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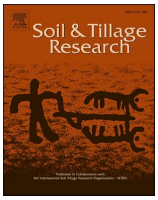

Cover crops in cereal rotations: A quantitative review

Marco Fioratti Junod [a,b,*], Brian Reid [c], Ian Sims [d], Anthony J. Miller [a,**]

[a] John Innes Centre, Norwich, UK
[b] WSL, Birmensdorf, Switzerland
[c] University of East Anglia, Norwich, UK
[d] Syngenta, Jealott's Hill, UK

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ABSTRACT

The use of cover crops in conventional agriculture is not fully accepted. This is probably due to the substantial variability in outcomes reported and is complicated by the conflation of a host of techniques under the same umbrella term, often without the appropriate benchmarking. This review addresses these issues with a quantitative synthesis of the last 11 years of research on cover crops in cereal rotations in temperate climates. Strict inclusion criteria focus the scope of the review to studies offering comparisons with an equally treated bare fallow control. Coded variables included duration, fertiliser, irrigation and tillage regime, cover and cash crop type and termination mode. The result is a quantitative review of 100 parameters covered by multiple publications, with an additional overview on 124 parameters covered by single studies. The investigated response variables range from microbiology and chemical parameters to hydrology, soil structure, weed and pest control and crop performance. Relevant trends were identified regarding strengths and weaknesses of cover cropping, with predictions formulated about the conditions necessary for their successful implementation. Additionally, trade-offs specific to cover cropping are discussed, together with the variables at play in determining the final balance of net gain or loss. The main findings are that cash crop performance is best enhanced by legume cover crops and in low-tillage regimes, and the soil biotic effects of cover crops tend to be short-lived, fading by the end of the season. Most importantly, a positive effect of cover cropping on soil carbon is potentially offset by increased GHG emissions.

1. Introduction

Despite their long history in agriculture, and the renewed interest in recent years, many aspects concerning the influence of cover crops on the soil microbiome, on chemo-physical parameters and on economic outputs are controversial. The scientific cover crop literature is characterised by knowledge gaps and conflicting evidence. Substantial variability in the effect of cover crops is often cited as one of the main obstacles to the widespread adoption of this practice and its inclusion in the definition of conventional agriculture (Chahal, Vyn, Mayers, & Van Eerd, 2020).

A rigorous focusing of the scope of the analysis should be the prerequisite of any review regarding cover crops. Moreover, while qualitative reviews provide useful references and identify the few parameters for which the effect of growing cover crops is well-established and univocal, they fail at providing articulated answers to many of the open questions about this practice. Simple lists of references supporting or refuting a claim serve well to highlight the areas where further research is needed (Abdalla et al., 2019). However, to shed light on the main experimental and agronomic variables influencing the outcome, an effort to extract and summarise quantitative information is required. Data regarding the magnitude and the variability of measurements across multiple studies is essential to frame the current state of research. A meta-analysis of the published literature can provide summary answers for farmers, environmentalists, and policy makers.

Within this analysis, identifying a series of key agronomic and experimental drivers consistently controlled and manipulated across a range of publications and systematically assessing their influence on outcome variability is paramount to the success of the attempt. In addition, the considerable diversity in the fields of expertise that are involved in the research on cover crops, spanning from pure agronomy to ecology, from molecular biology to agricultural engineering, all the

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* Corresponding author at: John Innes Centre, Norwich, UK.
** Corresponding author.
E-mail addresses: marco.fioratti@wsl.ch (M. Fioratti Junod), tony.miller@jic.ac.uk (A.J. Miller).

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way to economics and soil science, is reflected in the extreme heterogeneity in the way data are reported, graphically or numerically represented and statistically summarised. In particular, the size of an effect is seldom reported in a manner allowing the use of traditional meta-analytical techniques and the assessment of post-hoc significance is carried out through a host of different methods (Harris, 2017).

These are the main reasons why quantitative syntheses, especially across a range of parameters and a substantial number of publications, are rarely attempted in matters of agronomic interest, notwithstanding their already outlined potential importance. Devising a set of strict parameters for assessment and inclusion, a selection of manageable and meaningful explanatory variables to be evaluated for each study and a simple and logically sound procedure for extracting magnitude and significance data from heterogenous sources makes it possible to overcome most of the obstacles posed by such an undertaking.

2. Materials and methods

2.1. Reference selection

To keep the focus of the study both manageable and meaningful, the selection of literature was centred on experimental studies focusing on cereal rotations including cover crops in temperate climates and including appropriate control for pairwise comparisons. All major cereals were taken into consideration, except for rice, which is less commonly used in conjunction with cover crops and is agronomically a special case (e.g., flooded culture) that sets it apart from most other grain cereals. Bi-crops, a succession of two harvestable crops withing the same season (rare in temperate climates), and synchronous cover crops such as intercrops, living mulches or relay crops were all excluded from the meta-analysis. Harvest of cover crops was generally interpreted as an instance of bi-cropping and relevant papers were excluded, but exceptions were made for biomass harvesting, hay making and grazing.

A series of multiparameter whole-text searches were performed on the Web of Science – Clarivate database for the expression “cover crops” associated with “cereals” and with the names of several cereal crops other than rice (“wheat”, “corn”, “maize”, “barley”, “oat”, “millet”, “sorghum”). A further filter was set to focus the research to the last decade, with hits limited to papers published in or after 2011. The reasons for this choice are grounded in rapid methodological changes that occurred mainly prior to the cut-off date (such as the switch to high-throughput sequencing from biomarker fingerprinting) and would make comparisons on the same parameters less reliable, and the context of climate change and a shifting baseline that hinders comparisons across large chronological gaps.

Results pertaining to different search keys were then pooled and duplicates removed. The raw selection was made of 1316 papers that were subsequently individually screened for the presence of one of the following exclusion criteria:

- Focus on non-target crop: crops other than cereals, minus rice; rotations including non-target crops, such as soybean or oilseed rape, were accepted provided they included a target crop.
- Non-relevant practices: mentions of cover crops in the text were not followed by the inclusion of the practice in the experimental work.
- Non-temperate environmental context: tropical, equatorial or boreal high latitude field trials were excluded; in case of Mediterranean or borderline subtropical climates in Southern Europe and the South of the United States, the Middle East, South Africa, Southern Australia or Southern South America case by case decisions were made based on the type of rotation and the species included fitting more typical temperate contexts.
- Methodological studies, reviews, models or simulations: only papers based on collected experimental data were included.
- Synchronous cover crops: cover crops were not terminated before the start of the following cash crop season.
- Lack of an appropriate control: a treatment without the presence of cover crops, but otherwise undergoing the same agronomical treatment of the cover crop treatments was required; this led to the exclusion of papers based on the mere comparison of different cover crops and instances where an unfertilised control was compared to a fertilised cover crop treatment.

2.2. Coding and analysis

A total of 202 papers were found which passed the rigorous inclusion criteria and were processed for data extraction. A list of the parameters measured in the paper was made, focusing on agronomical or chemical parameters likely to be shared by other studies. In publications where treatments or experiments fitting exclusion criteria were paired to acceptable ones, only the latter were processed.

Data were then extracted from tabular or graphical summaries, in this latter case through pixel-based conversion algorithms, with one value for the control and one for the cover crop treatment in pairs (single comparisons). In instances where the same control was used for several cover crop treatments, the control measure was replicated in each pairwise comparison. Clearing of a post-hoc significance threshold for pairwise comparisons according to the method used by the authors was noted. When no such tests were performed, the lack of a significant effect was assumed. In a few cases the absence of any indication of significance was resolved by performing *post-hoc* analysis of the original data. In case of repeated measurements, only the latest available data referring to a target crop were selected.

Additionally, an experimental variable grid was filled noting for each comparison, including the following fields:

- Setting (field-based or controlled conditions)
- Duration of the rotation at the time of sampling, in seasons
- Cover crop type (legume, Brassica, cereal, mixture or other being the selected bins)
- Cash crop (the target crop included in the rotation; in case of more than one target crop, the one occurring later in the rotation was selected)
- Type of rotation (yearly cover crops, alternate cover crops, or cover crop only)
- Water regime (rainfed, irrigated or controlled drought)
- N-fertiliser regime (no fertiliser, low, standard, high, manure)
- Termination method (mechanical, chemical, biomass harvest, frost, grazing)
- Tillage regime (no-till, reduced tillage, conventional tillage)
- Time of sampling (cover crop growing, termination, cash crop growing, harvest or cumulative)
- Number of replicates (since the number of replicates in agronomical field studies is almost invariably comprised between 3 and 5, the parameter was not used for weighing purposes).

For each comparison, an effect size was calculated, expressing the difference between the cover crop reading and the bare fallow reading, divided by the bare fallow reading. The focus on effect size expressed in percentage stems from an effort to normalise results for the control value, focusing on the direction and relative magnitude of the change induced by cover crops. Such an approach was applied to smooth out, and render less important, variability due to slight methodological differences. As an example, for available P, extractions based on Olsen, Bray or Mehlich protocols were combined, but the variation in sign and magnitude of the effect is not affected as pairwise comparisons among raw measurements would be.

For parameters where only few publications were available, only the number of *post-hoc* significant comparisons in each direction were reported, together with the raw unweighted mean effect and standard deviation computed across all available comparisons. For parameters for which data from ten or more papers were available, a mixed-effect model was fitted, including the study identity as a random effect and all the categorical variables showing variability within the sample. Stepwise reduction from the full model was then carried out to identify significant explanatory variables.

3. Results

3.1. Cash crop performance

Performance data for cash crops following cover crop treatments shows a mildly positive trend, with a substantial amount of variability only partly explained by coded variables (Fig. 1, Table 1). The mean effect on dry yield (Supplementary figure 1) was found to be positive, but with remarkable variability straddling extensively in negative territory. The vast majority of papers converged around low-magnitude effects, but there are two noticeable outliers in opposite directions (Büchi et al., 2018; Eash et al., 2021). Stepwise simplification modelling allowed the removal of some drivers of the extremely high variability exhibited by some studies. Cover crop type and tillage regime emerged respectively as significant explanatory variables. Legume cover crops resulted in estimated considerable, whereas a preceding cereal cover crop resulted in a modelled decrease. This may occur through time-dependent competition effects, such as resource depletion and/or pathogen accumulation. No-till regimes resulted in substantial modelled yield increases, as opposed to conventional tillage, with a modelled outcome in negative territory. This result seems to suggest that soil mechanical disturbance voids, at least in part, the benefits of a cover crop season. Irrigation, termination technique and the type of cereal cash crop did not emerge as significant explanatory variables, but the duration of the rotation approached the significance threshold with a yearly negative modelled mean. This casts doubts over the common claim that cover crops build up effectiveness over several seasons in transitions to no-till or organic management (Boselli et al., 2020). Few papers have attempted to investigate whether the economic benefit of increased yield following cover crops (Chen et al., 2012; Dabin et al., 2015; Murungu et al., 2011; Rutan and Steinke, 2019) is compensated by the additional costs incurred in their establishment and termination; the effect of cover crops on profitability, although often large in magnitude, are widely divergent and do not allow to draw meaningful conclusions.

Indirect or partial crop performance indicators like thousand kernel weight TKW (Dabin et al., 2016; Kaufman et al., 2013; Virender Kumar, 2011; Mahama et al., 2016b, 2016a; Thapa, Ghimire, Acosta-Martínez et al., 2021; Zakikhani et al., 2016), plant height (Kalkan and Avci, 2020; Mahama et al., 2016b, 2016a; Samarappuli et al., 2014) and grain protein (Burgess et al., 2014; Chen et al., 2012; Eash et al., 2021; Janosevic et al., 2017; Kaufman et al., 2013) and N (J. L. Gabriel and Quemada, 2011; J.L. Gabriel et al., 2016; Hirsch et al., 2009; Kramberger et al., 2014; Krueger et al., 2011; Li et al., 2015; Northup and Rao, 2016; Perdigão et al., 2021; Thilakarathna et al., 2015b) content show a similar mildly positive and highly variable pattern. As for TKW, cover crop mixtures were associated to a better outcome in the following cash crop, whereas for grain N content the only indication of significant gains come from unfertilised settings. Cash crop biomass was similarly variable, with a single strong positive outlier (Karasawa and Takebe, 2011, in an atypical cabbage/maize rotation enriched with a sunflower cover crop).

