coefficient of temporal yield variation, ln (*CVR*), functioning as an inverse measure of yield stability. The diamond indicates the weighted overall effect with bias-corrected 95 % CIs. The dashed vertical line indicates conventional agriculture (CONV), and n is the number of independent studies.

and (2) MT involving shallow soil disturbance at a depth of 15 cm depth. Both systems adhere to the core principles of CA. The continuous variable "*clay content*" was represented by values for the top 20 cm of soil, obtained from the LUCAS (Land Use/Cover Area Frame Survey) soil map provided by the EC Joint Research Centre (JRC) (Orgiazzi et al., 2018; Ballabio et al., 2016).

Using the GLM framework, European-level maps were generated to evaluate the spatial patterns of the percentage change in cereal yields under each tillage scenario. These maps integrate the spatial variability of clay content with the modeled effects of tillage depth.

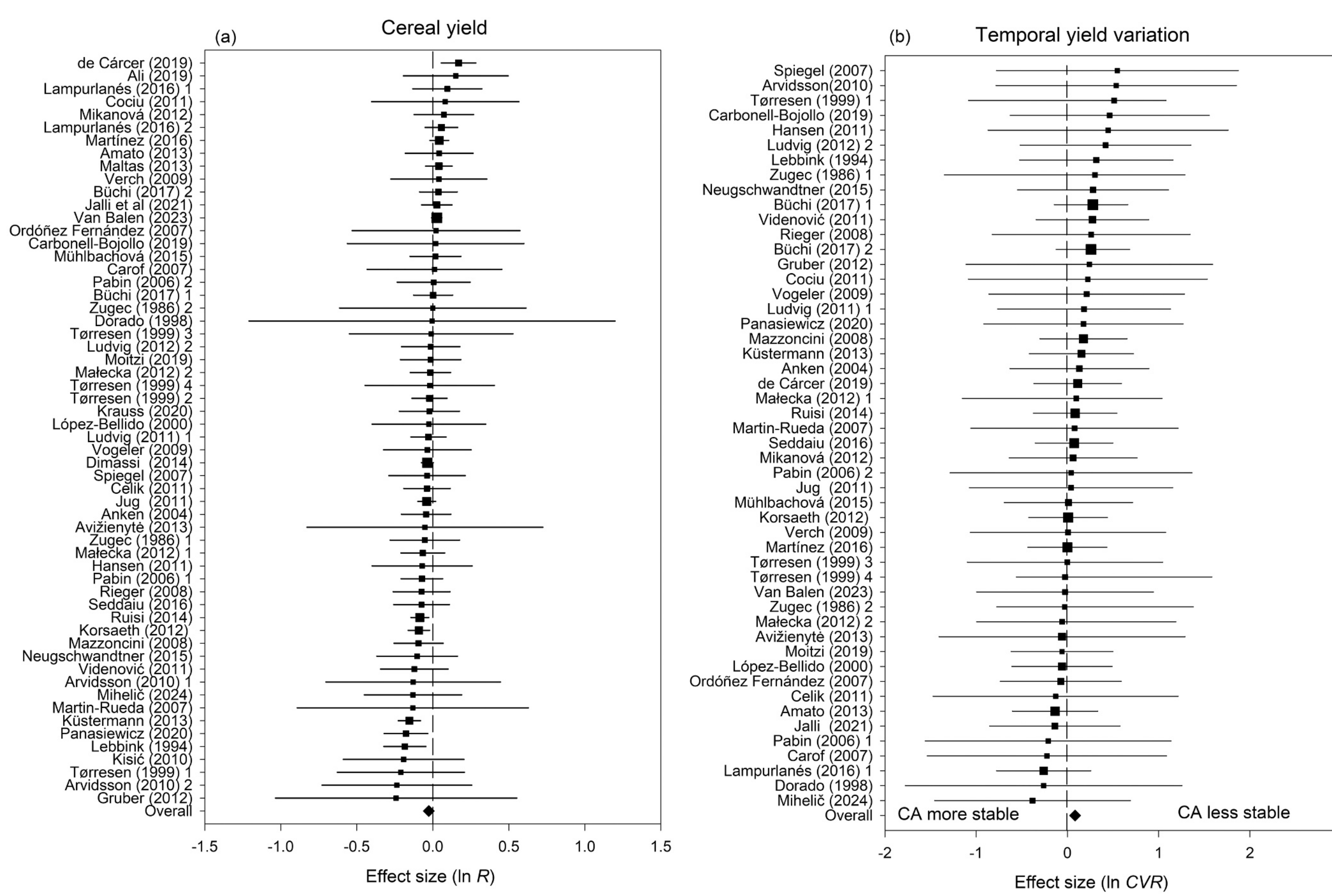

Fig. 3. Forest plots presenting for each individual study (a) the relative yield, ln (*R*), and (b) the relative coefficient of temporal yield variation, ln (*CVR*), functioning as an inverse measure of yield stability. The black squares indicate mean effect sizes, with 95 % CIs. The square size corresponds to study weight. The diamond indicates the weighted overall effect with bias-corrected 95 % CIs. The dashed vertical line indicates conventional agriculture (CONV).

To evaluate the sensitivity of the results to uncertainties in the clay content map, an additional analysis was conducted employing a Monte Carlo simulation (Harrison, 2010). The uncertainty in clay content was modeled as a truncated normal distribution, assuming a maximum standard deviation of $\sigma = 5\,\%$ (Eq. 12). This threshold was derived from the map of the average standard deviation of clay content provided by JRC (Ballabio et al., 2016), considering that, excluding mountain regions, the maximum uncertainty value falls within this threshold, and that for main crop regions of Europe standard deviation values are even lower (i.e., below 2 %), underscoring the reliability of the clay content estimates in these areas. Fifty random samples were then drawn from this distribution to represent possible realizations of clay content per each pixel, equally to 3140,800,650 total estimations. For each sample, the GLM was applied to compute the corresponding percentage change in cereal yields (Eq. 13). The resulting outputs were then analyzed to quantify the uncertainty in the model predictions associated with the input clay data. Specifically, the standard deviation of the outputs was calculated to estimate the central tendency and variability of the predicted yield changes.

$$clay \sim N_{trunc}\left(\mu_{clay}, \sigma^2_{clay}, \ a = 0, \ b = 77\right) \quad (12)$$

Where μ_{clay} = *actual value in the clay map*, $\sigma_{clay} = 5$

$$y_i(\%) = \left(e^{(\alpha \bullet tillage - \beta \bullet clay_i)} - 1\right) \times 100 \quad (13)$$

Where α and β are the weight for the calibrated GLM on clay content and tillage depth.

The choice of a GLM over more powerful but complex Machine Learning (ML) models was driven by the relatively small sample size of the dataset (n = 58), deemed insufficient to train such models without a high risk of overfitting.

