



Cover crop legacy impacts on soil water and nitrogen dynamics, and on subsequent crop yields in drylands: a meta-analysis

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Abstract

Cover crops can provide a wide range of ecosystem services including soil water conservation, improved soil nutrient supply and retention, and enhanced crop yields. However, achieving these services in dryland cropping systems can be highly challenging, and cover crops may carry a greater risk of causing ecosystem disservices. Assessment of the balance of ecosystem services vs disservices is critical for understanding the potential role of cover crops within dryland cropping systems. The objective of this meta-analysis was to assess the effects of cover cropping in drylands on soil water and soil mineral nitrogen content at sowing of subsequent cash crops and their yields compared to control fallows. A total of 38 articles were examined, for a total of 1006 cash crop yield, 539 soil water, and 516 soil mineral nitrogen independent studies, spanning the period 1994–2021. On average, cover cropping reduced cash crop yield by 7%, soil water content by 18%, and soil mineral nitrogen by 25%, with significant variation across climates, soil types, and crop management conditions. Subsequent cash crop yields changed by +15, +4, -12, and -11% following cover crops in tropical, continental, dry, and temperate dryland climates, respectively. The most significant yield benefits were proportionate to soil water content and soil mineral nitrogen at the time of cash crop sowing. This is the first meta-analysis to demonstrate that minimum annual precipitation of ~700 mm represents a “break-even” point to realize significant cash crop yield benefits of cover cropping compared to control fallows in dryland environments. The successful incorporation of cover crops into dryland cropping systems requires careful planning based on context-specific biophysical conditions to minimize trade-offs between ecosystem services and disservices.

Keywords Crop rotation · Ecological intensification · Ecosystem services · Fallow · Trade-offs

1 Introduction

Dryland regions are characterized by climatic water scarcity and an aridity index of < 0.65 (Mortimore 2009; He et al. 2016; Právělie 2016). Annual precipitation in dryland regions is often unpredictable and accounts for 20–35% of potential evapotranspiration (Stewart and Liang 2015). With increasing water deficit and climate variability, these “water-limited” regions require efficient capture and use of the most limiting resource—water—to maximize their productivity and sustainability. Fallowing—the practice in which a field is left out of

production for some part of or the entire growing season—is commonly adopted in water-limited environments. The purposes of fallowing are to maximize soil water storage and mineral nitrogen (N) for subsequent cash crops (Flower et al. 2012; Aiken et al. 2013; Reese et al. 2014a), break crop disease cycles (Fletcher et al. 2016; Robertson et al. 2018), and minimize risk of crop failure and stabilize yields (Nawaz and Farooq 2016; Pinto et al. 2017; Ghimire et al. 2018). Dryland cropping systems found in sub-tropical Australia and North America include a long fallow (14–16 months) followed by a summer cash crop, or a short fallow (6–8

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months) followed by a winter cash crop (Bell et al. 2006; Ghimire et al. 2018). However, fallowing is relatively inefficient in conserving soil water (i.e., < 30% of rainfall is used by crops) and soil mineral N. Fallowing also poses increased risks to the environment from erosion and potential leaching (Tonitto et al. 2006; Nielsen et al. 2017). Fallow efficiency (the proportion of fallow precipitation that is stored as plant-available water) and precipitation storage efficiency (fraction of precipitation that is stored in the soil) are often 25–35% in conventional fallows (Aiken et al. 2013; Erbacher et al. 2019). Moreover, fallowing is associated with decreased soil organic matter and nutrients (Blanco-Canqui et al. 2013; Duval et al. 2016), increased soil erosion, weed pressure, herbicide use, and soil water loss (Schillinger et al. 2010; Lyon et al. 2007; Wunsch et al. 2017; Daryanto et al. 2018; Martín et al. 2018), and decreased system water use efficiency (Deng et al. 2020).

One approach used to minimize the adverse effects of fallowing is to intensify the crop sequence by replacing a “portion” of the fallow period with non-cash crops, i.e., with cover crops (Fig. 1). Cover crops are increasingly considered as a critical component of the ecological intensification of cropping systems (Bommarco et al. 2013; Kleijn et al.

2019). Cover cropping has been an integral part of dryland crop rotations in many regions of the world for many decades, providing a range of ecosystem services such as water conservation (Lyon et al. 2007; Wunsch et al. 2017; Daryanto et al. 2018), N supply and retention (White et al. 2017; Wunsch et al. 2017), weed suppression (Schipanski et al. 2014; Ghimire et al. 2018), soil nematode break (Claudius-Cole et al. 2014; Jaffuel et al. 2017), and mitigation of nitrate leaching (Kaspar et al. 2012; Couëdel et al. 2018). In the long term, cover crops can increase soil organic carbon (SOC) and N (Bommarco et al. 2013; Poeplau and Don 2015; Cates et al. 2019) and decrease net N₂O and CO₂ emissions, thus providing climate change mitigation services (Kaye and Quemada 2017; Abdalla et al. 2019). More recently, the “Soil Carbon 4 per mille initiative (<https://www.4p1000.org/>)” has posited that cover cropping can improve SOC stocks and potentially contribute to climate stability and food security (Minasny et al. 2017). However, cover crops can also potentially introduce ecosystems disservices (i.e., derived negative effects), such as depletion of soil water and nutrients available for subsequent cash crops, reduction in cash crop yield, and increased management cost (Finney et al. 2017). Therefore, the