As for nutrient use, limited evidence supports positive effects on P uptake (Karasawa and Takahashi, 2015, Zhang Dabin et al., 2015) and P grain content (Norberg and Aronsson, 2020b; Kaufman et al., 2013). More substantial evidence is available for crop N uptake (Supplementary figure 2), with positive influence of mixed and legume cover crops and a negative modelled effect found after a preceding cereal cover crop. This effect is however counterbalanced by a generally negative trend in nitrogen use efficiency (NUE, Habbib et al., 2017; Mahama et al., 2016b, 2016a; Maris et al., 2021; Y. A. Mohammed and Chen, 2018; Plaza-Bonilla et al., 2017).

Chlorophyll content, estimated through SPAD (Soil Plant Analysis Development) readings, was assessed 57 times across 8 publications (Appelgate et al., 2017; Carciochi et al., 2021; Kalkan and Avci, 2020; Mahama et al., 2016b, 2016a; Rutan and Steinke, 2019; Salmerón et al., 2011; Ziveh et al., 2019). Mixed results were observed for cereal cover crops, with two significantly positive and three significantly negative comparisons (Carciochi et al., 2021; Rutan and Steinke, 2019)

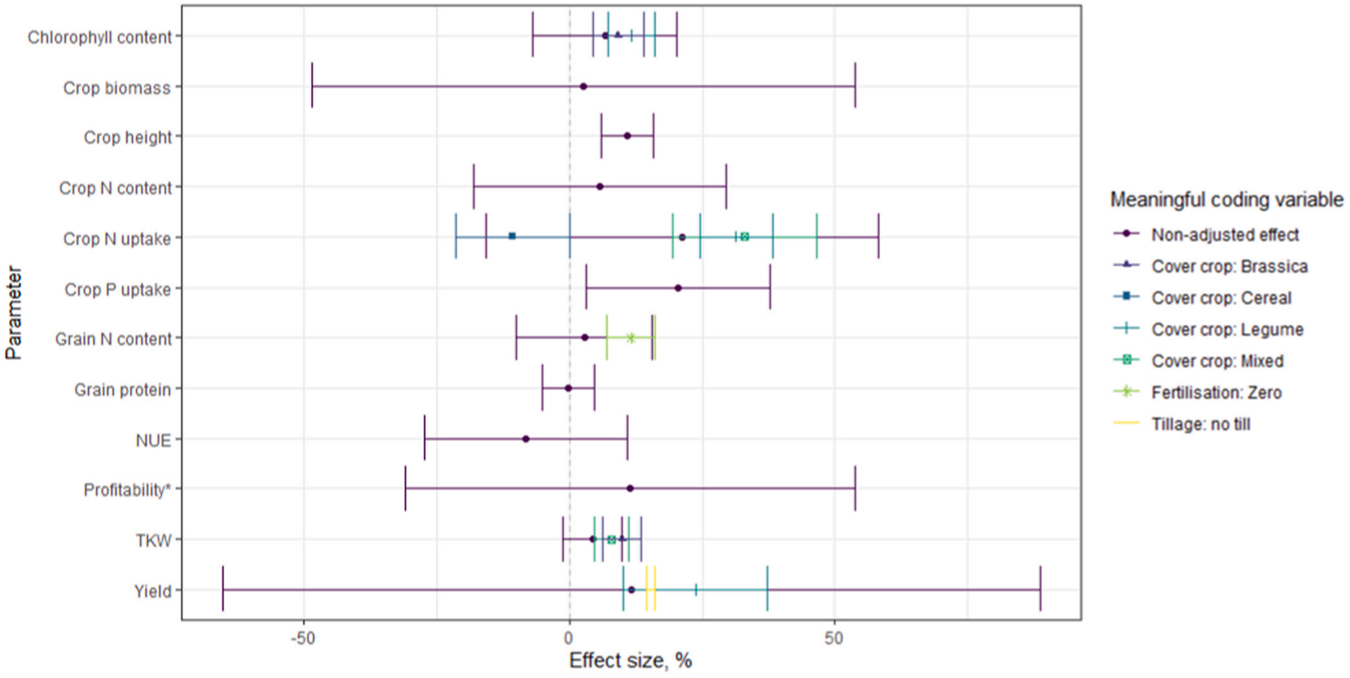

Fig. 1. Effect size, expressed in percentage variation over the bare fallow control, for a range of crop performance variables. The error bar refers to standard deviation. In cases where a substantial number of publication was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented. For variables marked with an asterisk, the real recorded effect is ten times larger than shown.

Table 1
Summary of metrics covered by more than one publication, with unweighted mean and standard error.

Class	Parameter	Publications	Comparisons	Positive	Negative	Mean effect	SE	Authors
Bacteria and protists	Actinobacteria	5	26	6	0	21.3	25.8	Calderón (2016), Singh J. (2021) b, Thapa (2021), Wang (2020), Xu (2020)
	Bacterial abundance	6	19	9	0	24	28	Karasawa (2015), Singh J. (2021) b, Somenahally (2018), Thapa (2021), Wang (2020), Xu (2020)
	Bacteroidetes	2	6	0	0	23.3	76.1	Alahmad (2019), Ashworth (2017) b
	Gemmatimonadates	2	6	0	0	17.8	22.1	Alahmad (2019), Ashworth (2017) b
	Gram-negative	2	24	6	0	23.6	23.8	Calderón (2016), Thapa (2021)
	Gram-positive	2	12	5	0	37.6	40.7	Calderón (2016), Singh J. (2021) b
	Proteobacteria	2	6	0	2	-21.3	28.7	Alahmad (2019), Ashworth (2017) b
	Protozoa	3	18	4	0	37.8	53.3	Calderón (2016), Thapa (2021), Xu (2020)
	Verrucomicrobia	2	6	2	0	82.5	153.8	Alahmad (2019), Ashworth (2017) b
Carbon and emissions	CO2 emissions	10	24	8	3	45.2	108.1	Boardman (2018), Forte et al. (2017), Guardia et al. (2016), Guardia (2019), Nguyen (2021), Sanz-Cobena (2014), Singh J. (2021) b, Stegarescu et al. (2020), Taghizadeh (2021), Zhou (2011)
	Methane emissions	4	14	2	0	61.8	76.9	Guardia et al. (2016), Sanz-Cobena (2014), Singh J. (2021) b, Stegarescu et al. (2020)
	N2O emissions	17	51	20	4	730	197	Boardman (2018), Duan (2018), Forte et al. (2017), Guardia et al. (2016), Jahangir (2014), Kim (2017), Li (2015), Mahama (2020), Mitchell (2013), Nguyen (2021), Pimentel (2015), Preza-Fontes (2020), Sanz-Cobena (2014), Schmatz (2020), Singh J. (2021) b, Stegarescu et al. (2020), Taghizadeh (2021)
	Potentially mineralisable C	3	16	7	0	46.8	67.3	Cates (2019) b, Ghimre (2019), Thapa (2021) b
	SOC	22	61	16	0	8.6	13.2	Alahmad (2019), Baldivieso-Freitas (2018), Blanco-Canqui (2011), Blanco-Canqui (2013), Blanco-Canqui (2014), Cates (2019) b, Chavarria (2018), Clark (2017), Ghimre (2019),Haruna (2019), Kaufman (2013), Kelly (2021), Mazzoncini (2011), Musunda (2015), Oliveira (2019), Restovich (2019), Sainju (2018), Singh J. (2020), Somenahally (2018), Steele (2012), Thapa (2021) b, Zhou (2011)
	SOC accumulation	2	9	0	0	6.64	682	Ashworth (2018), Maris (2021)
	Soil C accumulation	3	6	4	0	158	227	Balkcom (2013), García-González (2018), Verzeaux (2016)
	Soil C/N	3	6	0	0	4	6.6	Alahmad (2019), Ashworth (2020), Chavarria (2018)
	Soil organic matter	4	7	1	2	2.1	12	Blanco-Canqui (2019), Forte et al. (2017), Sapkota (2012), Xu (2020)
	Soil total C	6	15	2	0	9.8	9.1	Ashworth (2017), He (2019), Romaniuk (2018), Zhou (2011), Zhou (2016)
Crop performance	Chlorophyll content	8	57	19	8	6.7	13.5	Appelgate (2017), Carciochi (2021), Kalkan (2020), Mahama (2016), Mahama (2016) b, Rutan (2019), Salmerón (2011), Ziveh (2019)
	Crop biomass	7	52	2	5	2.6	51.2	Hirsh (2021), Karasawa (2011), Kramberger (2014), Li (2015), Maltais-Landry (2015) b, Nielsen et al. (2016), Rueda-Ayala et al. (2015)
	Crop height	4	15	11	0	10.9	4.9	Kalkan (2020), Mahama (2016), Mahama (2016) b, Samarappuli (2014)
	Crop N content	9	48	2	6	5.8	23.7	Kalkan (2020), Mahama (2016), Mahama (2016) b, Samarappuli (2014)
	Crop N uptake	15	79	33	15	21.2	37	Adeyemi (2020), Beslemes (2014), Chen C. (2012), Cicek (2015), Dabin (2015), Dabin (2016), Duan (2018), Fontes (2017), Mahama (2016), Mahama (2016) b, Mahama (2020), Maris (2021), Plaza-Bonilla (2015), Plaza-Bonilla (2017), Salmerón (2011), Samarappuli (2014), Singh G. (2019), Wittwer (2020)
	Crop P uptake	2	7	3	0	20.6	17.3	Dabin (2015), Karasawa (2015)
	Grain N content	12	52	6	9	2.8	12.8	Gabriel (2011), Gabriel (2016), Habbib (2017), Herrera (2017), Jilling (2020), Kramberger (2014), Norberg (2012), Reese et al. (2014), Salmerón (2011), Schmer (2020), Thilakarathna et al. (2015a), Yang (2019)
	Grain protein	5	13	2	1	-0.2	5	Burgess (2014), Chen C. (2012), Eash (2021), Janosevic (2017), Kaufman (2013)
	NUE	6	23	1	11	-8.2	19.1	Habbib (2017), Mahama (2016), Mahama (2016) b, Maris (2021), Mohammed (2018), Plaza-Bonilla (2017)

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Table 1 (*continued*)