2.6. Sensitivity analysis

Funnel plot asymmetry, which may indicate publication bias in meta-analysis, was examined by plotting effect sizes against its standard error (Sterne and Egger, 2001). Moreover, Egger's regression-based test was conducted, enabling the detection of funnel plot asymmetry. A statistically non-significant *p*-value of Egger's test indicates no publication bias. Trim-and-fill analysis was performed to allow one to enter values for "missing" studies to generate a symmetric funnel plot from which a new mean effect size can be estimated (Duval and Tweedie, 2000).

3. Results

3.1. Yield and yield stability

3.1.1. Overall effect

The effect size of CA on cereal yields, ln(*R*), followed a normal distribution as confirmed by the Shapiro-Wilk test (W = 0.98; $p = 0.35$, n = 58) (Fig. 2a). Across all studies, CA led to a small yield reduction of 3 % (95 % CI: 0.2 %–5 %, n = 58) compared to CONV. In contrast, the effect size on the relative coefficient of temporal yield variation, ln (*CVR*), was not normally distributed, and eight outliers were identified, seven using the interquartile range (IQR) method (Fig. S1a) and one additional outlier detected via a QQ plot (Fig. S1b). After their removal, the distribution was reassessed and found to be normal (W = 0.98, $p = 0.650$, n = 50) (Fig. 2b). Across all studies, the coefficient of temporal yield variation was increased statistically significantly by 9 % (95 % CI: 3–15 %, n = 50) under CA compared to CONV, indicating a decrease in yield stability.

Fig. 3a illustrates the forest plot depicting the relative cereal grain yield across various studies. The most substantial yield decrease of 21 % (ln(*R*) = –0.24) in comparison to CONV was observed in spring barley during a long-term experiment (LTE) carried out in Germany, located in the continental environmental zone (ID14. Gruber et al., 2012). Conversely, a statistically significant yield increase of 19 % (ln(*R*) = 0.17) under CA was recorded for winter wheat in a LTE conducted in Switzerland, situated in the Atlantic Central environmental zone (ID11. de Cárcer et al., 2019). These findings from the two LTEs exemplify the

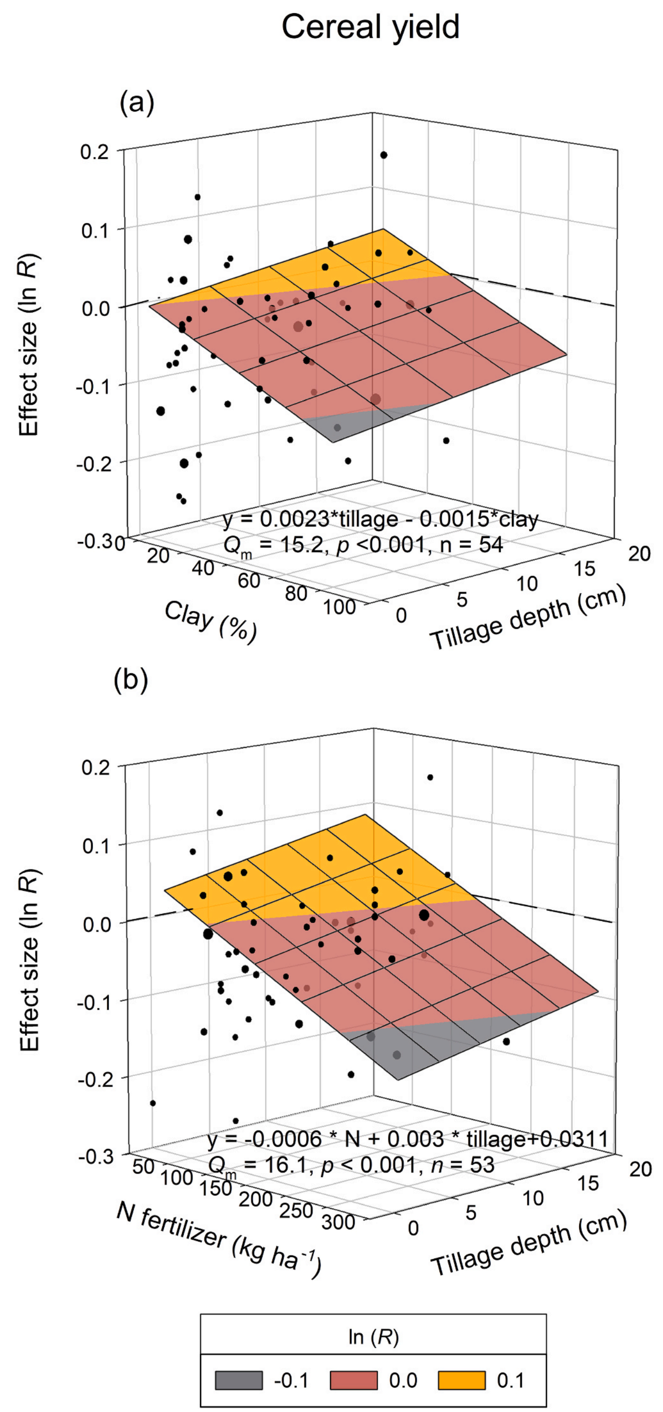

Fig. 4. Combined effects of (a) tillage depth in conservation agriculture and topsoil clay content and (b) tillage depth and mineral N fertilizer on the relative yield (ln *R*). The doses of mineral N fertilizer are similar in conventional agriculture (CONV) and conservation agriculture. Symbol size corresponds to study weight. The dashed horizontal line indicates CONV. Q_m, model heterogeneity, and *n* is the number of independent studies. Note that the clay content was documented in 54 studies, whereas the quantity of N fertilizer was reported in 53 studies.

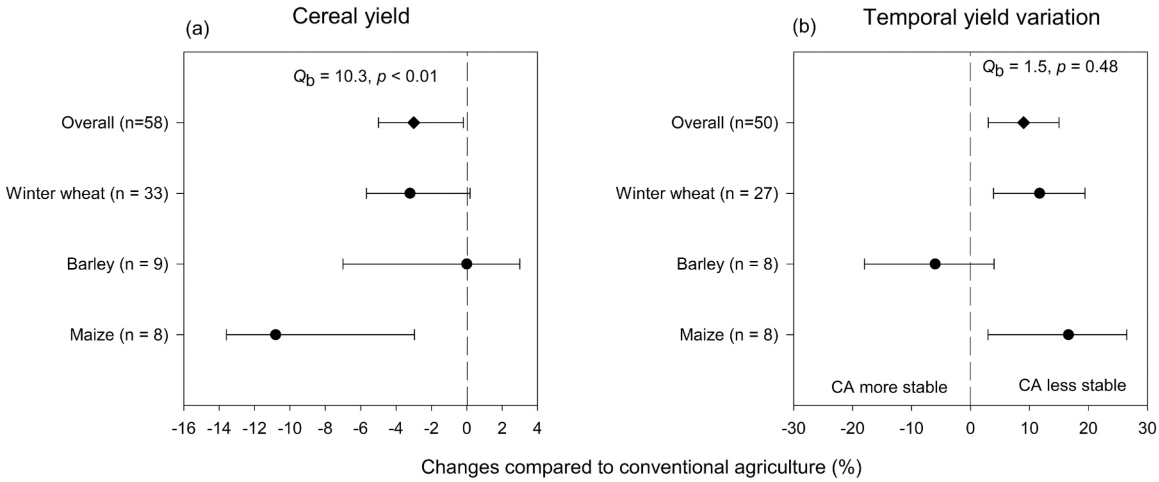

Fig. 5. Percentage change in (a) cereal yields and (b) the coefficient of temporal yield variation, functioning as an inverse measure of yield stability, due to the implementation of conservation agriculture (CA) in comparison to conventional agriculture (CONV) across different cereal types (winter wheat, spring and winter barley and maize). The dashed vertical line indicates CONV. The numbers in parentheses indicate the number of independent studies. The changes in yield or its temporal variation were considered significantly different from the CONV if the bias-corrected 95 % CIs did not overlap with zero. Q_b, between-group heterogeneity model, and n is the number of independent studies.

most pronounced cereal yield responses to CA observed in Europe.