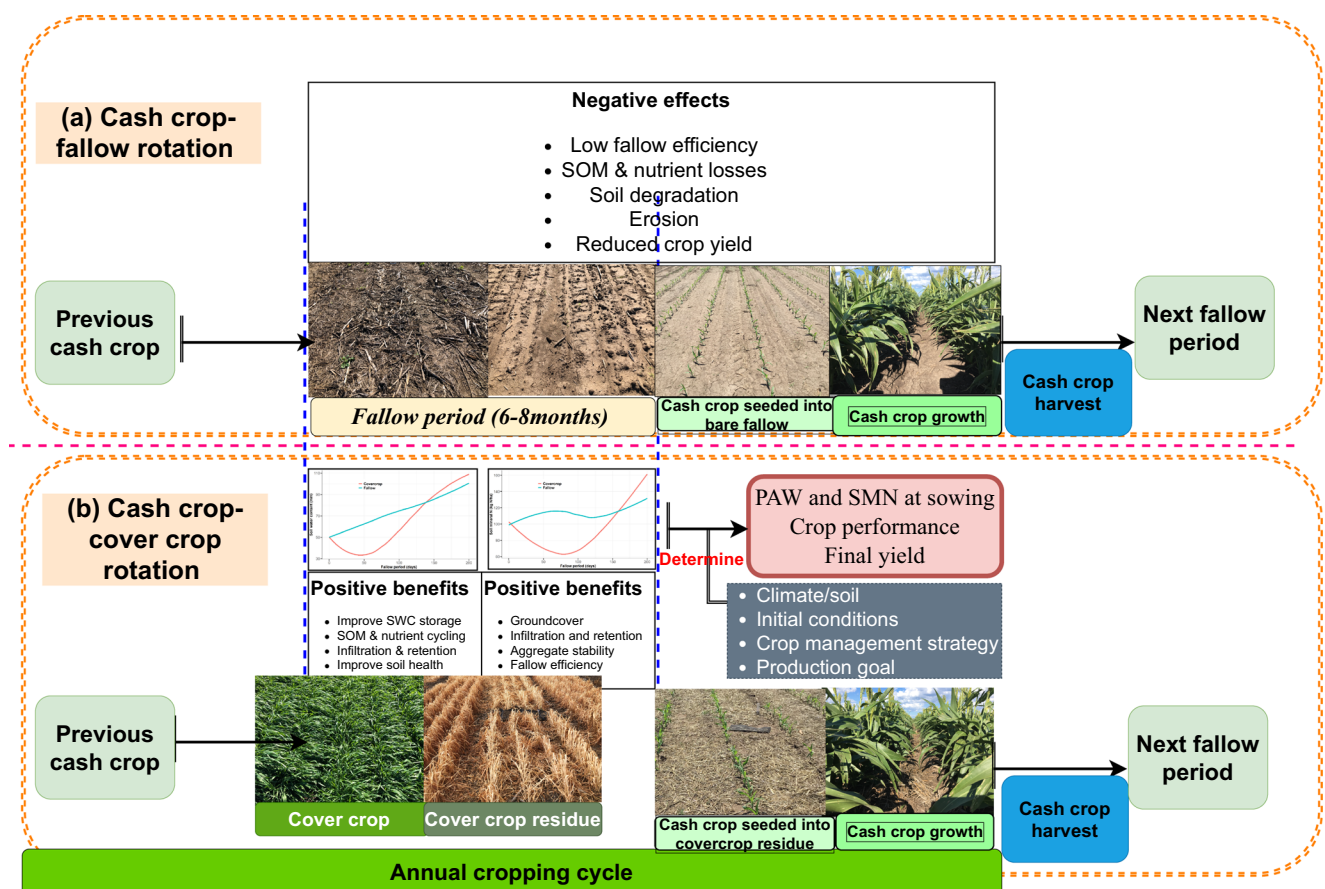


Fig. 1 Conceptual comparison of (a) a typical cash crop-fallow rotation, (b) a cover crop replacing a portion of the fallow periods within a typical annual rotation. The $y \sim x$ graphs show the potential soil water and N

dynamics within the fallow period for the crop-fallow rotation and cash crop-cover crop rotation. SOM soil organic matter; SWC soil water content.

introduction of cover crops to replace or reduce a portion of fallow periods requires management to mitigate these potential disservices in water-limited environments. This is because crop production in such regions is opportunistic, and the risks and economics associated with expected precipitation and soil water storage dictate cropping decisions.

Although many studies have documented various ecosystem service benefits from cover crops, there are many discrepancies and inconsistent results across different dryland areas due to the wide climate variability and fragility of these systems. The literature on the effect of dryland cover crops on subsequent cash crop yields generally lacks consensus. Results have ranged from negative, neutral, and positive effects on subsequent cash crops across various climates and crop management conditions. For example, while cover crops led to a 13% increase in wheat yield in a semi-arid continental climate in China (Zhang et al. 2016), a 31% yield reduction was observed in a dry climate in the USA (Aiken et al. 2013). Furthermore, while cover cropping can deliver a wide range of ecosystem services, it can also generate disservices. The potential trade-offs between cover crop-derived ecosystem services and disservices have not been thoroughly examined in dryland cropping systems. Complexity in seasonal and inter-annual variability in precipitation, residue decomposition, soil biophysical properties, and interactions with crop management histories makes it challenging to predict dryland crop yield responses to cover cropping. There remain fundamental knowledge gaps in terms of how cover crop species selection, timing and method of cover crop sowing and termination, and fertilization and tillage practices interact in a water-limited environment to affect soil water and N conservation and cash crop productivity. Narrowing these knowledge gaps is critical for understanding the sustainability of cover cropping in drylands agroecosystems in the context of ecological intensification.

Many studies have reported the use of fallow replacement cover crops across a range of environments. There are several attempts to unravel the complexities and inconsistent results from utilizing cover crops in dryland cropping systems. As a quantitative approach, meta-analysis has been used to investigate patterns in cropping system performance (Philibert et al. 2012; Krupnik et al. 2019). Other meta-analyses have reported on the relationship of cover cropping with subsequent cash crop yields (Marcillo and Miguez 2017; Toler et al. 2019), weed suppression (Toler et al. 2019), soil water and N dynamics (Tonitto et al. 2006; Thapa et al. 2018), and greenhouse gas emissions (Abdalla et al. 2019). However, these meta-analyses were typically limited to specific climatic conditions or cash crop types. For example, a previous meta-analysis focused on maize yield responses to cover cropping in the US and Canada which found neutral to positive effects (Marcillo and Miguez 2017). More recently, a global meta-analysis focused on cotton yield implications revealed that

cover crops increased cottonseed and lint yields by 6% and 5%, respectively, and that such effects were more profound with legume cover crops (Toler et al. 2019). In a global quantitative synthesis of ecosystem services from cover crops, Daryanto et al. (2018) showed cover crops can provide certain ecosystem services but potential disservices are also possible. This necessitates further synthesis to determine the major drivers of these ecosystem services and disservices associated with cover crop adoption, particularly in water-limited environments. Specifically, to our knowledge, no such meta-analysis has assessed the legacy effects of cover crops on soil water and nitrogen and subsequent cash crop yields within water-limited dryland cropping systems, where the constraints of rainfall are likely to create a different trade-off and value proposition than where previous analyses have focussed. The absence of such assessment risks over-generalizing the potential benefits of cover crops.

The objectives of this meta-analysis were to: (i) quantify the effects of cover crops in dryland environments on soil water content and soil mineral N at cash crop sowing and their legacy effect on subsequent cash crop yields; (ii) determine the impacts of environmental conditions and crop management practices on cash crop response to cover cropping in drylands; and (iii) examine the relationship between cash crop response to cover cropping and soil water content and soil mineral N at cash crop sowing in drylands.