Class	Parameter	Publications	Comparisons	Positive	Negative	Mean effect	SE	Authors
	Profitability	4	18	2	9	114.3	422.9	Chen C. (2012), Dabin (2015), Murungu (2011), Rutan (2019)
	TKW	7	21	9	0	4.4	5.5	Dabin (2015), Kaufman (2013),Kumar (2011), Mahama (2016), Mahama (2016) b, Thapa (2021) b, Zakikhani (2016)
	Yield	77	482	120	71	11.7	77	Acharya (2020), Adeux (2021), Adeyemi (2020), Baldivieso-Freitas (2018), Balkcom (2013), Basche (2016), Beslemes (2014), Blanco-Canqui (2012), Büchi (2018), Büchi (2020), Burgess (2014), Carciochi (2021), Cates (2019), Chen C. (2012), Chen G. (2011), Cicek (2015), Clark (2017), Coombs (2017), Cottney (2020), Ćupina (2017), Cutti (2016), Dabin (2015), Dorn (2015), Drury (2014), Eash (2021), Fontes (2017), Gabriel (2011), Gabriel (2016), Habbib (2017), Harasim (2016), Herrera (2017), Hirsh (2021), Hunter (2019), Hunter (2021), Ivancic (2019), Janosevic (2017), Jilling (2020), Kalkan (2020), Karasawa (2011), Karasawa (2015), Kaufman (2013), Kelly (2021), Krueger (2011),Kumar (2011), Li (2015), Mahama (2016), Mahama (2016) b, Mahama (2020), Maris (2021), Melero (2016), Mohammed (2018), Moitzi (2021), Murungu (2011), Musunda (2015), Nielsen et al. (2016), Norberg (2012), Northup (2016), Oliveira (2019), Pedersen (2021), Perdigão (2021), Petrosino (2015), Plaza-Bonilla (2016), Plaza-Bonilla (2017), Reese et al. (2014), Rutan (2019), Salmerón (2011), Samarappuli (2014), Schmer (2020), Sigdel (2018), Somenahally (2018), Thapa (2021) b, Thilakarathna et al. (2015a), Toom (2019), Wittwer (2020), Yang (2019), Zakikhani (2016), Ziveh (2019)
Enzymes and metabolism	Acid phosphatase	4	22	8	0	13.8	21.6	Chavarria (2018), Higo (2020), Housman (2021), Papp (2018)
	Alkaline phosphatase	6	27	5	0	18.7	21.2	Dabin (2016), García-González (2018) b, Higo (2020), Housman (2021), Melero (2016), Thapa (2021)
	Arylsulphatase	4	21	5	0	23.2	43.6	Dabin (2016), Housman (2021), Papp (2018), Singh J. (2021)
	Beta glucosaminidase	4	22	2	0	11.1	32.3	Calderón (2016), García-González (2016), Housman (2021), Thapa (2021)
	Beta glucosidase	6	35	16	0	64.7	88.9	Calderón (2016), Higo (2020), Housman (2021), Maltais-Landry (2015), Piotrowska-Dugosz (2015), Singh J. (2021)
	Cellulase	2	4	2	0	14.2	42.1	Gregorutti (2019), Piotrowska-D?,ugosz (2015)
	Chitinase	2	21	5	0	50.04	52.42	Maltais-Landry (2015), Papp (2018)
	Dehydrogenase	5	21	10	0	10.2	34.8	Dabin (2016), Harasim (2020), Melero (2016), Nivelle (2016), Wang (2020)
	Diesterase	2	16	6	0	146.4	179.6	Calderón (2016), Maltais-Landry (2015)
	Microbial biomass	3	10	2	0	14.9	12.1	Singh J. (2021) b, Thapa (2021), Xu (2020)
	Microbial C	11	38	22	2	26	36.7	Baldivieso-Freitas (2018), Chavarria (2018), Housman (2021), Papp (2018), Piotrowska-Długosz (2015), Sapkota (2012), Singh J. (2021), Somenahally (2018), Stegarescu et al. (2020), Wang (2020), Zhou (2016)
	Microbial N	6	28	21	0	78.1	79.3	Baldivieso-Freitas (2018), Papp (2018), Piotrowska-Długosz (2014), Singh J. (2021), Wang (2020), Zhou (2016)
	Microbial respiration	5	8	0	0	6.3	18.1	Cates (2019), Chavarria (2018), Piotrowska-Długosz (2015), Romaniuk (2018), Sapkota (2012)
	Protease	2	10	8	0	31.5	19.99	Piotrowska-Długosz (2014), Wang (2020)
	Urease	6	25	10	4	20.1	22	Dabin (2016), Harasim (2020), Nivelle (2016), Piotrowska-Długosz (2014), Singh J. (2021), Wang (2020)
Fungi	AMF abundance	14	105	44	1	101	233.1	Calderón (2016), García-González (2016), García-González (2018) b, Higo (2018), Higo (2019), Higo (2020), Karasawa (2011), Karasawa (2015), Lehman (2019), Murrell (2020), Singh J. (2021) b, Somenahally (2018), Thapa (2021), Xu (2020)
	AMF diversity	4	12	0	1	-5.5	12.9	Higo (2018), Higo (2019), Higo (2020), Hontoria (2019)
	AMF richness	4	12	0	0	-0.05	12.5	Higo (2018), Higo (2019), Higo (2020), Hontoria (2019)

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Table 1 (*continued*)

Class	Parameter	Publications	Comparisons	Positive	Negative	Mean effect	SE	Authors
	Fungal abundance	6	19	8	1	39.7	70.9	Karasawa (2015), Mielniczuk (2020), Somenahally (2018), Thapa (2021), Wang (2020), Xu (2020)
	Hyphal length	3	6	4	0	60.8	53.2	García-González (2016), García-González z (2018) b, Hontoria (2019)
	Micorrhizal colonisation	4	15	4	0	16.1	24.3	Hontoria (2019), Njeru (2013), García-González (2018) b, Housman (2021)
	Saprophytic fungi	3	18	7	0	43.2	39.6	Calderón (2016), Singh J. (2021) b, Thapa (2021)
Hydrology	Dissolved inorganic N	3	8	0	1	-15	27	Jahangir (2014), Salazar (2019), Singh G. (2019)
	Dissolved organic C	3	13	4	5	404	1460	Jahangir (2014), Salazar (2019), Sanz-Cobena (2014)
	Dissolved total N	3	7	1	4	-28	64.8	Fraser (2013), Singh G. (2019), Tosti (2014)
	Eroded sediment	2	10	0	6	-51	22	Blanco-Canqui (2013), Mohammed (2021)
	Hydraulic conductivity	3	5	2	0	998	1908	Çerçioğlu (2020), Singh J. (2020), Steele (2012)
	Infiltration rate	3	11	3	3	70.4	164	Hudek (2021), Singh J. (2020), Steele (2012)
	Nitrate runoff	2	8	0	2	-38.6	34.3	Blanco-Canqui (2013), Drury (2014)
	Soil water content	21	127	5	74	-14.1	16.5	Alonso-Ayuso (2014), Ammar (2020), Appelgate (2017), Barker (2018), Blanco-Canqui (2011), Blanco-Canqui (2019), Burgess (2014),Çerçioğlu (2020), Ćupina (2017), Daigh (2014), Eash (2021), Ghimre (2019),Haruna (2019), Holman (2021), Kelly (2021), Khan (2019), Krstic (2018), Mubvumba (2021), Nielsen et al. (2016), Restovich (2012), Singh J. (2020)
	Surface runoff	2	10	0	5	-15.6	22.2	Drury (2014), Mohammed (2021)
	Total drainage	5	15	0	5	-14.6	11.4	Gabriel (2012) b, Gabriel (2014), Meisinger (2017), Norberg (2012), Salazar (2019)
	Total leached N	4	9	0	4	-41	18	Gabriel (2012) b, Gabriel (2014), Meisinger (2017), Norberg (2012)
Pest control	Fusarium prevalence	2	10	1	2	121.3	294.6	Kadziene (2020), Walder (2017)
	Pest predation rate	3	8	3	0	39.37	53.54	Fox (2016), Lundgren (2011), Rowen (2021)
Soil chemistry	Apparent remaining N	2	11	3	1	70.3	81.5	Ćupina (2017), Perdigão (2021)
	CEC	2	7	4	0	7.6	9.2	Ashworth (2020), He (2019)
	EC	2	7	0	0	7.4	7.4	Ashworth (2020), He (2019)
	N accumulation	7	52	23	10	67.5	142.8	Maris (2021), Nivelle (2016), Sigdel (2018), Verzeaux (2016), Dabin (2016), Kaye (2019), Wittwer (2020)
	P accumulation	3	26	0	5	-21.1	57.3	Ashworth (2018), Maltais-Landry (2015), Maltais-Landry (2015) b
	Potentially mineralisable N	4	23	2	0	38.1	74.3	Housman (2021), Jilling (2020), Kelly (2021), Thapa (2021) b
	Soil ammonium	7	25	1	0	5.6	28.2	Alahmad (2019), He (2019), Jilling (2020), Nguyen (2021), Sainju (2018), Singh G. (2019), Zhou (2011)
	Soil available P	6	19	7	0	20.5	71.2	Ammar (2020), Chavarria (2018), Cober (2019), García-González(2018) b, Kelly (2021), Murrell (2020)
	Soil Ca	4	11	0	1	2.8	8.9	Ashworth (2017), Blanco-Canqui (2019), He (2019), Romaniuk (2018)
	Soil Cu	3	8	0	0	1.8	14.5	Ashworth (2017), He (2019), Romaniuk (2018)
	Soil Fe	2	5	0	0	16.8	13.2	He (2019), Romaniuk (2018)
	Soil K	5	15	1	3	1.7	21	Ammar (2020), Ashworth (2017), Blanco-Canqui (2019), He (2019), Romaniuk (2018)
	Soil Mg	4	11	0	1	1.5	11.6	Ashworth (2017), Blanco-Canqui (2019), He (2019), Romaniuk (2018)
	Soil mineral N	16	69	6	26	-22.9	42.9	Coombs (2017), Couëdel (2018), Drury (2014), Fraser (2013), Gabriel (2012) b, Ghimre (2019), Hunter (2021), Kaye (2019), Murrell (2020), Murungu (2011), Norberg (2012), Reese et al. (2014), Salmerón (2011), Thapa (2021) b, Thilakarathna et al. (2015a), Yang (2019)
	Soil nitrate	22	118	6	47	-8.4	52.2	Alahmad (2019), Alonso-Ayuso (2014), Ammar (2020), Andersen (2020), Appelgate (2017), Blanco-Canqui (2019), Carciochi (2021), Eash (2021), He (2019), Hirsh (2021), Jilling (2020), Khan (2019), Nguyen (2021), Restovich (2012), Rimski-Korsakov (2016), Sainju (2018), Sanz-Cobena (2014), Singh G. (2019), Singh J. (2021) b, Storr (2021), Yao (2018), Zhou (2011)
	Soil organic N	3	21	2	0	14.1	20.6	Plaza-Bonilla (2016), Restovich (2019), Zhou (2011)
	Soil pH	10	36	3	9	-11.7	36	Ashworth (2017), Blanco-Canqui (2014), Blanco-Canqui (2019), Chavarria (2018), He (2019), Higo

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Table 1 (*continued*)

Class	Parameter	Publications	Comparisons	Positive	Negative	Mean effect	SE	Authors
								(2018), Higo (2020), Maltais-Landry (2015), Nguyen (2021), Zhou (2011)
	Soil S	3	11	4	0	26.2	34	Carciochi (2021), He (2019), Romaniuk (2018)
	Soil total N	16	50	10	0	5.5	8.3	Alahmad (2019), Ashworth (2017), Baldivieso-Freitas (2018), Blanco-Canqui (2012), Chavarria (2018), Ghimre (2019), He (2019), Kaufman (2013), Kelly (2021), Mazzoncini (2011), Romaniuk (2018), Sainju (2018), Singh J. (2020), Thapa (2021) b, Zhou (2011), Zhou (2016)
	Soil total P	4	11	0	0	-0.2	9.7	Ashworth (2017), Blanco-Canqui (2019), He (2019), Romaniuk (2018)
	Soil Zn	2	5	0	0	15.6	20.3	He (2019), Romaniuk (2018)
Soil structure	Bulk density	13	29	1	5	-1.2	3.4	Basche (2016), Blanco-Canqui (2011), Blanco-Canqui (2013), Blanco-Canqui (2019), Çerçioğlu (2020), Cober (2019), Harasim (2020),Haruna (2019), Kelly (2021), Sapkota (2012), Singh J. (2020), Steele (2012), Tautges (2019)
	Dry aggregate mean diameter	2	6	1	0	60.3	38.8	Blanco-Canqui (2013), Blanco-Canqui (2014)
	Macroaggregates	5	14	4	0	36.4	99.2	Blanco-Canqui (2011), Blanco-Canqui (2019), Harasim (2020), Oliveira (2019), Yao (2013)
	Macropores	4	17	7	0	35.3	29.1	Çerçioğlu (2020), Hudek (2021), Restovich (2019), Singh J. (2020)
	MWD	7	21	14	2	29.9	33.6	Blanco-Canqui (2011), Blanco-Canqui (2013), Blanco-Canqui (2014), Blanco-Canqui (2019), Dabin (2016), Kelly (2021), Yao (2013)
	Penetration resistance	4	9	0	4	-8	10.4	Moitzi (2021), Singh J. (2020), Gabriel (2021), Harasim (2020)
	Porosity	3	5	4	0	7.4	6.5	Çerçioğlu (2020), Harasim (2020),Haruna (2019)
	Soil aggregate stability	6	22	14	1	48.63	48.1	García-González (2016), Hudek (2021), Restovich (2019), Sapkota (2012), Singh J. (2020), Steele (2012)
Weed control	Weed biomass	18	188	6	122	-46	96.9	Adeux (2021), Alonso-Ayuso (2018), Baraibar (2018), Brust (2014), Büchi (2018), Cottney (2020), Cutti (2016), Dorn (2015), Kadziene (2020), Masylionite (2017), Mesbah (2019), Murungu (2011), Musunda (2015), Petrosino (2015), Rueda-Ayala et al. (2015), Schappert (2019), Wittwer (2020), Ziveh (2019)
	Weed cover	2	42	0	12	-34	63	Büchi (2020), Dorn (2013)
	Weed density	3	41	0	26	-56.5	27.6	Kadziene (2020), Masylionite (2017), Ranaldo (2020)
	Weed diversity	2	6	0	1	-19	22.5	Alonso-Ayuso (2018), Musunda (2015)
	Weed emergence	2	4	0	1	-19.7	13.7	Cordeau (2015),Kumar (2011)

identified. Following brassica and crop mixtures, a significantly negative impact of cover crops was observed on three occasions (Appelgate et al., 2017; Rutan and Steinke, 2019), whereas the influence of legume cover crops was overwhelmingly positive, with 17 significantly positive comparisons across 4 papers (Carciochi et al., 2021; Kalkan and Avci, 2020; Mahama et al., 2016a, 2016b). The mean effect of a legume crop on cash crop SPAD readings was plus 11.8 ± 4.4%.