Fig. 3b shows the forest plot for the coefficient of temporal yield variation (or, alternatively, yield stability) across the studies. Spiegel et al. (2007) reported the results for an Austrian LTE, which showed the largest, but not statistically significant increase in a temporal yield variation for spring wheat by 73 % (ln(CVR) = 0.55; 95 % CI: –0.78–1.9) compared to CONV. The experiment was conducted within the Pannonian environmental zone and spanned a duration of 8 years. Conversely, the largest yield stability was observed for winter wheat in a LTE conducted in Slovenia, within the Alpine South environmental zone (ID30. Mihelič et al., 2024). The investigation revealed a 32 % reduction in temporal yield variation (ln(CVR) = –0.38; 95 % CI: –1.46–0.69) under CA, although this finding was not statistically significant, since the 95 % CI overlaps with zero. These results indicate the most pronounced temporal yield variations of cereals recorded in Europe.

Since there was no systematic association between ln(R) or ln(CVR) and the variation in CONV yields across the studies (Fig. S2), the subsequent moderator analyses were carried out without considering the different yield levels present in the CONV groups.

3.1.2. *Agronomic management and pedoclimatic factors*

The results of the meta-regressions and GLM indicated that topsoil clay content, tillage depth associated with CA, and the application of mineral N fertilizers served as significant moderators (Table S1). It is important to emphasize that the moderators did not act as confounding variables, as there were no significant intercorrelations observed between them (r_s = 0.01–0.10, $p > 0.05$). These moderators influenced yield changes attributable to CA, either independently (Table S1a,b,c) or in combination (Table S1d,e,f). For example, tillage depth and the topsoil clay content had a concurrent impact on the yield gap, which diminished with greater tillage depth and lower clay content (Fig. 4a; Table S1d). As an illustration, each 10 % increment in topsoil clay content led to a 1.5 % increase in the yield gap, assuming the tillage depth was unchanged. The analysis indicated that both tillage practices showed a yield gap in soils with clay contents at or above 30 %, but MT performed better in narrowing this gap relative to NT, both adhering to the core principles of CA. For example, for soils containing 30 % clay, the projected yield gap was 1 % for MT (15 cm depth) and 4.4 % for NT. When the clay content rose to 60 %, the yield gap expanded to 5.4 % and 8.6 % for MT and NT, respectively.

In addition, the combined effect of tillage depth in CA and N fertilization rates on yield gap demonstrated statistically significant outcomes (Fig. 4b; Table S1e). As tillage depth in CA increases and N fertilizer rates decrease in both CA and CONV, the yield gap diminishes. For instance, MT achieved no yield gap at the application rates of 120 kg N ha^{-1}. In contrast, NT at the same N fertilizer level exhibited a yield gap of 4 %. The break-even point occurs at 40 kg N ha^{-1}, where the yield gap between NT and CONV can be eliminated entirely. It should be noted that the quantity of fertilizers was not related to the geographical locations of the experiments, as the N fertilizer application rates did not correlate significantly with the average annual temperature ($r_s = -0.03$, $p > 0.05$) or with annual precipitation ($r_s = 0.26$, $p > 0.05$) across the different studies.

Yield responses to CA differed statistically significantly among different cereal types ($Q_b = 10.3$, df = 2,49; $p < 0.01$; Fig. 5a). Findings indicated that maize had the highest yield gap, recorded at 11 % (95 % CI: 3 %–14 %, n = 8), followed by winter wheat with a yield gap of 3 % (95 % CI: 0 %–6 %, n = 33). In comparison, there was no observable yield gap for spring and winter barley (Fig. 5a).

The findings indicated that there was no significant difference in the temporal yield variation among the various cereal types ($Q_b = 1.5$, df = 2,42; $p = 0.484$). Nevertheless, in comparison to CONV, winter wheat and maize were found to have increased temporal yield variation (or, alternatively reduced yield stability) by 12 % and 17 %, respectively, under CA compared to CONV, while winter and spring barley remained unaffected (Fig. 5b).

The investigation into other moderators such as climate (annual precipitation, annual average temperature, European environmental zones), soil characteristics (silt, sand, soil pH, SOC), agronomic management (number of crops in rotation, legumes in rotation, use of cover crops) revealed no significant alterations in relative yield (ln(R)) (Table S2, Table S3). Furthermore, the analysis revealed that effect sizes on the coefficient of temporal yield variation (ln(CVR)) for the entire database showed no significant influence or correlation with the specific pedoclimatic conditions or the agronomic management strategies employed (Table S4, Table S5).

The duration of CA, ranging from 3 to 44 years (median = 7 years), showed no significant relationship with relative yield, ln(R) ($Q_m = 2.25$, $p = 0.133$, n = 58; Fig. S3a). For instance, both long-term CA (>30 years; ID11, de Cárcer et al., 2019) and short-term CA (3 years; ID1, Ali et al., 2019) resulted in the largest yield increases (16–18 %) for winter wheat compared to CONV. Furthermore, there was no evidence that CA duration $\geq$ 10 years prevents yield loss, as statistically significant reductions were observed in three experiments (ID20, Küstermann et al.,