2 Materials and methods

2.1 Literature search, selection, and data extraction

From 2 February 2020 to 8 February 2021, a two-tiered literature search for relevant peer-reviewed publications in the Institute for Scientific Information (ISI) Web of Science, SCOPUS, and Google Scholar databases was conducted. Using the search terms (TS): TS= (Cover crop* AND Soil water* OR soil moisture* OR nitrogen* OR yield AND rainfed* OR dryland); or TS= (green manure* AND Soil water* OR soil moisture* OR nitrogen* OR yield AND rainfed* OR dryland); or TS= (catch crop* AND Soil water* OR soil moisture* OR nitrogen* OR yield AND rainfed* OR dryland), a total of 7329 unique publications were retrieved. This was further screened in the second tier based on the defined search criteria and produced 428 articles: SCOPUS (96), Web of Science (185), and Google Scholar (147). In addition, we identified 12 records from conference proceedings that were not identified through the search tools. These records were screened and included in the meta-analysis based on the following criteria: (i) the study was conducted under field conditions; (ii) the study reported a comparison between a control fallow treatment and a similarly managed cover crop treatment differing only in fallow-cover crop management;

(iii) the cover crop species or functional type/family was identified; (iv) subsequent cash crop yield data or soil water and mineral N for treatments under cover crop and fallow were reported; (v) the study specified the number of replications and defined experimental design; (vi) the sampling depth of soil water content and soil mineral N was specified; and (vii) information on measures of variability (e.g., standard error, variance) was provided to allow estimation of the variance of mean values for cash crop yield, soil water content, and soil mineral N. Based on these inclusion criteria, 38 articles published from 1994 to 2021 from nine countries (Supplementary Table S1) were selected. Intercropping or interseeding cover cropping (when cover crops are grown simultaneously with cash crops) was excluded because the focus was on the impact of replacing a portion of the fallow period with cover crops.

A total of 1203 studies (data points comparison between a control fallow and a cover crop treatment) were extracted from the 38 articles, of which 57% were from the USA (688), 14% were from Australia (169), 14% were from Canada (162), 7% were from China (80), 6% were from France (67), 1% from Thailand (12), 1% were from Ghana (15), and <1% were from Spain (6) and Iran (4) (Supplementary Table S2). This process is presented in Supplementary Figure S1 and is based on the updated PRISMA flowchart described in Page et al. (2021). Experimental factors such as cash crop type, tillage, and treatment combinations from different years within an article were examined as independent studies. The choice of soil water content (mm), soil mineral nitrogen (kg N ha^{-1}), and cash crop yield (t ha^{-1}) as the response variables was because the legacy effects of cover cropping are primarily manifested in their effects through soil water content and soil mineral N and their carry-over effect on subsequent cash crop yield. Data were extracted from plots and figures using *Web Plot Digitizer v4.4* (<https://automeris.io/WebPlotDigitizer/>) (Rohatgi 2020) and from tables using *Tabula v1.2.1* (<https://tabula.technology/>) (Aristarán et al. 2018).

We assessed the moderating effects of several environmental and crop management factors on the effects of cover cropping on the three response variables. Moderators were chosen based on their prevalence in the study datasets and their relevance to cover crop management in the context of soil mineral N, soil water content, and cash crop yield. For each study, we extracted the coordinates where the research was conducted and recorded the Köppen climate classification (Kottek et al. 2006) using the Google Earth Pro World Map of the Köppen-Geiger climate classification. Climates were grouped into tropical (Class A), dry/arid/semi-arid (Group B), temperate (Group C), and continental (Group D) climates. Only the first Köppen-Geiger classification was used because some levels had too few observations for valid comparisons when including secondary classification.

We categorized annual water input (precipitation + supplemented irrigation) for each study into five groups: < 300 mm, 300–500 mm, 500–700 mm, 700–900 mm, and > 900 mm, respectively. Soil order was presented as World Reference Base (WRB) for Soil Resources (WRB-IUSS 2014). When soil type was given in the USDA scheme (Soil Survey Staff 2014), they were harmonized using WRB classification. Soils in the Australian Soil Classification system II were harmonized to the WRB scheme based on Hughes et al. (2018).

Tillage practices were categorized into no-till, reduced-till, and conventional tillage. The binary variables of cover crop fertilization (fertilized vs unfertilized), cropping system (organic vs conventional), production system (rainfed vs supplemented with irrigation) were also used as moderating variables. Irrigated production was included to allow for comparison between fully rainfed vs supplementary irrigated systems. We also examined how cover crop type and management modified the effects of cover cropping on the response variables. Within this, cover crops were categorized based on their functional type (Asteraceae vs Poaceae vs Fabaceae vs Brassicaceae vs Mixtures), cover crop termination time (Early termination [< 60 days] vs mid-termination [60–90 days] vs late termination [> 90 days]), and termination method (chemical vs mechanical vs integrated vs frost); where “chemical” refers to termination by herbicide application; “mechanical” includes any studies for which cover crops were green manured or “disked-in” without herbicide; “integrated” comprised termination by herbicide followed by mechanical incorporation; and “frost” was based on studies in which the cover crop was allowed to grow until termination by a killing frost Liebig et al. (2015). The fate of the cover crop residue post-termination (mulched vs rolled vs incorporated vs burnt) was also used as a moderator. To elucidate the effect of cover crop biomass production, cover crop above-ground biomass at termination was grouped into < 1, 1–2, 2–3, 3–4, 4–5, 5–6, 6–7, and > 7 t ha^{-1} . Comparison between cover crop composition (monoculture vs mixture) was also made. In addition, to evaluate whether there were any N fertilizer replacement benefits of cover cropping, the quantity of N fertilizer applied to each cash crop following a cover crop was categorized into ranges of 0–50, 50–100, 100–150, 150–200, and > 200 kg N ha^{-1} (Table 1). The definition and units of these major moderator subgroups can be found in Table 1.

2.2 Response ratio and moderator variables

We used the methodology recommended by Krupnik et al. (2019) to estimate the size of the effect (ES) of cover crops on each of the response variable; soil water content, soil mineral N, and subsequent cash crop yield, where the response ratio of means (RR) was calculated as the natural logarithm [$\ln(R)$] of the ratio of cover crop to fallow control:

Table 1 Description of moderator variables included in the meta-analysis. †Only the first classification was used because some levels had too few observations for valid comparisons when including secondary

classification. ^ Aridity index (AI) was defined as the ratio of rainfall to potential evapotranspiration. CC cover crop.