An additional 13 parameters were assessed in a single study (Table 2). Significantly lower levels of water efficiency and significantly higher levels of water use were recorded under a variety of cover crop rotations (Nielsen et al., 2021). On a similar note, energy inputs were found to be higher under cover crops, resulting in significantly lower energy efficiency (Harasim and Gawęda, 2016). The presence of cereal cover crops was additionally found to increase primary productivity above-ground, but not below ground (Cates and Jackson, 2019). Additionally, legume cover crops showed potential to enhance cash crop K uptake.

Overall, variability in crop performance indicators were substantial, with yield showing a mildly positive global trend, compensated by more dubious results in actual economic profitability. Mixed results were observed for other parameters within the category but cover crop type and tillage regime seem to be important drivers, with legumes and no-till regimes outperforming the alternatives.

3.2. *Soil chemistry*

The behaviour of N pools following cover crops is the object of a substantial corpus of literature, whose analysis allows to identify several relevant trends (Fig. 2, Table 1). Total N (Supplementary figure 3) showed substantial variability, with the only modelled positive effects arguably coming from legume and mixed cover crops.

The mineral N pool (Supplementary figure 4) was characterized by a similar variability and a generally negative trend, arguably driven by more vigorous cash crop development following cover crops. The decline was significant for mixed cover crops, whereas for legume cover crops the balance was mildly positive. The substantial variability recorded in nitrate-N outcomes (Supplementary figure 5) can be partially explained by the time of sampling, with a strongly negative effect at termination contrasted with an opposite trend at cash crop harvest. N accumulation rates measured over extended timeframes show an even greater variability, with the only significant modelled positive effect established under drought conditions.

Limited numbers of comparisons did not allow the detection of relevant trends for organic N (Zhou et al., 2011; Plaza-Bonilla et al., 2016; Restovich et al., 2019), ammonium (Alahmad et al., 2019; He et al., 2019; Jilling et al., 2020; Nguyen and Kravchenko, 2021; Sainju et al., 2018; G. Singh et al., 2019; Zhou et al., 2011) and potentially mineralizable N (Housman et al., 2021; Jilling et al., 2020; Kelly et al.,

Table 2
Summary of metrics covered by single publications, with a general summary of trends.

Class	Parameter	Author	Outcome
Above-ground biology	Bee abundance	Bryan (2021)	Inconclusive
	Bird abundance	Wilcoxen (2018)	Higher under cover crops
	Bird diversity	Wilcoxen (2018)	Higher under cover crops
	Floral richness	Bryan (2021)	Lower under cover crops
	Grey partridge diet, diversity	Orłowski (2011)	Lower under cover crops
Arthropods	Collembola abundance	Rowen (2021)	Inconclusive
	Earthworms	Blanco-Canqui (2011)	Higher under cover crops
	Earthworms, endogeic	Ashworth (2017)	Lower under cover crops
	Mite abundance	Rowen (2021)	Inconclusive
	Soil invertebrate diversity	Sapkota (2012)	Inconclusive
	Soil invertebrate richness	Sapkota (2012)	Higher under cover crops
Bacteria	Acidobacteria	Xu (2020)	Higher under cover crops
	Bacterial diversity	Alahmad (2019)	Higher under cover crops
	Burkholderiales	Xu (2020)	Higher under cover crops
	Clostridia	Xu (2020)	Lower under cover crops
	Diversity	Verzeaux (2016)	Higher under cover crops
	Microbial P	Dube (2014)	Higher under cover crops
	Myxococcales	Xu (2020)	Inconclusive
	Nitrifiers	Gregorutti (2019)	Inconclusive
	Nitrospirales	Xu (2020)	Lower under cover crops
	Richness	Verzeaux (2016)	Inconclusive
	Soil Escherichia coli count	Sarr (2020)	Inconclusive
	Sphingobacteria	Xu (2020)	Higher under cover crops
	Thermomicrobia	Xu (2020)	Higher under cover crops
Cash crop performance	Crop emergence	Kumar (2011)	Inconclusive
	Crop K uptake	Dabin (2015)	Higher under cover crops
	Crop P content	Maltais-Landry (2015) b	Inconclusive
	Energy efficiency	Harasim (2016)	Lower under cover crops
	Energy input	Harasim (2016)	Higher under cover crops
	Grain nitrogen recovery	Chen C. (2012)	Inconclusive
	Net primary productivity (above ground)	Cates (2019)	Inconclusive
	Net primary productivity (below ground)	Cates (2019)	Higher under cover crops
	Nitrification efficiency index	Gregorutti (2019)	Inconclusive
	Tillers	Burgess (2014)	Inconclusive
	Total starch	Kaufman (2013)	Inconclusive
	Water use	Nielsen et al. (2016)	Mixed results
	Water use efficiency	Nielsen et al. (2016)	Lower under cover crops
Enzymes and metabolism	C-cycle enzymes	Papp (2018)	Higher under cover crops
	Cellulolytic efficiency index	Gregorutti (2019)	Higher under cover crops
	Decomposition rate	Cates (2019) b	Inconclusive
	Denitrification rate	Jahangir (2014)	Lower under cover crops
	Fluorescein diacetate	Chavarria (2018)	Higher under cover crops
	Invertase	Dabin (2016)	Higher under cover crops
	Microbial degradation activity	Nivelle (2016)	Higher under cover crops
	Microbial functional diversity	Nivelle (2016)	Higher under cover crops
	Monoesterase	Maltais-Landry (2015)	Higher under cover crops
	nirk	Duan (2018)	Inconclusive
	nirS	Duan (2018)	Inconclusive
	Nitrate reductase	Piotrowska-D?ugosz (2014)	Higher under cover crops
	Nitrification	Gregorutti (2019)	Inconclusive
	nosZ-1	Duan (2018)	Inconclusive
	nosZ-2	Duan (2018)	Inconclusive
	Phosphatase	Karasawa (2015)	Inconclusive
	Sucrase	Wang (2020)	Higher under cover crops
Fungi	Acaullospora, density	Cloutier (2020)	Mixed results
	Claroideoglomus (AMF)	Cloutier (2020)	Mixed results
	Funneliformis (AMF)	Cloutier (2020)	Inconclusive
	Glomus (AMF)	Cloutier (2020)	Inconclusive
	P-solubilising fungi abundance	Karasawa (2015)	Higher under cover crops
Hydrology	C, runoff	Blanco-Canqui (2013)	Inconclusive
	Dissolved C	Singh J. (2021)	Inconclusive
	Dissolved O	Jahangir (2014)	Inconclusive
	Dissolved organic N	Salazar (2019)	Higher under cover crops
	Dissolved P	Norberg (2012)	Inconclusive
	Dissolved salts	Gabriel (2012)	Lower under cover crops
	Dissolved sulfate	Jahangir (2014)	Inconclusive
	Eroded organic matter	Mohammed (2021)	Lower under cover crops
	Evapotranspiration	Sharma (2017)	Inconclusive
	N, runoff	Blanco-Canqui (2013)	Inconclusive
	P, runoff	Blanco-Canqui (2013)	Lower under cover crops
	Permanent wilting point	Basche (2016)	Inconclusive
	Phosphate, runoff	Blanco-Canqui (2013)	Inconclusive
	Precipitation storage efficiency	Holman (2021)	Higher under cover crops
	Saturated water content	Basche (2016)	Inconclusive
	Soil water EC	Jahangir (2014)	Inconclusive
	Soil water pH	Jahangir (2014)	Inconclusive
	Soil water redox potential	Jahangir (2014)	Lower under cover crops
	Time to runoff	Blanco-Canqui (2013)	Higher under cover crops
Pest control	Arthropod predator abundance	Fox (2016)	Inconclusive
	Arthropod predator diversity	Fox (2016)	Inconclusive
	Disease index	Mielniczuk (2020)	Lower under cover crops
	Entomopathogenic nematodes	Jaffuel (2017)	Inconclusive
	Paeliciomyces (Insect parasite)	Cloutier (2020)	Inconclusive
	Plant pest-defense compounds	Malone (2020)	Higher under cover crops
	Pythium, density	Acharya (2020)	Inconclusive
Soil chemistry	Base saturation	He (2019)	Mixed results
	C, mineral associated	Restovich (2019)	Inconclusive
	C, POM	Oliveira (2019)	Inconclusive
	Ca accumulation	Ashworth (2018)	Lower under cover crops

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Table 2 (*continued*)

Class	Parameter	Author	Outcome
	Global warming potential	Boardman (2018)	Inconclusive
	Glomalin	García-González (2016)	Higher under cover crops
	K accumulation	Ashworth (2018)	Lower under cover crops
	Mg accumulation	Ashworth (2018)	Inconclusive
	Mn	He (2019)	Inconclusive
	N, recovered	Habbib (2017)	Inconclusive
	N, retention rate	García-González (2018)	Higher under cover crops
	Na	He (2019)	Inconclusive
	Organic acids	Maltais-Landry (2015)	Higher under cover crops
	P, fulvic acid	Dube (2014)	Inconclusive
	P, HCO3	Dube (2014)	Higher under cover crops
	P, HCO4	Dube (2014)	Higher under cover crops
	P, HCO5	Dube (2014)	Inconclusive
	P, HCO6	Dube (2014)	Inconclusive
	P, hexanol extractable	Maltais-Landry (2015) b	Inconclusive
	P, humic acid	Dube (2014)	Mixed results
	P, organic	Maltais-Landry (2015) b	Higher under cover crops
	P. HCl	Dube (2014)	Higher under cover crops
	POM	Restovich (2019)	Higher under cover crops
	POM, free	Jilling (2020)	Lower under cover crops
	POM, occlused	Jilling (2020)	Inconclusive
	SOM	Blanco-Canqui (2019)	Mixed results
Soil structure	Coarse mesopores	Çerçio?lu (2020)	Inconclusive
	Dry aggregate stability	Blanco-Canqui (2014)	Inconclusive
	Erodible fraction	Blanco-Canqui (2014)	Inconclusive
	Fine mesopores	Çerçio?lu (2020)	Inconclusive
	Root density	Herrera (2017)	Inconclusive
	Wind erodible fraction	Blanco-Canqui (2013)	Lower under cover crops
	Abutilon, emergence	Tabaglio (2013)	Inconclusive
	Amaranthus, emergence	Tabaglio (2013)	Lower under cover crops
	Chenopodium, emergence	Tabaglio (2013)	Inconclusive
	Portulaca, emergence	Tabaglio (2013)	Lower under cover crops
	Volunteer biomass	Masylionite (2017)	Lower under cover crops
	Volunteer density	Masylionite (2017)	Lower under cover crops
	Weed richness	Bryan (2021)	Lower under cover crops

2021; Thapa, Ghimire, and Marsalis, 2021) whereas for apparent remaining N the evidence is more substantial, but still limited (Ćupina et al., 2017; Perdigão et al., 2021).