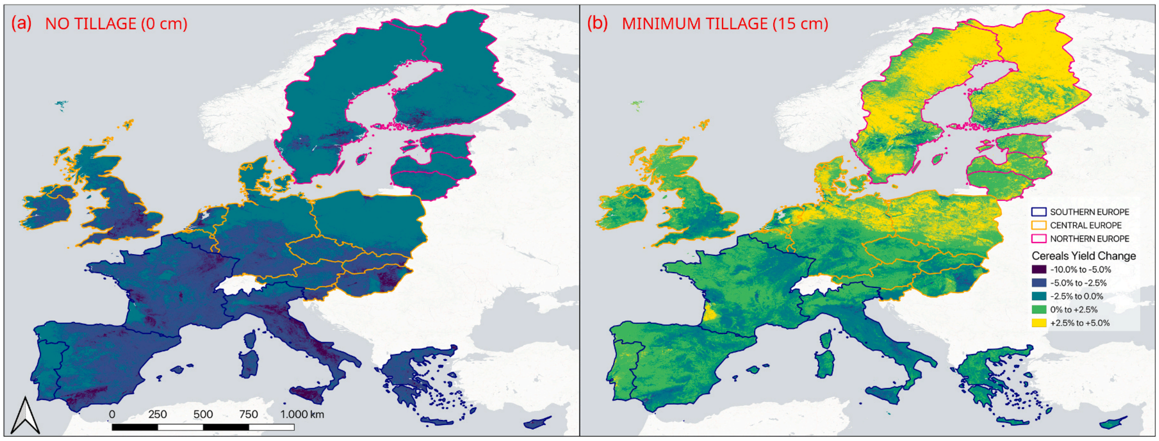

Fig. 6. Predicted change in cereal yield across Europe under two conservation agriculture scenarios: (a) no-tillage and (b) minimum tillage (15 cm depth), both adhering to the core principles of CA. Predictions are from a spatialized General Linear Model (GLM), and changes are expressed as a percentage relative to conventional agriculture.

2013; ID39, Ruisi et al., 2014; ID48, Korsaeth, 2012), with ten additional experiments showing a tendency toward yield decline (Fig. S3a). Similarly, no significant relationship was detected between CA duration and the relative coefficient of temporal yield variation, ln(*CVR*) (Q_m = 0.42, p = 0.519, n = 50; Fig. S3b), indicating no evidence that longer CA systems provide more stable yields.

3.1.3. *Geospatial analysis*

The geospatial analysis was executed, illustrating the meta-analysis GLM models (Fig. 4a) based on the LUCAS spatially explicit data on topsoil clay content. Analyzed CA practices included the MT at tillage depth of 15 cm, and NT, adhering to the core principles of CA. As illustrated in Fig. 6a, the implementation of NT throughout Europe is projected to lead to a reduction in yields (range: –13 % to –0.82 %, average: –3.3 %), with no regions showing higher yields than in CONV. In contrast, MT demonstrated more geographically heterogeneous results, with certain regions experiencing yield increases and reduced losses relative to NT practices (range: –7 % to +2 %, average: –0.35 %; Fig. 6b).

At the regional scale, soils in Southern Europe, characterized by an average clay content of 30 % (with variations reaching up to 60 %), exhibit distinct trends regarding the influence of CA techniques on cereal production. No tillage practices led to an average yield reduction of 4 %, with fluctuations between –9 % and –1 %. Countries such as Southern Italy, Spain, and Greece experienced marked declines in yields when employing NT. Conversely, MT techniques resulted in a more limited average yield decrease of 1 %, ranging from –7 % to + 2 %. Italy and Greece are notably among the most adversely affected countries under MT practices, while Spain and France generally report results that are more aligned with conventional farming practices. Interestingly, northern Portugal demonstrates some beneficial outcomes from MT, highlighting regional differences within Southern Europe.

In Central Europe, characterized by an average clay content of 16 %, similar patterns were noted. The implementation of NT practices led to an average yield decrease of 3 %, with reductions ranging from 1 % and 9 %, reflecting a consistent downward trend in cereal production. Conversely, MT exhibited a neutral impact on average yields, with variations ranging from a decline of 6 % to an increase of 2 %.

Certain areas, including northern Germany, Poland, and the central Netherlands, demonstrated moderate yield improvements under MT, achieving increases of up to 2 % (Fig. 6b). Nevertheless, regions such as central and southern Germany, southern UK, Austria, Slovakia, the Czech Republic, and Hungary continue to face yield declines even with MT practices, underscoring the variability of results across the region.

In Northern Europe, where the average clay content is approximately 8 %, NT practices had the least negative influence on cereal yields compared to other regions, showing an average yield decrease of 2 % (range: 1 %–9 %). On the other hand, MT exhibited slightly beneficial effects, with an average yield increase of 1 % and variations from –6 % to + 2 %. Nevertheless, certain high-clay soil hotspots, such as the Stockholm region in Sweden and the southern and southwestern areas of Finland, encountered yield reductions of 5 % and 3 % under NT and MT, respectively (Fig. 6).

The impact of two sources of uncertainty (i.e. soil clay content data and GLM parameters) on yield change prediction was evaluated. Firstly, Monte Carlo simulations were used to propagate the reported standard deviations of the clay soil content estimations map (Ballabio et al., 2016) into the GLM framework (Fig. 4a), allowing the quantification of how uncertainties in clay content estimation influence the predicted yield changes. The results, illustrated in Figure S4, highlight clear geographic patterns, with generally lower uncertainty in the north/northeast and higher uncertainty in the west and south regions. The areas with lower values included Scandinavia, the Baltic States, Northern Poland, and Northern Germany, with values approximating to 0.3–0.4 %. Overall, the standard deviation ranges from 0.31 % to 0.60 %, with an average value of 0.53 %. This level of uncertainty is minimal in comparison to the anticipated yield changes, thereby affirming the reliability of the analysis against uncertainties in soil clay content.

Secondly, the 95 % CIs of lower and upper bounds of GLM, derived from the meta-analysis, were used for both NT and MT scenarios to evaluate the impact of the CIs on yield change predictions (Fig. S5). This analysis produced a worst-case scenario, involving considerable yield losses (Fig. S5a, c), contrasted with a best-case scenario that revealed minimal losses in several areas under NT (Fig. S5b), and numerous regions indicating potential for beneficial yield changes under MT (Fig. S5d). This variability in the results underscores the significant influence of the GLM parameter uncertainty on the range of predicted yield changes, far outweighing the impact of soil clay content uncertainty. The uncertainty in the GLM parameters highlights areas where further research and field data could help refine the model and narrow the spectrum of potential yield outcomes.

3.2. *N_2O emissions*

Conventional agricultural soil management resulted in released nitrous oxide (N_2O) within a range of 0.07–6.4 kg N ha^{-1}, whereas CA exhibited emissions between 0.04 and 10.2 kg N ha^{-1} over a median monitoring duration of 297 days. The forest plot illustrates that in four and three out of 11 studies, N_2O emissions exhibited a statistically significant reduction or increase, respectively, while four studies indicated