Moderators	Definition	Categories
Climate type [†]	The climate of the experimental site is classified by Köppen Classification (Amfield 2017).	(i) Tropical (A), (ii) dry/arid/semi-arid (B), (iii) temperate (C), and (iv) continental (D)
Mean annual rainfall (mm)	Mean annual rainfall of the experimental site:year	(i) < 300, (ii) 300–500, (iii) 500–700, (iv) 700–900, and (v) > 900
Aridity [^]	Dryland grouped into semi-arid and subhumid based on UNCCD classification (Safriel 2005)	(i) Semi-arid (AI: 0.20–0.50) and (ii) sub-humid (AI: 0.50–0.65)
Soil type	Classification of the soil of the experimental site in WRB Soil Taxonomy equivalents to order level.	(i) Vertisols, (ii) Regosols, (iii) Luvisols, (iv) Cambisols (v) Gleysols, (vi) Chernozems, and (vii) Phaeozems
Tillage type	Tillage practice applied within any phase of the rotation	(i) No-till, (ii) reduced, and (iii) conventional
CC functional type	Cover crop plant family with distinguished functional traits	(i) Asteraceae, (ii) Poaceae, (iii) Brassicaceae (iv) Fabaceae, and (v) mixtures
CC termination method	Method of cover crop termination	(i) Mechanical, (ii) chemical, (iii) integrated, and (iv) frost
CC termination time	The CC growth durations	(i) Early (<60 days), (ii) medium (60–90 days), and (iii) late (> 90 days)
CC residue fate	The fate of CC residues post-termination	(i) Incorporated, (ii) mulched, (iii) rolled, and (iv) burnt
Irrigation status	Crop production systems, i.e., whether the cover crop or cash was grown under fully rainfed or supplementary irrigation	(i) rainfed, (ii) supplementary irrigation used
Fertilization	A binary factor indicating whether fertilizer was applied to cover crop	(i) Fertilized and (ii) unfertilized
N fertilizer rate	A categorical factor of the rate of N fertilizer applied to subsequent cash crop	(i) 0–50, (ii) 50–100, (iii) 100–150, (iv) 150–200, and (v) > 200 kg N ha ⁻¹

$$ES = RR = \frac{\ln(\bar{Y}_{cc})}{\ln(\bar{Y}_{ncc})} \quad (1)$$

Where: \bar{Y}_{cc} is the mean of the cover crop yield and \bar{Y}_{ncc} is the mean of the fallow control yield. The RR was calculated using the Escal function in the metafor package (Viechtbauer 2010) in R v4.1.0 (R Core Team 2021) using RStudio v1.3.959 (R Studio Team 2020). Because the estimate of overall RR was based on pairwise comparisons between \bar{Y}_{cc} and \bar{Y}_{ncc} within a study, the variability in the depth of soil sampling for soil water and mineral N determination did not influence the magnitude of the RR .

Meta-analysis was conducted using a multilevel mixed-effects model (Philibert et al. 2012) within the metafor package, considering that actual effects are likely to have varied across studies. The RR were considered as fixed effects, whereas study and article (*Article:Study*) were considered as nested random effects to account for dependencies between multiple effects size with common control (\bar{Y}_{ncc}) (Thapa et al. 2018; Hallama et al. 2019). Finally, a cluster-based robust variance estimation technique (clustering on the study) was employed using the clubSandwich package to estimate robust standard errors (SEs) for mean effect sizes (Pustejovsky 2017). The calculated robust SEs were used to estimate the 95% confidence interval (95% CI) for the weighted RR . For

ease of interpretation, the RR values were exponentially back transformed to mean RR and expressed as the percentage of change in response with cover cropping:

$$\text{Change with cover crops (\%)} = [(e^{RR} - 1)] \times 100 \quad (2)$$

The mean effect sizes for each response variable were considered significantly different from the controls (i.e., fallows) at $P < 0.05$ only if the 95% CI did not include zero.

A multiple regression was used to determine the relationship between the categorical moderators and the cover cropping response ratio. A main effect (the relative contribution of a given moderator to the overall response ratio) and the total effect (the total contribution of a given moderator together with other moderators) were determined to assess variable of importance contributing the most to the response ratio based on Monte Carlo uniform inputs (Saltelli 2002).

2.3 Moderator analysis

Whether the cover cropping effect size varied with different moderators was assessed to explain between-study variation. The multilevel rma.mv function from the metafor package was used to evaluate the moderating effects of each moderator on the RR . We utilized analysis of variance (ANOVA) to

provide the overall significance of a given moderator. Assessment of between-study heterogeneity as the extent to which true effect sizes vary within a meta-analysis was conducted using Cochran's Q (Cochran 1954) and the I^2 statistic (Higgins et al. 2002). Subgroups within a moderator were considered significantly different ($P < 0.05$) if their 95% CI did not overlap. All figures were produced using the ggplot2 package (Wickham 2016).

2.4 Risks associated with cover cropping

When conducting meta-analyses, inferences are often based on the mean and 95% CIs; however, inference based on mean only can sometimes be misleading, particularly if the probability distribution of the response variable is unknown (Sileshi et al. 2010). To avoid this, we calculated the probability of exceedance for a given RR . This provides the probability distribution of the responses as the cumulative probabilities of RR exceeding a given value. We generated the frequency distribution of RR s and then calculated the cumulative probabilities of RR . Risks (disservices) were considered as the probability of RR being below 0. In other words, $RR < 0$ means there was a negative consequence of the cover crop relative to control fallow on that response variable, while $RR > 0$ indicates cover crop performed better than the control fallow.

2.5 Potential publication bias and sensitivity analysis

Publication bias was investigated based on funnel plots using the funnel function in the metafor package to visualize if significant heterogeneity was present for each response variable. Funnel plot asymmetry was tested using the regtest function from the metafor package. The overall effect size for biases toward publishing significant positive or negative results was assessed using histograms of the individual RR (Møllerand and Jennions 2001). Finally, the Jackknife procedure for sensitivity analysis was utilized to test the robustness of the overall RR to individual variation in a study (Philibert et al. 2012). Using this stepwise procedure, one study at a time was systematically excluded from the dataset, and the overall RR estimates were re-run to examine how each study contributed to the overall RR . In addition, whether publication bias could be safely ignored was tested using the fail-safe N approach (type = "Rosenberg") as recommended by Rosenberg (2004).

There was large variance and heterogeneity among and between studies largely due to differences in climate, site type, and both cover crop and cash crop management practices. Moderator analysis revealed significant between-study heterogeneity for the three response variables. This suggests that the between-study heterogeneity observed in the datasets was due

to true variation in the datasets, as indicated by Cochran's Q (Q_{between}) and I^2 (Supplementary Tables S4a–c).

No significant evidence of publication bias was observed. Regression tests for funnel symmetry revealed no pattern of bias toward not reporting small or negative effect sizes in the respective funnel plots (Fig. S3a–c). In addition, the individual RR was found to be equally distributed between slightly positive and slightly negative values on the histogram, indicating no significant publication bias (Supplementary figure S4a–c). Sensitivity analysis also did not show a significant change in the overall RR due to the omission of any study, indicating that the estimates from this meta-analysis were highly robust.