Globally, N-fixing endosymbionts are arguably the driver for the positive effect of legumes on soil N on both total and mineral N and potentially mineralisable N. Less clear are the effects of cover crops in general on scarcer and more labile N compounds (Fig. 2).

Trends for P are less clear with sampling time appearing as the main driver of variability in topsoil available P, with significantly higher levels measured in the cover crop phase (Cober et al., 2019), a less marked difference at termination (Ammar et al., 2020; Kelly et al., 2021) and no measurable difference during the cash crop season (García-González, Hontoria et al., 2018; Murrell et al., 2020) and at harvest (Chavarria et al., 2018). P scavenging and solubilising properties of cover crops seem to be at play, but the contribution of stored tissue P during decay seems negligible later in the season. For total soil P and its accumulation rates, the available literature does not allow to speculate on definite trends.

The same can be said for all the other macro- and micronutrients. Soil K (Ammar et al., 2020; Ashworth, DeBruyn et al., 2017; Blanco-Canqui and Jasa, 2019; He et al., 2019; Romaniuk, Beltrán et al., 2018), Ca (Ashworth, Allen et al., 2017; Blanco-Canqui and Jasa, 2019; He et al., 2019; Romaniuk, Beltrán et al., 2018), Mg (Ashworth, DeBruyn et al., 2017; Blanco-Canqui and Jasa, 2019; He et al., 2019; Romaniuk, Beltrán et al., 2018), S (Carciochi et al., 2021; He et al., 2019; Romaniuk, Beltrán et al., 2018), Zn (He et al., 2019; Romaniuk, Beltrán et al., 2018) and Cu (Ashworth, Allen et al., 2017; He et al., 2019; Romaniuk, Beltrán et al., 2018) all showed variabilities more substantial than speculated effect sizes. More promising is the evidence for soil Fe enhancement with cover crops, although still with a limited corpus of literature (He et al., 2019).

For soil pH, within a general mildly acidifying trend (Ashworth, DeBruyn et al., 2017; Blanco-Canqui et al., 2014; Blanco-Canqui and Jasa, 2019; Chavarria et al., 2018; He et al., 2019; Higo et al., 2018, 2020; Maltais-Landry, 2015b; Nguyen and Kravchenko, 2021; Zhou et al., 2011), the type of cover crop resulted as a significant factor in explaining the variability, with legume crops entailing a mean modelled decrease in pH and cereals inducing a modelled opposite effect.

A tentative positive effect of cover crops seems to emerge for cation exchange capacity (CEC; Ashworth et al., 2020; He et al., 2019), whereas no trend was observed in terms of electric conductivity (Ashworth, Allen et al., 2017; He et al., 2019).

Among parameters taken examined by single publications (Table 2), cover crops were found to significantly enhance glomalin levels (García-González et al., 2016), nitrogen retention rates (García-González, Hontoria et al., 2018), total particulate organic matter (Restovich et al., 2019) and several P fractions (Dube et al., 2014; Maltais-Landry and Frossard, 2015). Conversely, soil calcium accumulation was found to be slower in rotations enriched with cover crops (Ashworth et al., 2018).

3.3. *Carbon and GHG emissions*

Carbon metrics were investigated by limited number of papers, hindering the detection of relevant trends (Fig. 3). The exception is soil organic carbon, measured in a substantial number of publications (Supplementary Figure 6). The general trend under cover crops appears to be positive, with moderate variability. The interaction effect between cover crop type and fertiliser regime was found to be a significant factor in explaining the variability, with particularly high values recorded under zero N and cereal and mixed cover crops. The emergence of stronger effects under unfertilised conditions limits the applicability of the finding in real-world contexts and suggests fertilization of cash crops overshadows cover crop contributions. Soil total carbon (Ashworth, Allen et al., 2017; He et al., 2019; L. Li et al., 2019; Romaniuk, Beltrán et al., 2018; Zhou et al., 2016), C accumulation rates (Balkcom et al., 2013; García-González, Hontoria et al., 2018; Verzeaux et al., 2016), potentially mineralizable soil C (Cates et al., 2019; Ghimire et al., 2019; Thapa, Ghimire, Acosta-Martínez et al., 2021), soil organic C accumulation (Nivelle et al., 2016; Tautges et al., 2019) all show promising positive trends under cover cropping, but more extensive databases are required to established the existence of unequivocal trends.

As for C/N ratio in topsoil (Alahmad et al., 2019; Ashworth et al., 2020; Chavarria et al., 2018), no trend was detected, which might be the logical consequence of mild increases in soil N previously discussed.

The global picture for soil C metrics was generally positive for cover crops, although even long-term trends appear to be low in magnitude. The contribution of cover crops can come directly through deposition of recalcitrant C (Landriscini et al., 2020), as well as from increased exudates following more vigorous growth in the following cash crop

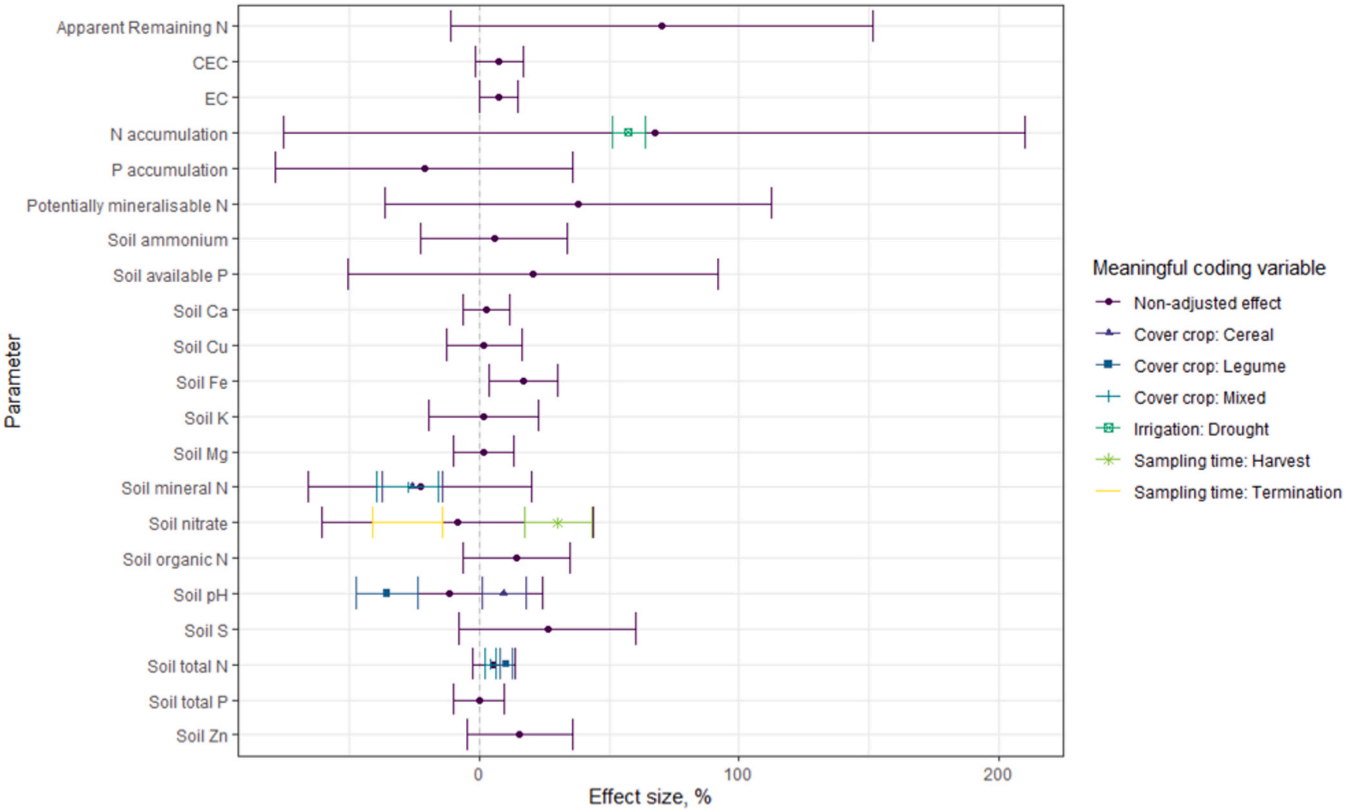

Fig. 2. Effect size, expressed in percentage variation over the bare fallow control, for a range of soil chemistry variables. The error bar refers to standard deviation. In cases where a substantial number of publication was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented.

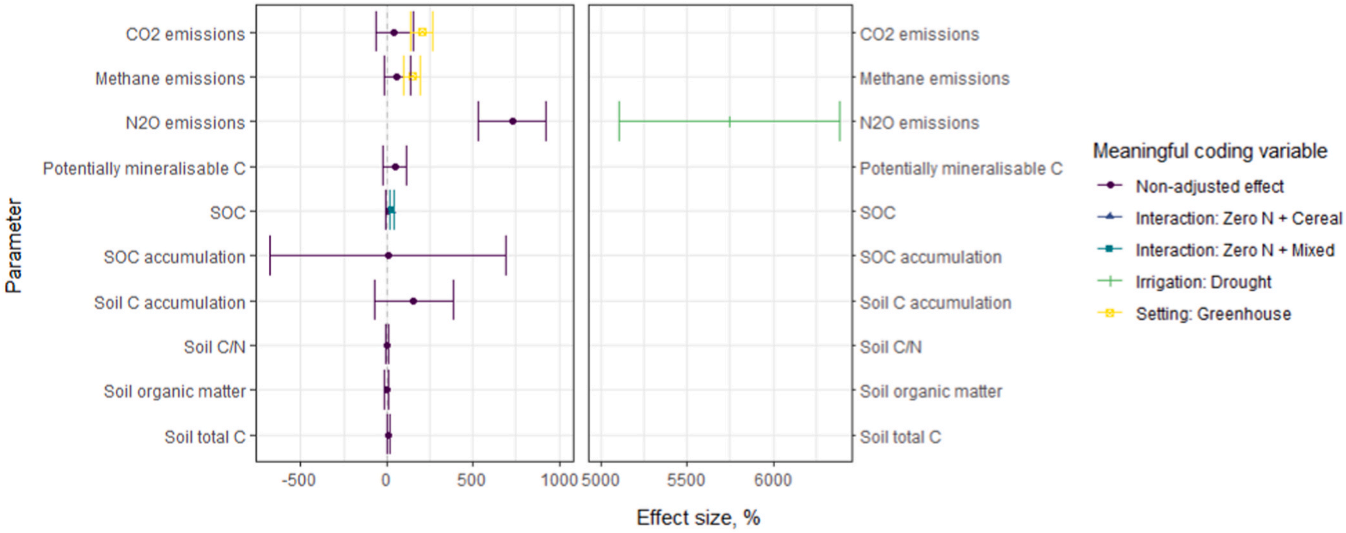

Fig. 3. Effect size, expressed in percentage variation over the bare fallow control, for a range of carbon and greenhouse gas emission variables. The error bar refers to standard deviation. In cases where a substantial number of publication was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented.

(Treseder et al., 2015).

On the other hand, a totally different picture emerges from synthesising greenhouse gas emission data (Fig. 3, Table 1). For carbon dioxide (Supplementary Figure 7) and methane, strong increase trends under cover cropping are detected. In both cases though, the detrimental effect of cover crops in exacerbating emissions was recorded as more pronounced in greenhouse settings as opposed to field trials.

As for nitrous oxide (Supplementary Figure 8), the recorded increase is even larger in magnitude across a substantial number of publications. In this case, though, the main coding factor to explain the variability in outcomes emerged as the watering regime. Under drought treatments an increase by an order of magnitude in the severity of the emissions is recorded.