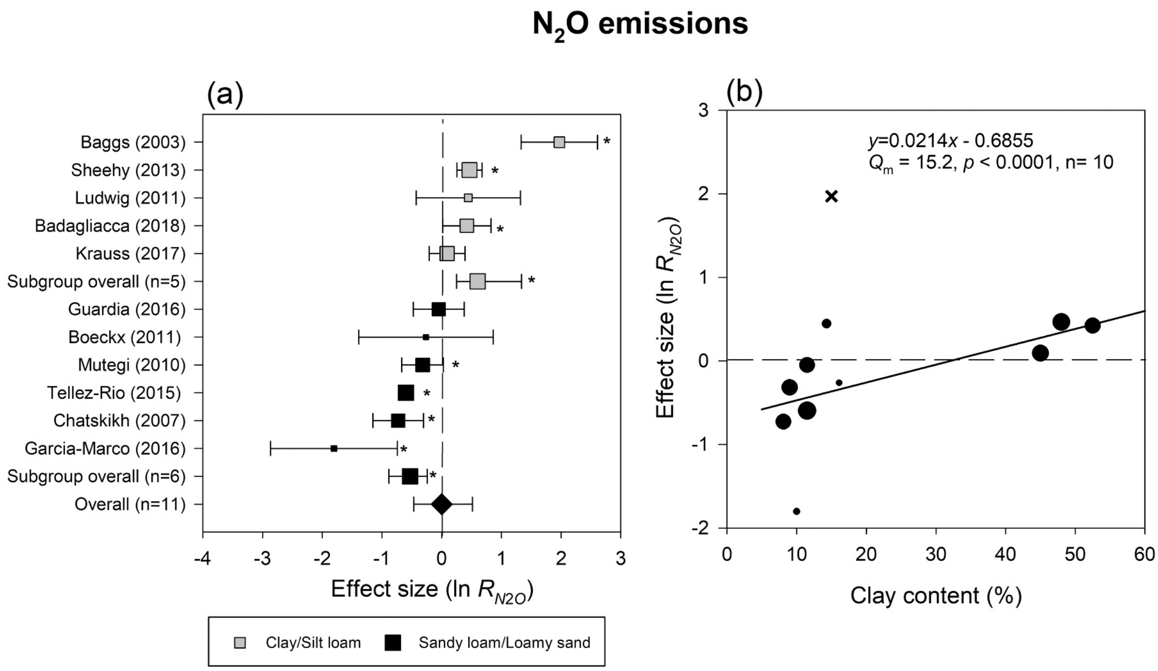

Fig. 7. (a) Forest plot showing relative N_2O emissions (ln R_{N2O}) for each study and subgroup overall for soil texture groups. The squares indicate mean effect sizes, with 95 % CIs. The diamond square indicates the weighted overall effect with bias-corrected 95 % CIs. Asterisks indicate statistically significant effects of conservation agriculture at $p < 0.05$. (b) Weighted meta-regression between clay content and effect size (ln R_{N2O}). Q_m, model heterogeneity, and n is the number of independent studies. Cross symbol indicates outlier (Baggs et al., 2003). The dashed lines indicate conventional agriculture (CONV). The symbol size corresponds to study weight.

no statistically significant effects (Fig. 7a). García-Marco et al. (2016) reported extreme reductions of up to 84 %, while Baggs et al. (2003) noted increases of 620 % when compared to CONV (Fig. 7a). The research conducted by Baggs et al. (2003) may exhibit bias due to the limited duration of the transition to CA which raises significant concerns regarding the representativeness of the soil conditions in relation to the assessment of CA impact on N_2O emissions. It should be noted that the 95 % CIs reported in non-significant studies were the widest in Ludwig et al. (2011) (with a range of –35–275 %) and Boeckx et al. (2011) (with a range of –75–135 %). Conversely, the largest CIs found in statistically significant studies were documented in García-Marco et al. (2016) (with a range of –95 % to –50 %).

Overall, N_2O emissions linked to CA did not differ statistically from those of CONV (Fig. 7a). Moreover, the corresponding 95 % CI was broad (–37 % to +67 %, n = 11), suggesting the relevance of moderators. The primary moderator identified was soil texture, which elucidated the variations found across studies with high levels of statistical significance (Q_b=18, df=1,10, $p < 0.0001$; Fig. 7a). In soils characterized by clay or silt loam textures, the implementation of CA resulted in an 80 % increase in N_2O emissions (95 % CI: 28–280 %, n = 5). In contrast, loamy sand or sandy loam soils exhibited a 40 % decrease in emissions (95 % CI: –60 % to –20 %, n = 6).

The meta-regression analysis revealed a statistically significant relationship between topsoil clay content and relative N_2O emissions (Q_m=15.2, df=1,9, $p < 0.0001$; Fig. 7b). As clay content increased, the effectiveness of CA in mitigating emissions diminished, and a stimulation effect was noticed when clay content exceeded 30 %. Conversely, the effect size (ln(R_{N2O})) showed no significant correlation with climatic factors, the agricultural management practices examined, or the duration of the monitoring period (Table S6). Likewise, the levels of mineral N fertilizer, which varied across studies from 56 to 200 kg N ha^{-1}, but not between CA and CONV within a study, revealed no relationship with the effect size (ln(R_{N2O})) (Table S6).

The duration of CA, ranging from 1 to 38 years (median = 10 years), showed no significant relationship with relative N_2O emissions, ln(R_{N2O}) (Q_m = 0.10, p = 0.755, n = 10; Fig. S3c). Notably, both long-term CA (16 years; ID11. Tellez-Rio et al., 2015) and short-term CA (2 years; ID4. Chatskikh and Olesen, 2007) resulted in the largest reduction in N_2O emissions (45–52 %) compared to CONV. Conversely, prolonged CA duration was associated with increased N_2O emissions (50–60 %) in three experiments (Fig. S3c).

3.3. Sensitivity analysis

To assess the robustness of the meta-analytic results and potential publication bias, we conducted several sensitivity analyses. The Funnel plots of the effect sizes - ln(R), ln(CVR), ln(R_{N2O}) - against study precision showed no visual asymmetry (Fig. S6), suggesting a low likelihood of small-study effects or publication bias. We further applied the trim-and-fill method to estimate the number of potentially missing studies due to publication bias. The method imputed three and two missing studies for ln(R) and ln(CVR), respectively (Fig. S6a, b). However, these additions did not alter the overall effect size estimates, indicating that the meta-analytic conclusions are stable. For ln(R_{N2O}), no missing studies were identified, reinforcing the reliability of the emission-related findings (Fig. S6c).

Additionally, Egger's regression test was performed to statistically evaluate funnel plot asymmetry. The test results did not indicate significant asymmetry for any of the three effect size metrics ($p > 0.05$), further supporting the absence of publication bias (Table S7). Together, these sensitivity analyses confirm that the observed effects of CA on cereal yield, yield stability, and N_2O emissions are robust and not substantially influenced by selective reporting (i.e., the tendency of studies to publish only statistically significant, favorable results or align with expected outcomes), or small-study effects (i.e., the tendency of small studies to report more extreme effect size).

4. Discussion

4.1. Overall effects of conservation agriculture

The results of meta-analysis indicated a modest but statistically significant decrease in both cereal yields (by 3 %) and yield stability (by 9 %) across all studies when comparing CA practices to CONV. Meta-analyses conducted by Pittelkow et al. (2015a), Sun et al. (2020), and Van den Putte et al. (2010) revealed similar outcomes in terms of crop yield, as well as findings on yield stability in humid climates reported by Knapp and van der Heijden (2018). Our meta-analysis also indicated that there was no statistically significant impact of CA on N_2O emissions compared to CONV when considering all studies, which aligns with the conclusions of global meta-analyses (Feng et al., 2018; Jat et al., 2020). The conducted sensitivity analysis demonstrated the robustness of the results and the absence of publication bias.