3 Results

3.1 Overview of the dataset

Across the 38 published articles identified that fitted the search criteria, 1203 independent comparisons were identified that reported the legacy effects of cover cropping compared to a fallow control. This included 1006 comparisons of subsequent cash crop yield, 539 comparisons of soil water content, and 516 comparisons of soil mineral N prior to sowing the cash crop (Supplementary Table S2). The studies comprised 33 cover crop species of diverse functional types, including those in Asteraceae, Brassicaceae, Fabaceae, and Poaceae families (Supplementary Table S3). The frequency of the studies found was highest with Fabaceae (49%) cover crops and lowest with Asteraceae (< 1%). Cover crop biomass production ranged from 0.1 to 11 t ha⁻¹ and varied widely between monoculture and mixture cropping patterns. The studies represented different dryland climate types with mean annual precipitation ranging from 212 to 1267 mm. Based on the Köppen-Geiger dryland climate classification, tropical climates constituted 3% ($n = 27$), dry/arid/semi-arid climates 45% ($n = 450$), temperate climates 29% ($n = 291$), and continental climates 23% ($n = 238$) of the crop yield datasets. The studies covered most soil types found in dryland environments, namely Chernozems (54%), Vertisols (14%), Regosols (11%), Phaeozems (8%), Cambisols (5%), Luvisols (4%), and Gleysols (1%). More than 60% of the studies were conducted under conservation tillage (no-till and reduced-till) and 38% under conventional (full inversion) tillage.

3.2 Summary effects of cover cropping

The regression analyses showed lower cash crop yield, soil water, and mineral N content at cash crop sowing relative to

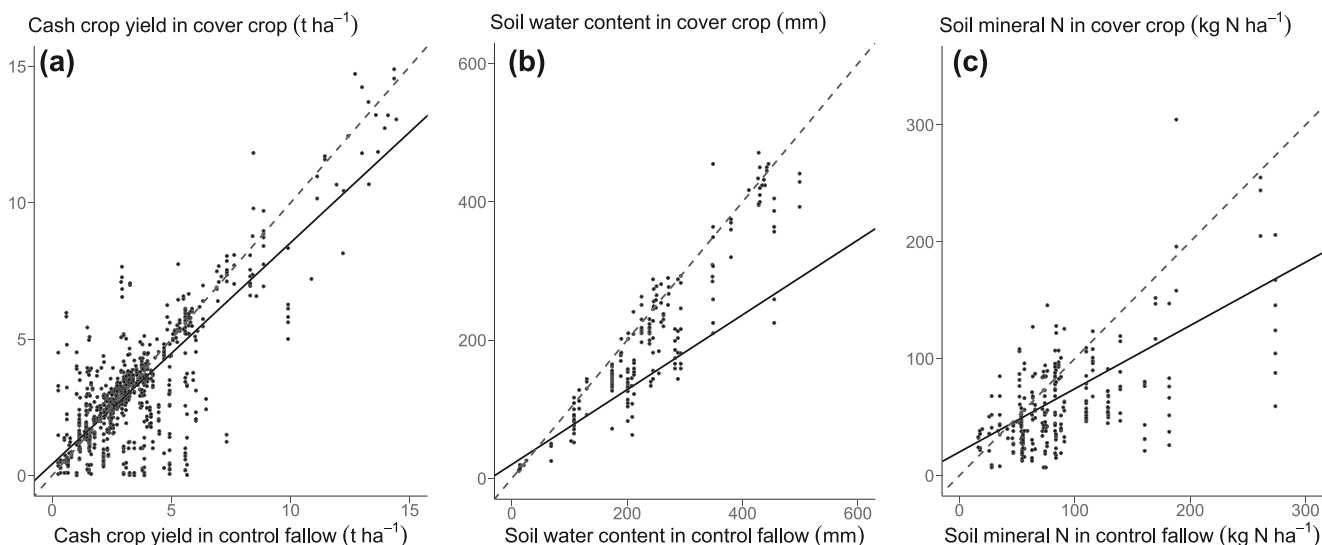


Fig. 2 Relative effects of cover cropping compared to fallow controls on (a) cash crop yield, (b) soil water content and (c) soil mineral N at cash crop sowing across the range of experimental studies. Fitted equations $y = 0.42 + 0.81x$, $R^2 = 0.68$, $P < 0.01$ for cash crop yield; $y = -12 + 0.89x$,

$P < 0.01$, $R^2 = 0.86$ for soil water content; and $y = 20 + 0.54x$, $R^2 = 0.36$, $P < 0.01$ for soil mineral N. The dashed lines (- -) show the 1:1 relationship where variable values would be equal for the cover crop and fallow control; the solid lines (—) show the linear regression fits.

fallow controls, indicating the importance of different moderators in influencing the response ratios (Fig. 2). The overall mean global change (%) with cover cropping was significantly different ($P < 0.05$) than zero for the three response variables. The average effect was a 7% decline in cash crop yield ($P = 0.002$) across the 1006 yield datasets (Fig. 3a). Cover cropping decreased soil water content at cash crop sowing by an average of 18% ($P < 0.0001$), whereas soil mineral N was reduced by 25% ($P < 0.0001$). Cover crops produced a positive cash crop yield, soil water, and soil mineral N response by 10%, 34%, and 52% of the time, respectively, as shown where

the probability of effect size exceeds 0 (as an indicator of risk/disservices associated with a cover crop for control fallow replacement) (Fig. 3b).

3.3 Moderator effects on responses to cover crop implementation

3.3.1 Climate and soil type

Several environmental moderators (climate and soil type) were found to have an association with the size of the cover