The global picture for cover crops from an emission point of view has worrying elements. The losses to atmosphere from crop decay appear to be not negligible, and need to be weighted against potential increases of carbon deposition rates in soil, or indirectly against possible yield gains. On the other hand, there is still substantial variability in the results, with huge differences depending on the experimental setting. There is ample scope for additional research to clarify whether the higher values measured in greenhouse conditions are due to more rigorous methodological control or if they fail to actually represent conditions in the field.

3.4. Hydrology and soil structure

The effect of cover crops on hydrological parameters is two-sided (Fig. 4, Table 1). On one hand, reduced water availability after crop termination, one of the most feared negative effects of cover cropping emerges very clearly by synthesizing available data (Supplementary Figure 9). The global effect is of moderate magnitude, but without substantial variability. Cover crop type emerges as a significant factor for explaining variability, with more severe effects in the case of cereal cover crops and milder ones in the case of legume cover crops.

On the other hand, the data concerning infiltration, conductivity and the reduction of leachate paint a much more positive picture. Total drainage (Gabriel et al., 2012; Gabriel et al., 2014; Meisinger and Ricigliano, 2017; Norberg and Aronsson, 2020a; Salazar et al., 2019), eroded sediment (Blanco-Canqui et al., 2013; S. Mohammed et al., 2021), surface runoff (Drury et al., 2014; S. Mohammed et al., 2021), runoff N (Blanco-Canqui et al., 2013; Drury et al., 2014), total leached N (J. L. Gabriel et al., 2012; Meisinger and Ricigliano, 2017; Norberg and Aronsson, 2020a), dissolved total N (Fraser et al., 2013; G. Singh et al., 2019; Tosti et al., 2014), C (Jahangir et al., 2014; Salazar et al., 2019; Sanz-Cobena et al., 2014) and inorganic N (Jahangir et al., 2014; Salazar et al., 2019; G. Singh et al., 2019) all show promising, if not uniform, reduction trends. Even for legume cover crops, the danger of increased N leaching is rarely reported in literature. Hydraulic conductivity also shows beneficial effects of cover cropping, whereas the outcome for water infiltration rate seems highly dependent on the setting of the experiment, whether field or greenhouse (Hudek et al., 2021; J. Singh et al., 2020; Steele et al., 2012).

Additional hydrological parameters were investigated in single publications (Table 2). Among the most relevant trends that can be cited are cover crops reducing soil water redox potential (Jahangir et al., 2014), P surface runoff (Blanco-Canqui et al., 2013), the amount of eroded organic matter (S. Mohammed et al., 2021) and the concentration of dissolved salts in leachate (Gabriel et al., 2014). Conversely, time to runoff (Blanco-Canqui et al., 2013), precipitation storage efficiency (Holman et al., 2021) and the concentration of organic N in leachate (Salazar et al., 2019) all showed substantial decreases following cover cropping. In summary, while cover crops are effective at controlling surface runoff and leaching, there is strong supporting evidence for the well-known Achilles' heel of cover cropping in hydrological terms. The decrease of soil water content for cash crop establishment, which depending on stochastic rainfall patterns, can be negligible or have huge impacts on crop development.

As for soil structure, control of erosion, improved infiltration and reduction of leachate are among the most frequently cited benefits of cover crops, and a strongly positive global trend emerges across a variety of parameters. Cover crops have been shown to work in repeatable and mechanistically clear ways. Bulk density under cover cropping shows a promising negative trend, but with one substantial caveat (Supplementary Figure 10). The main driver of variability was identified as the time of sampling. At cover crop termination, the mean modelled effect is strongly in negative territory, while at the time of cash crop harvest the effect switches to a positive one. It appears that cover crops have the potential to relieve soil compaction in the short term, but further mechanical operations can void, or even reverse, the initial effect.

All other soil structural parameters show a common pattern, albeit not supported by large numbers of publications. Dry aggregate mean diameter (Blanco-Canqui et al., 2013, 2014), macroaggregates (Blanco-Canqui et al., 2011; Blanco-Canqui and Jasa, 2019; Harasim et al., 2020; Oliveira et al., 2019; Yao et al., 2019), macropores (Hudek et al., 2021; Çerçioğlu, 2020; Restovich et al., 2019; Singh et al., 2020), total porosity (Çerçioğlu, 2020; Harasim et al., 2020; Haruna, 2019), mean weight diameter (MWD; Blanco-Canqui et al., 2011, 2013, 2014; Blanco-Canqui and Jasa, 2019; Zhang Dabin et al., 2016; Kelly et al., 2021;

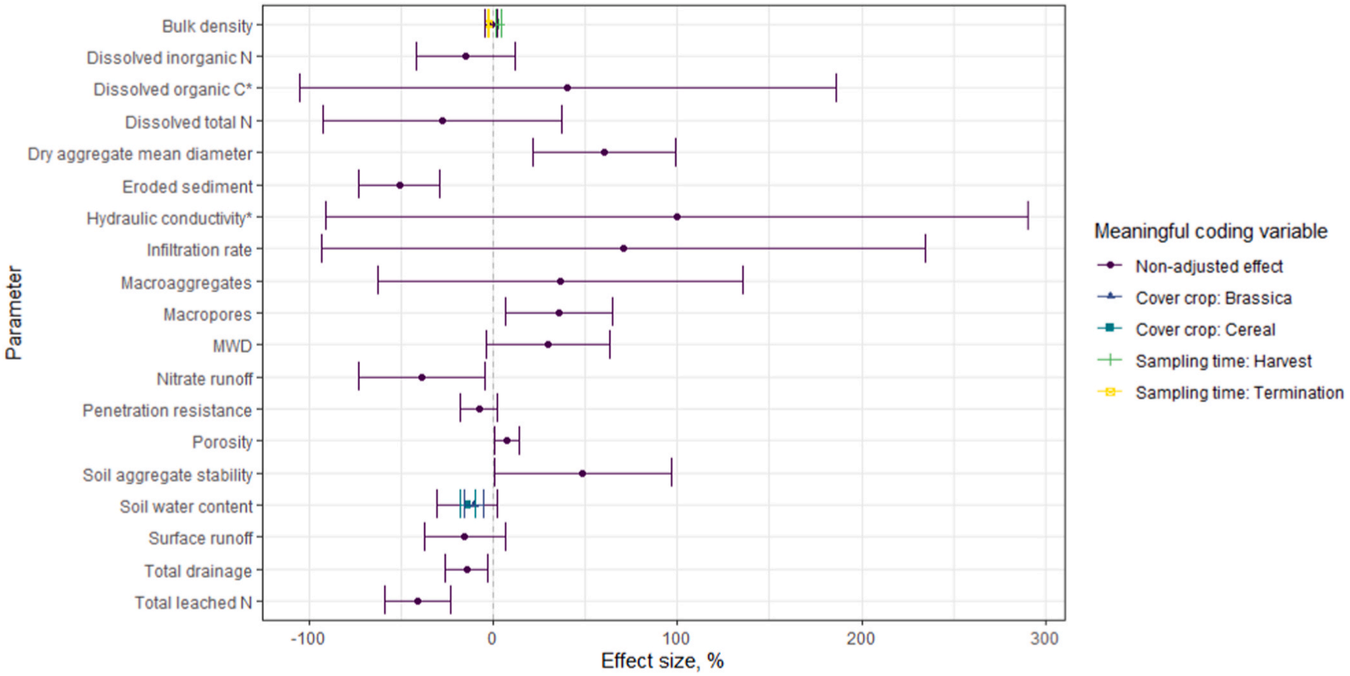

Fig. 4. Effect size, expressed in percentage variation over the bare fallow control, for a range of hydrology and soil structure metrics. The error bar refers to standard deviation. In cases where a substantial number of publications was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented. The parameters marked.

Yao et al., 2019), soil aggregate stability (García-González et al., 2016; Hudek et al., 2021; Restovich et al., 2019; Sapkota et al., 2012; J. Singh et al., 2020; Steele et al., 2012) all show a generalized trend of enhancement under cover crops. Conversely, the overall impact of cover crops on soil penetration resistance seems to be a negative one (Gabriel et al., 2021; Harasim et al., 2020; Moitzi et al., 2021; Singh et al., 2020).

Among the additional parameters taken into consideration, which were the object of a single study (Table 2), the estimation of wind erodible soil fraction, found to be significantly lower in cover crop rotations under no till, is particularly noteworthy (Blanco-Canqui et al., 2013).

As with hydrological parameters, improvement of soil structure through root development under cover crops is well supported and has been ascertained from the microscopic to landscape scale. However, additional operations needed to terminate and integrate the cover crop have the potential to undo most of the gains, in particular when mechanical termination or standard ploughing prior to drilling are required, as cash crop measurements show a substantial decline.

3.5. *Weed and pest control*

The effect of cover crops on weed control appeared to be overwhelmingly positive (Fig. 5, Table 1), with a substantial number of studies and only a handful of observations seeming to contradict the general trend in weed biomass (Supplementary Figure 11). The large variability in outcome was partly explained when fitting a model including the interaction effect between experimental setting and sampling time. Detrimental effects of cover crops in greenhouse settings at cash crop harvest time were observed, whereas in the field at cover crop termination the modelled mean effect on weed biomass is negative and large in magnitude.

The literature on other weed control parameters is more limited but shows the same beneficial effects of cover cropping. Weed cover (Büchi et al., 2020; Dorn et al., 2015), density (Kadziene et al., 2020b; Masilionyte et al., 2017; Ranaldo et al., 2020), diversity (Alonso-Ayuso et al., 2018; Musunda et al., 2015) and emergence (Cordeau et al., 2015; Vipan Kumar et al., 2019) all show contractions following the use of cover cropping.

Fusarium prevalence was the subject of two papers, with opposite findings. On one side Kadziene et al. (2020a) found that a mustard cover crop was instrumental in reducing Fusarium infestation the following year. On the opposite Walder et al. (2017) demonstrated that a vetch cover crop can act as a host bridge and facilitate infestation in the following season.

Three publications focused on pest predation rate in the presence of cover crops, with two (Fox et al., 2016; Rowen and Tooker, 2021) supporting the hypothesis of a neutral effect of cover crops on predation and one (Lundgren and Fergen, 2011) reporting substantially increased predation activity.

Among the most relevant findings emerging from metrics covered by single papers, it is worth mentioning the strong suppressing effect of cover crops on the previous cash crop volunteers (Masilionyte et al., 2017), the stimulating effect of cover crop residue in the production of pest-defence compounds on the part of cash crop plants (Malone et al., 2020) and their general reduction of disease index (Mielniczuk et al., 2020). Additionally, the effect of cover crop on the emergence of specific weeds was found to be strongly species dependent (Tabaglio et al., 2013).

There is little doubt that cover crops in their growth phase can suppress weed growth by outcompeting weeds present in the soil seedbank and limiting their access to light and resources. However, the evidence for legacy effects of cover crops in the following cash crop season is not as extensive. Successful application of herbicides for termination of the cover crop likely plays a bigger role in suppression than the cover crop residue itself.

3.6. *Soil enzymes and metabolism*

Soil enzyme activity seems to be enhanced by cover cropping across the whole range of commonly measured markers, and irrespective of the type of cover crops included in the rotation (**Fig. 6** , **Table 1**).