Notably, the reduction in the yield stability of cereals was particularly pronounced, suggesting potential consequences for the long-term resilience of agriculture, particularly in relation to climate change and extreme weather events. Moreover, it is important to highlight that in 52 out of 58 studies included in this meta-analysis, the diversity of rotation in CA was comparable to that in CONV, thus, decrease in yield and yield stability was probably due to reduced tillage intensity and crop residues left or partly left on the soil surface, as reported in 48 and 10 studies, respectively. Negative yield effects in no-till systems, compared to reduced or conventional tillage, are often linked to increased disease and pest pressure due to large amounts of crop and root residues near the soil surface (Arvidsson, 1998), as well as delayed soil warming and slower early crop development (Koch et al., 2009). It should also be considered that CA practices could be further integrated with other regenerative agriculture approaches that aim to improve soil health, biodiversity, and other ecosystem services as highlighted in a report on regenerative agriculture in the United Kingdom (Wade et al., 2025). Although regenerative practices may initially lead to reduced yields, in the long term, improvement in ecosystem services can help to stabilize yields suggesting a potential pathway toward more sustainable management (Wade et al., 2025).

4.2. Crop-specific responses to conservation agriculture

Our results indicate crop-specific responses to CA, as yield reductions were observed in maize and winter wheat, which were associated with diminished yield stability. In contrast, winter and spring barley did not exhibit these reductions (Fig. 5). Similarly, Pittelkow et al. (2015b), in their global meta-analysis, reported an average yield reduction of 5 % associated with NT. This impact varied across crop types, with cereal crops such as maize, rice, and wheat experiencing notable yield declines of 7.6 %, 7.5 %, and 2.6 %, respectively. Achankeng and Cornelis (2023) similarly observed that grain maize was the crop type most adversely impacted by all conservation tillage practices, experiencing an 8 % reduction in yield under NT conditions.

Such yield reduction can be attributed to the biological and agronomic characteristics of these cereals. Maize, being a warm season crop with a deep root system, often requires well-aerated soil to support root penetration and access to nutrients (Drew, 1992; Liang et al., 1996). Under NT or MT systems, the compaction and limited soil loosening can restrict root development, resulting in reduced yields. Similarly, winter wheat, a cool-season crop typically sown in autumn, relies heavily on adequate soil-seed contact and early nutrient availability to establish strong root systems before winter dormancy (Douglas et al., 1994; Beres et al., 2016; Blunk et al., 2021). In conservation systems, particularly NT, the accumulation of crop residues on the soil surface may reduce seedling emergence and root growth due to cooler soil temperatures and reduced mineralization of nutrients (Turmel et al., 2015; Yang et al., 2018). These factors could collectively explain why these two crops are particularly sensitive to the reduced soil disturbance inherent in conservation practices.

4.3. The role of soil properties

The findings of our meta-analysis underscore the significant role that soil properties and management strategies play in influencing CA performance. For example, both topsoil clay content and tillage depth were found to influence the yield gap, which decreased with greater tillage depth and lower clay content (Fig. 4a). This is consistent with expectations, as clayey soils typically require deeper tillage to facilitate root growth, nutrient mineralization, and water retention (Stepniewski et al., 1994). In such soils, the adoption of reduced tillage under conservation farming may result in lower yields. This finding is particularly relevant given that many soils in Southern and Central Europe, as well as South and South-West of Finland and Sweden are characterized by high clay content (Ballabio et al., 2016).

The relationship between soil type and its influence on the management of CA practices is a critical issue in current soil science discussions. Our findings corroborate the “one size does not fit all” approach to soil health, emphasizing the need for soil-type-specific management strategies, and align with recent literature indicating that soils with elevated clay content pose unique challenges for designing effective CA practices, related to their hydrological and structural characteristics. High clay content can intensify challenges related to CA practices, especially with regard to soil structure and SOC dynamics. Edlinger et al. (2025) highlighted that clay content is a crucial determinant of SOC stocks, Cation Exchange Capacity (CEC), and nutrient availability, often overshadowing the effects of agricultural management practices. Thus, while high clay content offers potential for SOC preservation, it also demands a nuanced approach to CA to consider the complex interplay between soil physical properties and biological processes.

To mitigate the negative effects on clayey soils, strategies could include crops into the rotation that have deep root systems capable of naturally tilling the soil, such as alfalfa or cover crops like radishes and rye (Crotty and Stoate, 2019; Blanco-Canqui and Ruis, 2020). Additionally, increasing soil organic matter through the use of organic amendments or cover crops can improve structural stability of aggregates, aeration, and reduce compaction, thereby offsetting some of the challenges posed by clayey soils (Lal, 2006).

The soil texture, in particular the topsoil clay content, was identified as an important moderator in determining the effect of CA on N_2O emissions (Fig. 7). Indeed, experiments characterized by loamy sand or sandy loam textured soil demonstrated reduced emissions by 40 % compared to CONV, while a clay or silt loam textured soil resulted in a stimulation of N_2O emissions by 80 % (Fig. 7a). The finer pore structure of clay and silt loam soils compared to sandy loam and loamy sand soils may have resulted in a higher incidence of waterlogging and thus in a more favorable anaerobic environment for denitrification and emission of N_2O. In CA this effect could be enhanced by reduced tillage practices, which disturb the soil pore network less and allow waterlogging to persist for longer periods. Likewise, Pelster et al. (2021) noted that fine-textured silty clay soils produced greater N_2O emissions than sandy loam soils under reduced tillage conditions, attributing this increase to the higher moisture content associated with such practices.

The continuous presence of soil covers may have enhanced the retention of soil moisture and contributed to prolonged waterlogging within the finer pore structures of the soil. Mulching at the soil surface can indeed foster a more anaerobic environment, which in turn increases the availability of degradable carbon, thereby promoting the emission of N_2O (Baggs et al., 2003). Other field studies have also reported elevated levels of extractable organic carbon in reduced tillage or no-till practices, which were associated with increased N_2O emissions (Guardia et al., 2016; Badagliacca et al., 2018).

The interaction effect between tillage practices and crop residue type was clearly demonstrated by Baggs et al. (2003). Furthermore, Badagliacca et al. (2018) linked the enhanced N_2O emissions in NT systems to elevated soil moisture levels associated with increased bulk density. Sheehy et al. (2013) also reported higher soil bulk densities in NT treatments. Notably, Badagliacca et al. (2018) observed an increase in the potential denitrification enzyme activity that was only partially counterbalanced by increased nitrous oxide reductase (nosZ) gene abundance, indicating that N_2O emissions were also elevated under NT compared to conventional tillage methods. The observed phenomenon can be linked to the increased bulk density of the soil. Conversely, in soils with coarser textures, such as sandy loam, the practice of reduced tillage or NT may enhance soil structure relative to conventional tillage methods. This improvement can facilitate water infiltration and gas diffusion, ultimately leading to a decrease in N_2O emissions (García-Marco et al., 2016). Additionally, research by Mutegi et al. (2010) indicates that in soils with lighter textures, the implementation of NT can mitigate N_2O emissions, particularly when crop residues are retained in the field.