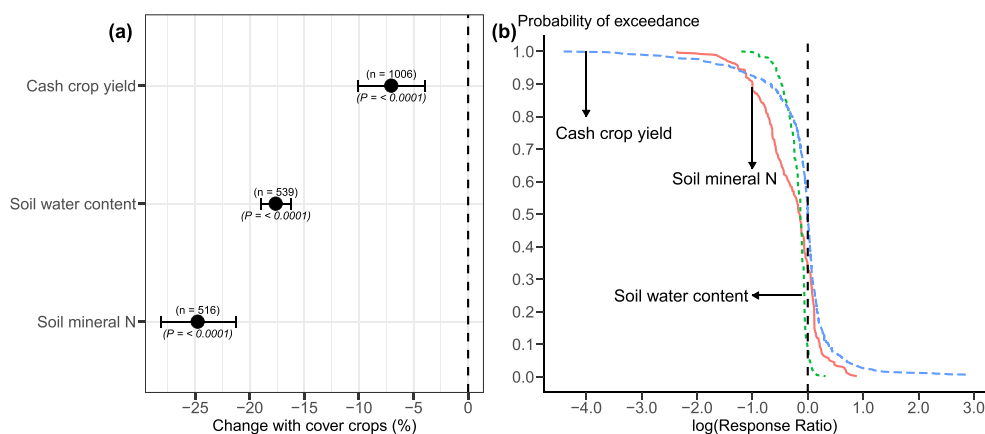
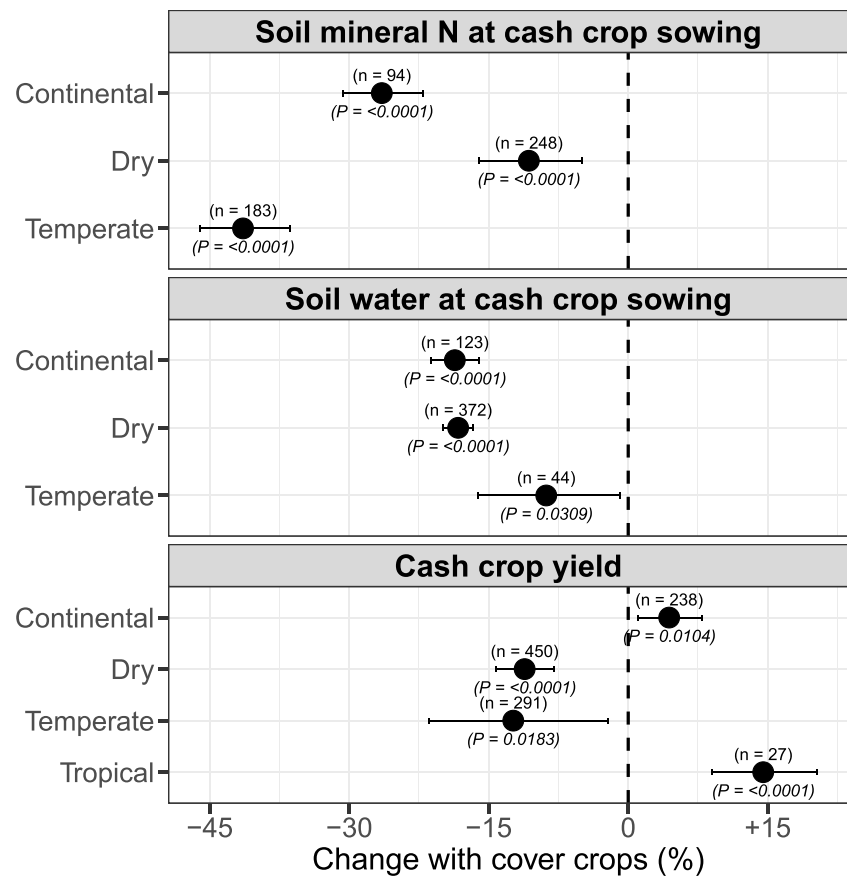


Fig. 3 (a) Average change (%) in cash crop yield, soil water content, and soil mineral N concentration (soil mineral N) at cash crop sowing induced by cover cropping across all studies included in the meta-analysis; error bars show 95% confidence intervals. $P < 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero. (b) Probability of exceedance (risk/disservice) of a given response ratio in

soil mineral N and soil water content at cash crop sowing and cash crop yield; a response ratio over 0 indicates greater soil mineral N, soil water content, or cash crop yield after cover cropping, while a ratio below 0 indicates lower soil mineral N, soil water content, or cash crop yield after cover cropping in comparison to bare fallow.

Fig. 4 Forest plot of the change (%) in soil mineral N concentration, soil water content, and cash crop yield induced by cover cropping with climate type. Climate classification was based on Köppen-Geiger climate classification; tropical, dry/arid/semi-arid, temperate, and continental. The number in parentheses represents the number of studies contributing to that effect size. Error bars show 95% confidence intervals (95% CIs). $P \leq 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero.



cropping effect on the three response variables (Tables S4a–c). The mean change (%) in cash crop yield with cover cropping varied significantly between dryland climate types. Larger positive effects were reported in tropical (+14.5%; $P < 0.0001$) followed by continental (+4.4%; $P = 0.0104$) climates, and negative effects in dry (−11.1%; $P < 0.0001$) and temperate climates (−12.4%; $P = 0.0183$) (Fig. 4). The greatest reduction in soil mineral N at cash crop sowing was in temperate climates (−41.4%; $P < 0.0001$) and lowest in dry climates (−10.7%; $P \leq 0.0001$). The greatest reduction in soil water content at cash crop sowing was in continental (−18.6%; $P < 0.0001$) and least in temperate climates (−8.8%; $P = 0.0309$). Significant decreases in soil water content (−43%) and soil mineral N (−25%) at cash crop sowing were observed in Vertisols (Fig. 5). Cash crop yield showed a significant difference across all soil types except Phaeozems ($P = 0.3060$) and Regosols ($P = 0.2770$). There was an 8.1% increase in cash crop yield on Gleysols ($P = 0.0347$) and a 30% decrease on Vertisols ($P < 0.0001$). However, the response on Vertisols changed from negative to positive depending on whether the studies were from temperate vs dry climates (Fig. 6).

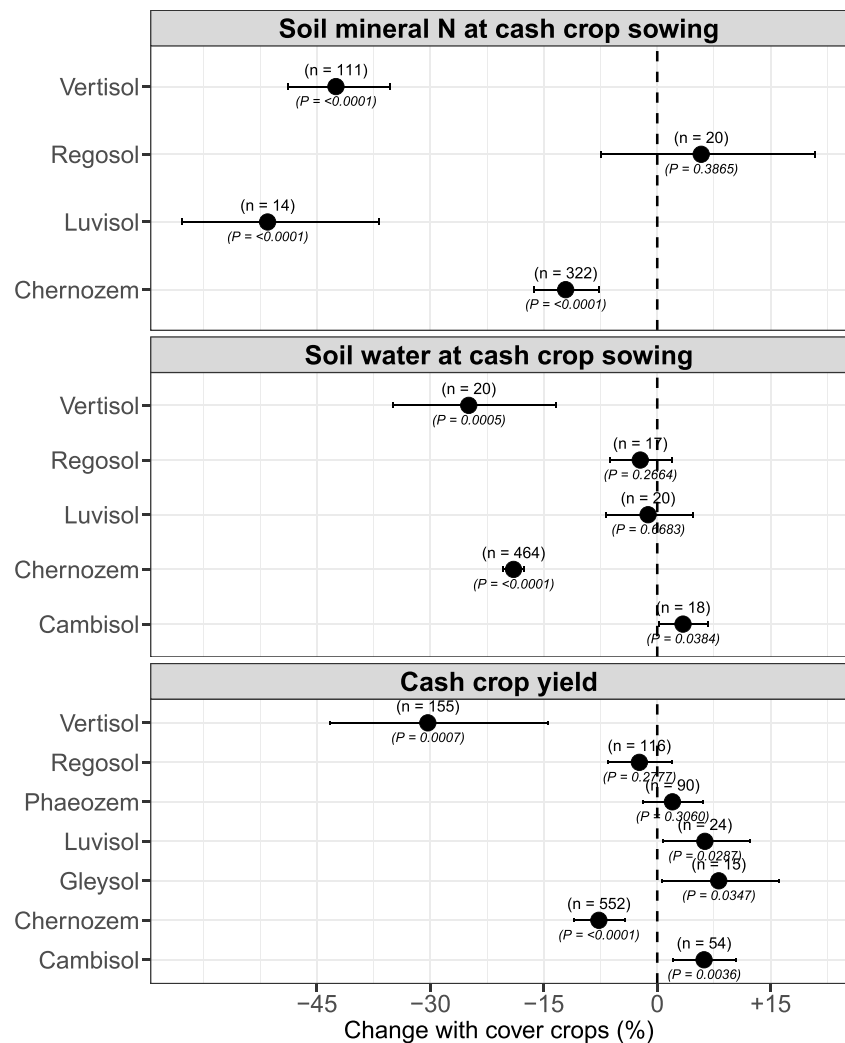
Mean annual rainfall (mm) received in an *Article:Study* [site.year] significantly influenced the magnitude of cover cropping effect sizes on the three response variables. In