Acid (Chavarria et al., 2018; Higo et al., 2020; Housman et al., 2021; Papp et al., 2018) and alkaline phosphatase (Zhang Dabin et al., 2016; García-González, Hontoria et al., 2018; Higo et al., 2020; Housman et al., 2021; Melero et al., 2011; Thapa, Ghimire, and Marsalis, 2021), arylsulfatase (Zhang Dabin et al., 2016; Housman et al., 2021; Papp et al., 2018; J. Singh and Kumar, 2021b), beta glucosaminidase (Calderón et al., 2016; García-González et al., 2016; Housman et al., 2021; Thapa, Ghimire, and Marsalis, 2021), cellulase (Gregorutti and Caviglia, 2019; Piotrowska-Długosz and Wilczewski, 2015), dehydrogenase (Zhang Dabin et al., 2016; Harasim et al., 2020; Melero et al., 2011; Nivelle et al., 2016; Wang et al., 2020) and protease

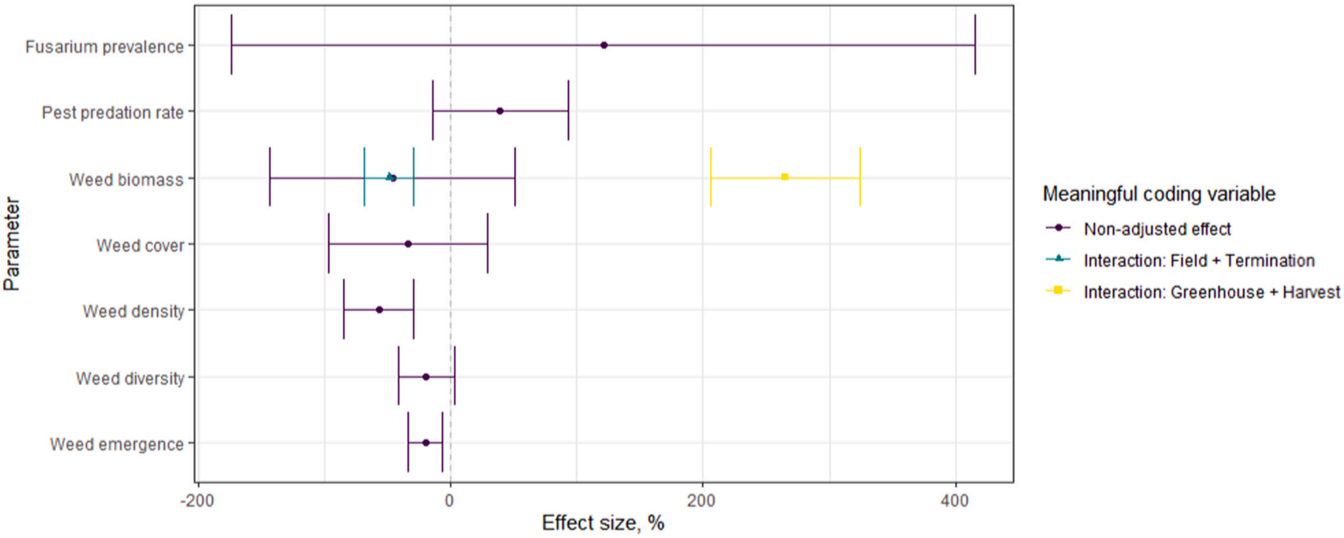

Fig. 5. Effect size, expressed in percentage variation over the bare fallow control, for a range of weed and pest control metrics. The error bar refers to standard deviation. In cases where a substantial number of publications was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented. For variables marked with an asterisk, the real recorded effect is ten times larger than shown.

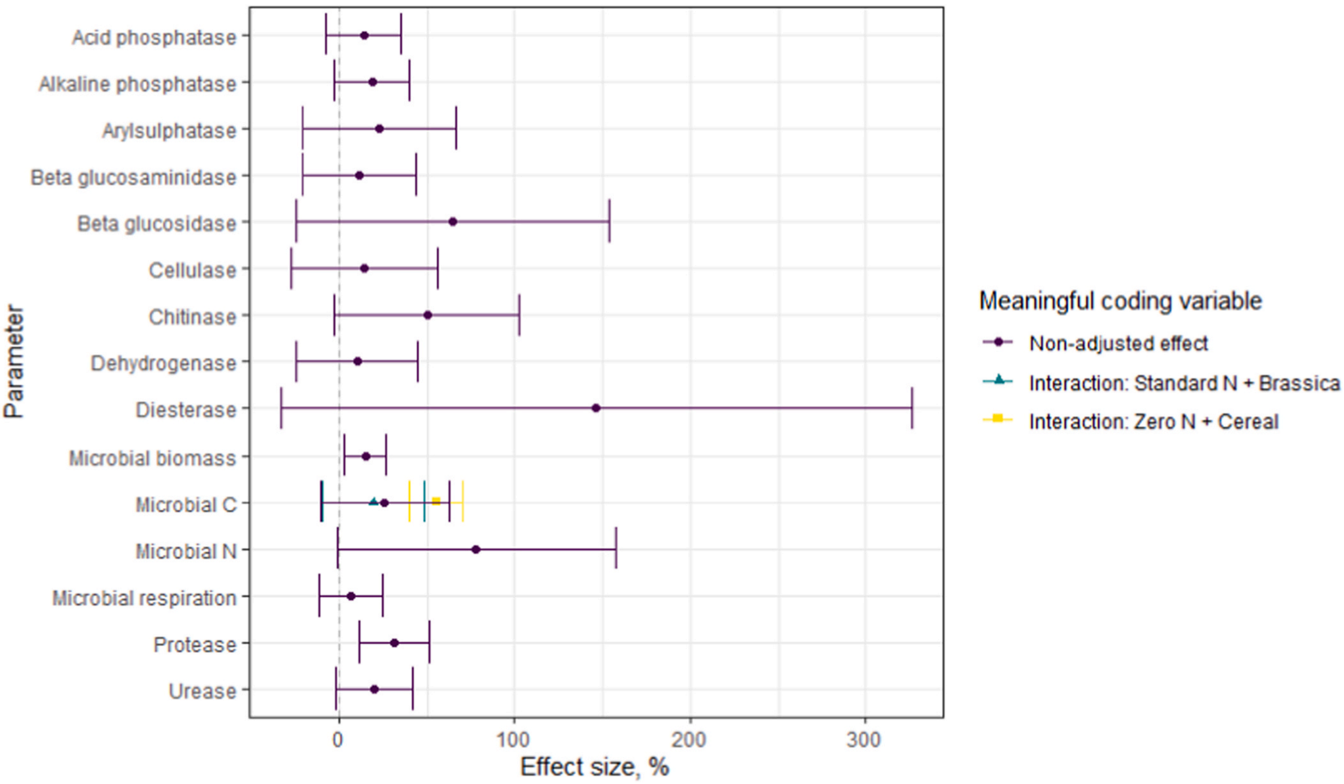

Fig. 6. Effect size, expressed in percentage variation over the bare fallow control, for a range of enzyme activity and metabolism metrics. The error bar refers to standard deviation. In cases where a substantial number of publications was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented.

(Piotrowska-Długosz and Wilczewski, 2014; Wang et al., 2020) activity all show moderate but uniform increases following cover cropping. Beta glucosidase (Calderón et al., 2016; Higo et al., 2020; Housman et al., 2021; Maltais-Landry, 2015a; Piotrowska-Długosz and Wilczewski, 2015; J. Singh and Kumar, 2021a), chitinase (Maltais-Landry, 2015a; Papp et al., 2018), and especially diesterase (Calderón et al., 2016; Maltais-Landry, 2015a) show increases of even higher magnitude, albeit with substantial variability, whereas urease is the only enzyme where, in addition to a generalized increase (Zhang Dabin et al., 2016; Harasim et al., 2020; Nivelle et al., 2016; J. Singh and Kumar, 2021b; Wang et al., 2020), instances of the opposite trend are also represented (Piotrowska-Długosz and Wilczewski, 2014).

Microbial respiration (Cates and Jackson, 2019; Chavarria et al., 2018; Piotrowska-Długosz and Wilczewski, 2015; Sapkota et al., 2012) was not found to show a uniform and significant increase with cover cropping. More substantial is the evidence of an increase for microbial biomass (Singh & Kumar, 2021; Thapa et al., 2021; Xu et al., 2020) and microbial N (Baldivieso-Freitas et al., 2018; Papp et al., 2018; Piotrowska-Długosz and Wilczewski, 2014; Singh & Kumar, 2021; Wang et al., 2020; Zhou et al., 2016), whereas the picture for microbial C is more complex (Supplementary Figure 12). The large variability was tested in many models, with the interaction between fertiliser regime and cover crop type yielding the best results as a predictor. Brassicas under standard fertilisation predicted a strongly negative effect, possibly mediated by isothiocyanates, against the bare fallow control, whereas the figure for cereal cover crops under zero fertilizer is positive and large in magnitude.

Of the parameters assessed by a single paper only, it is worth reporting the significantly enhanced levels of sucrase (Wang et al., 2020), monoesterase (Maltais-Landry, 2015a), invertase (Zhang Dabin et al., 2016) and nitrate reductase (Piotrowska-Długosz and Wilczewski, 2014) in presence of cover crops.

Overall, the beneficial influence of cover cropping when it comes to stimulating soil biotic activity and metabolism is apparent. However, more research is needed to establish whether this effect carries over with measurable benefits to the following cover crop or is just a transient phenomenon of limited relevance occurring just in the growth phase or soon after termination.

3.7. *Bacteria and fungi*

Both bacterial and fungal populations seem in general terms to be enhanced by cover cropping, but to different extents and some important trends linked to fertiliser use (Fig. 7, Table 1).

Total bacterial abundance is a parameter that was estimated across several publications (Karasawa and Takahashi, 2015; J. Singh and Kumar, 2021a; Somenahally et al., 2018; Thapa, Ghimire, and Marsalis, 2021; Wang et al., 2020; Xu et al., 2020) with significantly higher values associated to cover crops. This holds true for both Gram-positive (Calderón et al., 2016; Singh and Kumar, 2021a). and Gram-negative bacteria (Calderón et al., 2016; Thapa, Ghimire, Acosta-Martínez et al., 2021), although just under active cover crops and not the following cash crop.

Among bacterial phyla that were found to be enhanced under the cover crop phase of rotations are actinobacteria (Calderón et al., 2016; Singh and Kumar, 2021a; Thapa, Ghimire, Acosta-Martínez et al., 2021; Wang et al., 2020; Xu et al., 2020), whereas no significant effect was found on Gemmatimonadetes (Alahmad et al., 2019; Ashworth et al., 2017) and Bacteriodetes.

Only two publications provided data for Gemmatimonadetes and Bacteriodetes (Alahmad et al., 2019; Ashworth et al., 2017), with six single comparisons indicating a neutral effect of cover crops. Two papers quantified Proteobacteria and Verrucomicrobia abundance, with Ashworth, DeBruyn et al. (2017) reporting a neutral effect after legume and cereal cover crops and Alahmad et al. (2019) a marked decrease in Proteobacteria and a sharp increase in Verrucomicrobia following a