4.4. Agronomic management

The impact of mineral N fertilization rates on the yield gap between CA and CONV remains controversial in the literature (Ingraffia et al., 2023; Wang et al., 2023; Wu et al., 2025). Our meta-analysis, accounting variations in moderators such as soil texture and climate, reveals that the yield gap is not solely driven by N inputs, but is significantly influenced by the tillage depth (Fig. 4b). Notably, N fertilizers were applied at equal rates for both CA and CONV within individual experiments, though total quantities varied widely across studies, ranging from 55 to 300 kg N ha $^{-1}$. In low-input systems, where N application is limited, CA tends to narrow the yield gap compared to CONV. However, in high-input systems, deeper tillage emerges as a key factor in mitigating yield losses. These differences could be related to how N dynamics interact with soil management practices. When N fertilizers are applied, they undergo nitrification, with mineral N converted into plant-available forms, that requires both oxygen and water (Gebauer et al., 1996; Girsang et al., 2020; Tan et al., 2024). Under high N levels, oxygen becomes a limiting factor, slowing nitrification and accelerating denitrification, which produce nitrogenous gases, unavailable for plant uptake (Sahrawat, 2008; Rochette, 2008; Zhang et al., 2025). Conventional systems address this challenge through intensive soil tillage, which aerates heavy soil and facilitates mineral N nitrification. In contrast, CA's minimal soil disturbance does not provide this benefit, particularly in the short term. This difference means that soils under medium-deep tillage might support higher rates of nitrification when fertilizers are applied.

4.5. Region-specific effects of conservation agriculture

The geospatial analysis conducted in this research offers important insights into the regional differences in yield responses associated with CA. The maps produced from our analysis facilitate the visualization of potential outcomes stemming from widespread CA adoption across Europe, while also evaluating the impacts of various tillage systems, particularly NT and MT at a depth of 15 cm (Fig. 6). The findings indicate that under the NT system, yield reductions are anticipated across all European regions, averaging a decrease of 3 % (with a range from 1 % to 13 %), with particularly pronounced impacts observed in the Mediterranean zones and Central Europe. Conversely, the implementation of MT, adhering to the core principles of CA, may result in slight yield increases in Northern Europe and could alleviate some of the adverse effects associated with NT in the Mediterranean and Central regions. These geographically specific results underscore the necessity for tailored strategies that address the trade-offs inherent in CA practices, thereby optimizing their advantages across different pedoclimatic regions.

In regions where topsoil clay content exceeded 30 %, a stimulation effect of CA on N_2O emissions can be expected (Fig. 7b). Our results imply that soil texture should be considered when addressing trade-offs inherent in CA practices. Likewise, the recent review by Maenhout et al. (2024) pointed out that the interaction effects of soil management strategies and soil properties are vital and should be more effectively addressed as they can considerably influence trade-offs between SOC accrual and GHG emissions. This is further supported by the absence of a relation between the relative cumulative N_2O emissions, and the climatic characteristics of the geographic areas considered in the analyzed studies of our meta-analysis. Indeed, the effects of CA were found to be independent of climatic zones, as significant emission increases were recorded in Finland (Sheehy et al., 2013) and Italy (Badagliacca et al., 2018), while notable emission reductions occurred in Denmark (Chatskikh and Olesen, 2007) and Spain (García-Marco et al., 2016). Likewise, a global meta-analysis by Li et al. (2023) showed that the differences in soil N_2O emissions due to CA were not well explained by climatic factors.

While CA may offer environmental and cost benefits (reduced operating, input and labor costs) (Kertész and Madarász, 2014), its effects on yields and yield stability require careful consideration, particularly when promoting the adaption of CA practices to different regions and environmental contexts in Europe. It is also important to stress that the performance of a specific crop management depends not only on yields and its stability, but also on the economic and environmental costs associated with its application. In the case of CA, the economic benefits associated with reduced costs and environmental improvements – such as diminished erosion, potential decreased greenhouse gas emissions, and increased carbon storage – largely compensate for the modest yield reductions observed in some areas of Europe (Tilman et al., 2002).

4.6. Limitations

The dataset on which our analyses were based was the result of a thorough and strict selection process. Over one hundred sixty initial studies on yields and 16 European studies on N_2O emissions were excluded for not meeting the predefined criteria (Table 2), with the primary reasons being non-comparable N fertilization between control and treatments, yield data reported for fewer than three years, or a failure to implement all three core principles of CA simultaneously, i.e., permanent soil cover (e.g., crop residues or cover crops), diversified crop rotations, and minimal soil disturbance. Articles were excluded if they were lacking statistical robustness, such as not being replicated, not reported variability measures, or ANOVA and Multiple Comparison Test results, which would allow for the estimation of the experimental error associated with statistical analysis results. As a result of this selection, a deficiency of field experiments investigating the influence of CA on cereal yields was observed in the following European environmental zones: Anatolian (Turkey), Lusitanian (Portugal, Spain, France), and Mediterranean Mountains (Spain, Portugal, Greece, Cyprus). Among cereal types, winter wheat was the predominant crop ($n = 33$), while spring wheat ($n = 2$) was underrepresented. Only 5 of the 58 field experiments were irrigated; the remainder were rainfed, limiting the inclusion of irrigation as a moderator in the analysis.

The number of experiments that monitored N_2O emissions in the field was limited to 11, which constrains the robustness of the collected dataset. The dataset covered the following zones: Boreal (Finland), Atlantic North (Denmark, Germany), Atlantic Central (UK, Belgium), Continental (Switzerland), and Mediterranean South (Italy, Spain) while eight environmental zones were not included due to a scarcity of studies, namely Alpine North, Alpine South, Anatolian, Lusitanian, Nemoral, Pannonian, Mediterranean North, and Mediterranean Mountains. In a total of 9 studies, no-tillage methods were utilized, whereas 2 studies implemented minimum tillage practices, preventing a comparative analysis of their effects. This limited number of available field studies on N_2O emissions underscore the necessity for additional European