studies with low mean annual rainfall (< 300 mm), cover cropping led to significant reductions in soil water content, soil mineral N, and cash crop yield (−24%, −48%, and −29%, respectively). The benefit of cover cropping on subsequent cash crop yield increased along a rainfall gradient (Fig. 7). Where annual precipitation exceeded 700 mm, neutral cash crop yield response to cover cropping was observed (95% CI: −1 to 22.7%). In higher rainfall regimes (> 900 mm), cover cropping increased cash crop yield by 14.5% ($P < 0.001$). Linear regression of the annual rainfall regime and cover cropping response showed a break-even point of 693 mm of annual precipitation (95% CI = 536–838 mm) where cover cropping *RR* was significantly higher than the control fallow (Fig. 8). The main effect variables that contributed most to the response ratio were cash crop type (0.27), rainfall regime (0.11), and climate type (0.10). Cash crop type interactions with other moderator variables led to significantly higher total effects ($P = 0.001$, total effect = 0.30), followed by climate by other moderator interactions ($P = 0.030$, total effect = 0.14) (Table 2).

3.3.2 Cover crop management and choice

Cover crop and cash crop management practices including species selection, termination time, and method and tillage

Fig. 5 Forest plot of the change (%) due to cover crop implementation across soil types, in soil mineral N concentration and soil water content at subsequent cash crop sowing, and cash crop yield. The number in parentheses represents the number of studies contributing to that effect size. Error bars show 95% confidence intervals (95% CIs). $P \leq 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero.

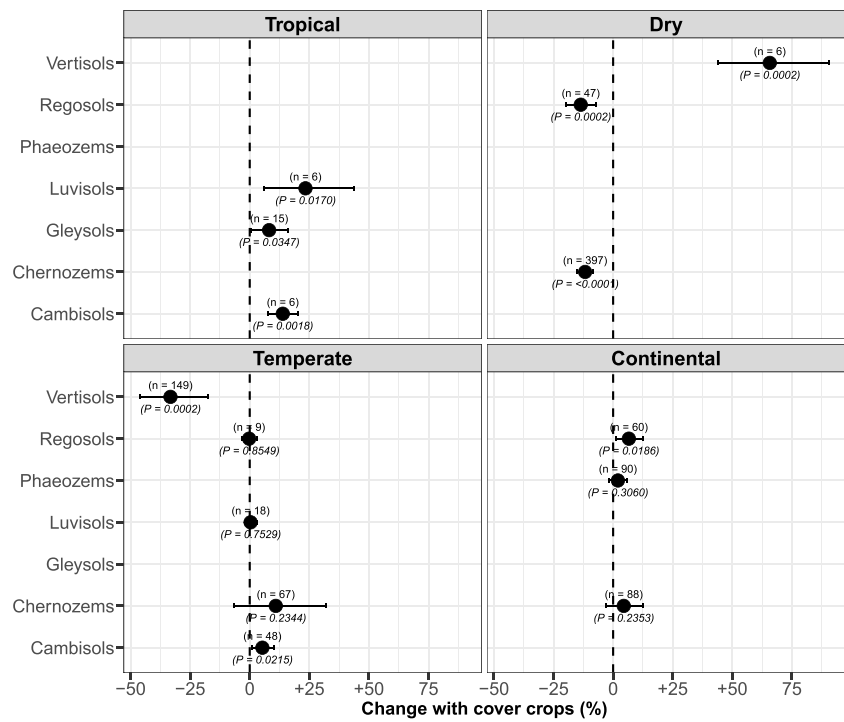


had significant moderating effects on cover crop effect sizes on the three response variables. The magnitude of reduction on soil mineral N and crop yield associated with legumes (Fabaceae) and mixture cover crops was lower compared with non-legume cover crops (Table 3). Non-legume cover crops reduced soil mineral N at cash crop sowing more, indicating their potential as catch crops. Grasses (Poaceae) significantly ($P < 0.05$) reduced soil water by an average of 25% and soil mineral N by 58%. Brassicaceae led to a significant decline in cash crop yields (-26.5%) compared with other functional types. The change in soil water content, soil mineral N, and cash crop yield with cover cropping varied significantly with cover crop biomass production. Cash crop yield was higher with moderate biomass production (3–5 t ha⁻¹) across all cover crop functional types (Fig. 9). Higher Fabaceae biomass production was not associated with changes in cash crop yield and soil mineral N (Fig. S2a), and soil water content (Fig. S2b) compared with a control fallow. An inconsistent trend was observed with Poaceae cover crops. Generally, the frequency

of negative yield outcomes increased with higher biomass in Poaceae and Brassicaceae cover crops while this effect was smaller in legume cover crops. Reductions in cash crop yields with cover cropping were pronounced when the cover crop was terminated early or late in the season (Fig. 10a). Mid-termination did not differ significantly from zero ($P = 0.465$), indicating no yield penalty on average. A similar trend was observed with soil mineral N at cash crop sowing. Early termination cover crops reduced soil water less than later termination, with soil water reduced by 24% when they were terminated after 120 days ($P = 0.006$). All termination methods except the integrated method led to significant yield declines and significant reductions in soil water content after cover crops compared to control fallow (Table 3).