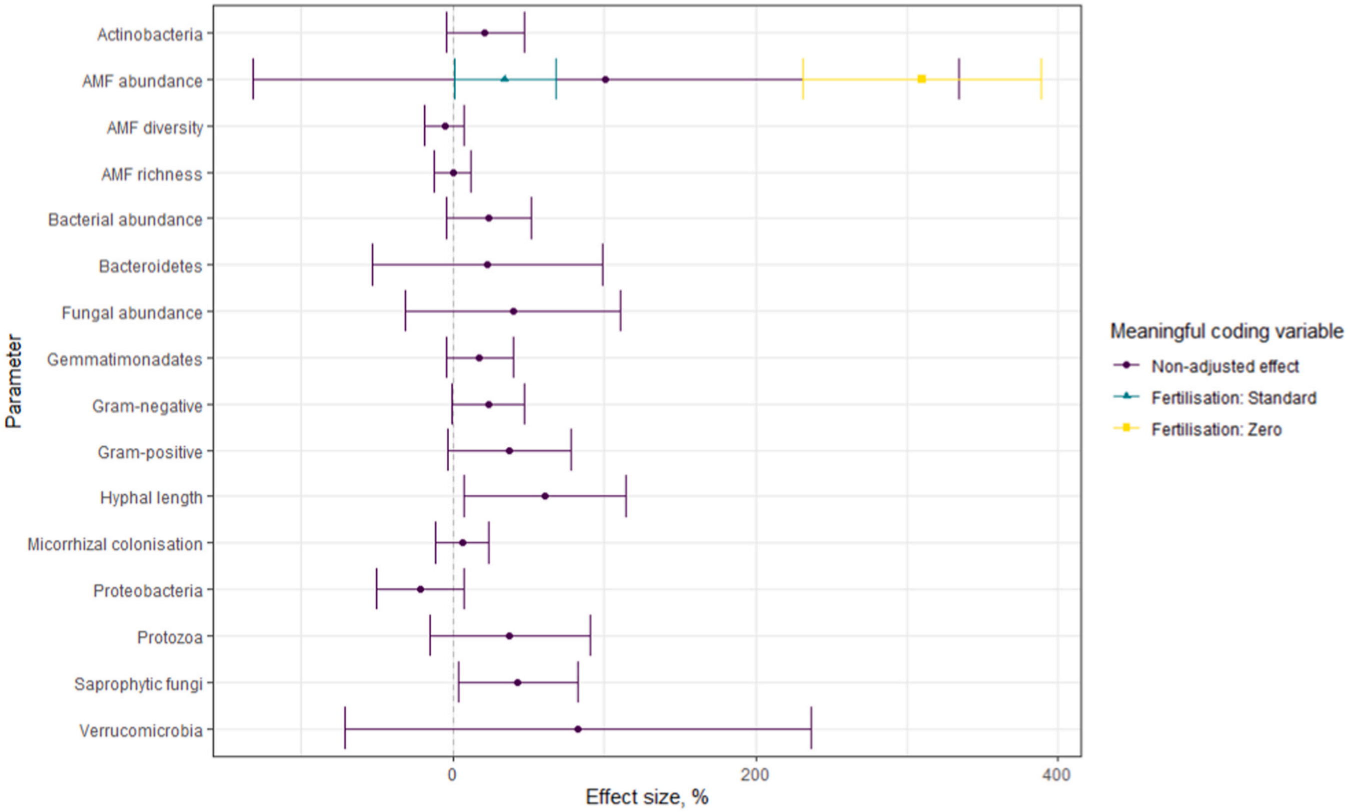

Fig. 7. Effect size, expressed in percentage variation over the bare fallow control, for a range of bacterial and fungal metrics. The error bar refers to standard deviation. In cases where a substantial number of publications was available and a model was fitted, the modelled mean and standard error for the variable resulted as significant in the ANOVA is presented.

cover crop mixture.

Data for Protozoa, estimated through PLFA markers, followed a trend common among bacterial clades (Calderón et al., 2016; Thapa, Ghimire, Acosta-Martínez et al., 2021; Xu et al., 2020), with instances of enhancement recorded only at cover crop termination.

As for fungi, overall abundance (Karasawa and Takahashi, 2015; Mielniczuk et al., 2020; Somenahally et al., 2018; Thapa, Ghimire, Acosta-Martínez et al., 2021; Wang et al., 2020; Xu et al., 2020) appears to be generally enhanced by cover crops, with a single instance of the opposite happening after a Brassica cover crop. Within fungi, saprophytes, whose abundance was estimated with PLFA markers (Calderón et al., 2016; J. Singh and Kumar, 2021a; Thapa, Ghimire, Acosta-Martínez et al., 2021) were also found to be benefited by cover cropping, but the evidence of the effect extending to the following cash crop season is very limited.

Arbuscular mycorrhizal fungi (AMF) have unsurprisingly been the object of substantial scrutiny. AMF abundance was measured in a substantial corpus of works (Supplementary figure 13), with a nearly universal growth recorded under cover crops. However, the trend comes with substantial variability. This can be partly explained by fitting a model with fertiliser regime as a fixed effect. Unfertilised treatments recorded large-magnitude AMF growth when associated to cover crops, compared to a much more modest modelled effect for conventionally fertilised crops.

It is remarkable that increases in AMF abundance are not accompanied by enhanced diversity and species richness (Higo et al., 2018, 2019, 2020; Hontoria et al., 2019). Both hyphal length (García-González et al., 2016; García-González, Quemada et al., 2018; Hontoria et al., 2019) and mycorrhizal colonization (García-González, Quemada et al., 2018; Housman et al., 2021) seem to show a crop-specific pattern, with enhancement observed under legume – as opposed to cereal – cover crops.

Among markers measured in single papers, particularly noteworthy are the increased Acidobacteria, Burholderiales, Sphingobacterial and Thermomicrobia abundance (Xu et al., 2020) and higher levels of microbial P (Dube et al., 2014) associated to cover crops.

As with other biotic activity parameters, there is strong evidence that cover crops during their growing phase can enhance microbial communities. The persistence in time of this effect, beyond termination, tillage and the following cash crop season is not as widely supported. As for AMF and fungal development, in addition to a beneficial effect of legumes, which are probably capable of stimulating mutualistic relations within soil better than cereal or Brassica species, it is worth noticing that the most striking effects are obtained in unfertilised contexts, which are very unusual in common agricultural practice. Unsurprisingly, the application of fertiliser is a strong negative driver for AMF.

3.8. *Biodiversity*

All parameters evaluated within this category are only mentioned in single papers (Table 2). The lack of research on biotic aspects other than microbial is one of the most striking findings of the present analysis.

Earthworm numbers were found to be substantially increased by cover crops (Blanco-Canqui et al., 2011), but also a reduction in endogeic earthworms was recorded (Ashworth et al., 2017). Both bird diversity and bird abundance were found to be increased at landscape level by cover crops (Wilcoxen et al., 2018). However, the diet of a species of commercial importance such as the Grey Partridge was found to be less varied in presence of cover crops (Orlowski et al., 2011), sustaining the importance of winter stubble for conservation. The spontaneous regrowth of wild species in bare fallow plots increased overall floral richness for the benefit of pollinators compared to cover crops (Bryan et al., 2021), but the presence of cover crops was associated with higher levels of soil invertebrate species richness, although not of diversity (Ashworth et al., 2017).

4. Discussion

With the benefit of hindsight and given the importance of quantitative synthesis in the fields of agriculture and food production, it becomes clear that a common standard in terms of data reporting and experimental coding should be considered for future research. The adoption of such a system by publishers would allow a full implementation of meta-analytical protocols and make compiling large synthetic datasets a less strenuous undertaking. Nevertheless, the quantitative approach adopted in the present work helped highlight a number of relevant issues. Substantial variability is apparent across variety of key parameters. However, the systematic nature of the quantitative review approach allows us to identify some coherent patterns.

From a general point of view, it is possible to identify several processes in the cover crop literature of recent years (Fig. 8). First of all, the renewed interest in cover crops is apparent in the steady growth of yearly publications, even within the shifting framework of paper inflation. Second, the proportion of publications dealing with legume cover crops and cover crop mixtures as opposed to cereal and brassicas has increased over time, indicating a shift in agricultural practice, which is reflected in the generally more positive outcomes involving these rotations. Third, the instances of cover crops failing to deliver substantial benefits compared to the bare fallow alternative tend to be concentrated around very specific clusters of parameters, including water balance, greenhouse gas emissions and -critically – crop performance; conversely, biotic activity, weed control and soil structural properties show almost without exceptions the beneficial potential of cover crops.

From a global land-use perspective, cover crops show potential to replenish soil C stocks and be an important asset in the toolkit of carbon farming (Keenor et al., 2021). However, gains seem to be quantitatively small and probably constrained by photosynthetic structural limits (Janzen et al., 2022). Moreover, data pertaining to all major GHG components from arable land indicate the existence of a potential trade-off, linking the presence of crop residue to increased emissions. This phenomenon seems to be observed more strongly in experiments carried out in controlled conditions. It is envisaged that refinements of field scale techniques (Xie et al., 2022) will clarify whether the discrepancy is an artifact of controlled conditions or a failure to accurately detect losses with previously used field methods.

Another relevant trend is that the magnitude of the change compared to the bare fallow treatment is almost invariably highest during the cover crop rather than during the subsequent cash crop phase. This is particularly true for biotic factors, from enzymatic activity to the abundance of specific bacterial or fungal clades. Such a phenomenon can be explained partly by the decreasing influence of crop residue as it degrades in the soil, as well as the uniforming effect of following practices, chiefly mechanical stress from termination and seed drilling (Coulibaly et al., 2022), as well as the reversion to monoculture in the case where preceding cover crops were composed of multiple species. The key to the success of cover crops is their effects can persist as a legacy during the cash crop season, and possibly accumulate marginal benefits on a yearly basis to result in long term trends.

Biotic indicators in general tend to perform more strongly when cover crops are associated to reduced use of fertilizer and less intensive tillage. A similar effect is crucially observed also for yield. Within the dramatic variability induced by climate and environmental factors, reduced tillage and the use of legume cover crops, or mixtures including legumes can be identified as the most promising drivers of positive outcome. This reinforces the idea that the integration of cover crops within low-input systems is key to their successful implementation from a land-use perspective (Porwollik et al., 2022). Ultimately, the conventionalization of cover crops will largely depend on the ease of obtaining reliable gains in yield and economic margins. Identifying the conditions that make these possible is key to the success of cover crops, and the present work indicates clear preferential pathways for further research.

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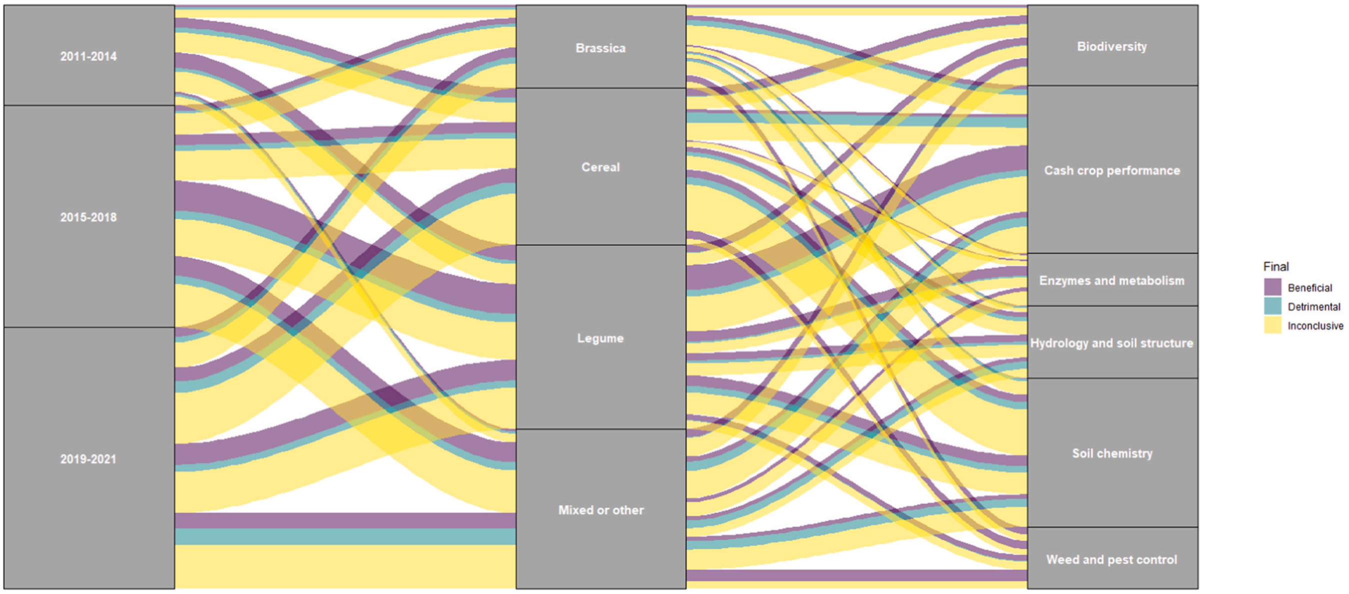

Fig. 8. Alluvial plot showing the outcome and distribution of cover crop / bare fallow comparisons per year, cover crop and metric category. The width of flow lines is proportional to the number of single comparisons.

CRediT authorship contribution statement

Sims Ian: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Miller Anthony John:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Fioratti Junod Marco:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Reid Brian:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anthony J Miller reports financial support was provided by Biotechnology and Biological Sciences Research Council, and the Department for Environment, Food and Rural Affairs. Marco Fioratti reports financial support was provided by John Innes Centre.

Data Availability

No data was used for the research described in the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105997.

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