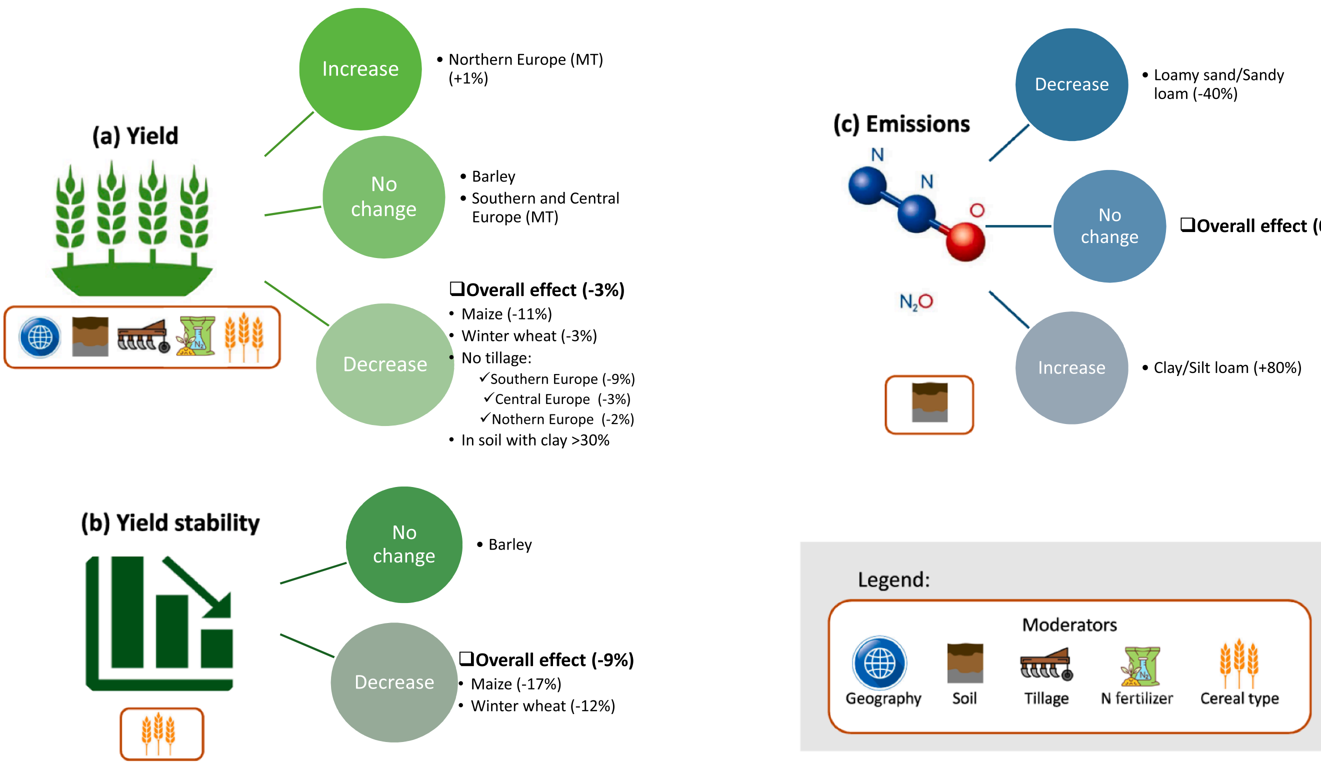

Fig. 8. A diagram illustrating the main results of this meta-analysis on the effect of conservation agriculture on (a) cereal yield, (b) yield stability, and (c) soil N_2O emissions when compared to conventional agricultural practices. MT, minimum tillage, NT no-tillage, both adhering to the core principles of conservation agriculture (CA). Key moderating factors are highlighted in brown boxes.

research focused on monitoring N_2O emissions in real-world settings, particularly, in clay-rich soils where our results suggest elevated N_2O emissions. Likewise, the recent meta-analysis addressing the effectiveness of soil management strategies for the mitigation of N_2O emissions recognized this same requirement, as the number of European field experiments related to strategies that involve the application of organic matter inputs was quite limited, ranging from 3 to 10 depending on the type of inputs (Valkama et al., 2024). Specifically for CA, long-term experiments may be required to properly evaluate the effect of tillage practices but also crop diversification (Maenhout et al., 2024). In this way the impact of the conversion to a new tillage system typical for CA on soil structure and eventually N_2O emissions but also SOC accrual can be considered.

5. Conclusions

This meta-analysis synthesized the diverse impacts of CA on yield, yield stability and N_2O emissions in comparison to CONV practices. As illustrated in Fig. 8, the implementation of CA systems in Europe reduced yields on average by 3 % and yield stability by 9 %, yet, had no effect on N_2O emissions. Different moderators (geography, soil, tillage depth, N fertilizer, type of crops) drove this pattern, with topsoil clay content being the property that can be least influenced by farmers. Taking this pre-determined property into account, the estimated yield gaps between CONV and CA were largest in regions with high soil clay content. The geospatial analysis of the yield changes indicated that Central and Southern Europe are more susceptible areas, where NT practices may contribute to larger yield gaps (up to 9 %), primarily due to the high clay content in the soils. Consequently, the promotion of MT rather than NT in these regions could be important for narrowing the yield gaps for cereal crops, potentially even enabling an increase in yield in certain areas.

Furthermore, our results indicate crop-specific response to CA, since winter and spring barley had yields and yield stability comparable to CONV, whereas maize and winter wheat exhibited yield gaps and a considerable yield instability. This finding has important implications for the promotion of CA across cereal crops, particularly in cases such as those investigated in this study, where CA systems are aimed at improving the environmental performance of industrial agriculture.

Although the number of field studies on N_2O emissions was limited, a strong positive relationship was observed between the relative N_2O emissions and increasing soil clay content. This suggests a possible trade-off associated with promotion of CA to achieve policy goals related to the climate mitigation potential of CA in promoting carbon accrual in soils. It highlights the need for European studies that investigate both N_2O emissions as well as soil carbon storage under CA practiced in soils with high clay content.

While CA practices provide a clear pathway toward more sustainable agriculture, their efficacy is not absolute, as it is strongly influenced by moderating factors. This integrated perspective underscores that a transition to CA offers a robust strategy for building more environmentally friendly cropping systems, but its application needs to be tailored to specific local conditions and farming systems to mitigate possible trade-offs. Our study suggests that success of CA will depend on informed, region-specific strategies that balance productivity with environmental considerations. These findings are particularly relevant in addressing the challenges posed by climate change and extreme weather events, which are pushing the need for yield stability, while a growing population increases the demand for higher cereal production.

More studies are required to comprehensively evaluate the economic and environmental impact of CA compared to CONV in a European context. Such analyses would help to balance agronomic performance with financial viability, providing farmers and policymakers with a broader understanding of the benefits, but also the trade-offs associated with adopting conservation farming practices.

CRediT authorship contribution statement

Klaus A. Jarosch: Writing – review & editing, Validation, Project administration, Investigation, Funding acquisition, Conceptualization. **Peter Maenhout:** Writing – original draft, Investigation, Data curation. **Julia Fohrafellner:** Writing – review & editing, Investigation. **Rodolfo Ceriani:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Francesco Fava:** Writing – review & editing, Visualization, Supervision, Formal analysis. **Elena Valkama:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Milena Stefanova:** Writing – review & editing, Investigation. **Valentina Mereu:** Writing – review & editing, Investigation. **Gianluca Carboni:** Writing – review & editing, Investigation. **Valentina Baratella:** Writing – review & editing, Investigation. **Claudia Di Bene:** Writing – review & editing, Project administration, Investigation, Funding acquisition. **Lena Weiss:** Visualization, Investigation.

Declaration of Competing Interest

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2026.110386.

Data availability

Database is free to download in Zenodo (https://doi.org/10.5281/zenodo.18456263).

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