Fertilization of cover crops reduced cash crop yield by 4.4%, compared to a reduction of 9% for unfertilized cover crops. Although cash crop yield did not differ significantly from zero ($P = 0.127$; $n = 372$), it did increase by 3% under conventional tillage. Under conservation tillage (reduced and

Fig. 6 Forest plot of interactions between climate type and soil type effects on the change (%) in subsequent cash crop yield induced by cover cropping. Numbers in parentheses show the number of studies contributing to the effect size. Error bars show 95% confidence intervals (95% CIs). $P \leq 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero.



no-till), cash crop yield and soil mineral N both declined with cover cropping in the range of -10 to -27% and -20 to -43%, respectively (Table 4). The fate of cover crop residue post-termination also influenced cover crop effects on the three

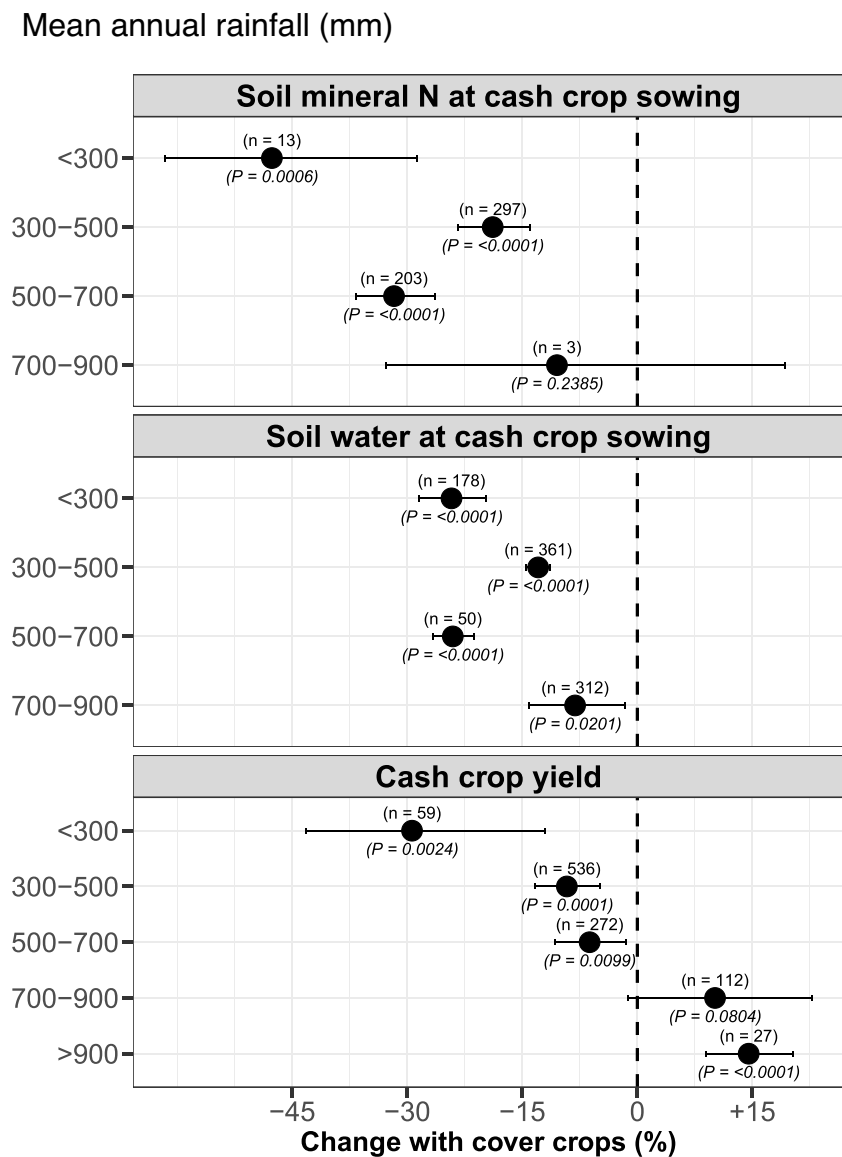
response variables. Burning residues resulted in a 43% and 30% decrease in soil mineral N and cash crop yield, respectively (Fig. 10b). Rolled and incorporated residues did not induce a response differing significantly ($P > 0.05$) from zero

Table 2 Effects summary of the multiple linear regression of different moderators of the cover cropping effects of subsequent cash crop yield, soil water, and mineral N content at cash crop sowing. ME main effect (the average relative contribution of each moderator on the response). TE total effects (the relative contribution of the moderator both alone and in

interaction with other moderators). Logworth (defined as $-\log_{10}(P \text{ value})$) showed the scaled P values where Logworth above 2 corresponds to a P value below 0.01. Where cells are blank, insufficient data were available. CC cover crop.

Source	Cash crop yield				Soil water content at cash crop sowing				Soil mineral N content at cash crop sowing			
	ME	TE	LogWorth	P value	ME	TE	LogWorth	P value	ME	TE	LogWorth	P value
Climate type	0.10	0.14	1.29	0.031	0.11	0.14	2.50	0.003	0.03	0.05	0.39	0.410
Soil type	0.02	0.05	0.07	0.296	0.07	0.09	2.39	0.004	0.07	0.09	0.29	0.515
Rainfall regime	0.11	0.05	4.11	< 0.0001	0.01	0.02	1.52	0.031	0.03	0.08	0.13	0.749
Cropping pattern	0.02	0.01	0.28	0.289	0.01	0.02	0.03	0.925				
Dryland type	0.00	0.02	0.16	0.885								
Tillage practice	0.01	0.02	0.75	0.157	0.01	0.02	0.47	0.338	0.01	0.05	0.01	0.974
N fertilizer rate	0.01	0.04	0.22	0.635	0.10	0.12	2.41	0.004				
Fertilization	0.01	0.02	0.36	0.418	0.08	0.11	20.67	< 0.0001	0.14	0.21	1.76	0.017
CC functional type	0.01	0.03	1.47	0.032	0.01	0.02	1.76	0.018	0.04	0.10	3.95	0.000
CC biomass production	0.02	0.05	0.82	0.118	0.01	0.02	6.92	< 0.0001	0.06	0.12	1.18	0.067
CC termination time	0.01	0.02	0.02	0.920	0.01	0.03	9.88	< 0.0001	0.01	0.06	0.56	0.274
CC termination method	0.04	0.08	0.65	0.251	0.13	0.15	8.76	< 0.0001	0.07	0.13	1.40	0.039
CC residue fate	0.06	0.10	1.01	0.095	0.01	0.02	0.53	0.292	0.02	0.07	0.04	0.914
Cash crop	0.27	0.30	3.43	0.001								
Sampling depth					0.20	0.23	19.57	< 0.0001	0.11	0.16	1.73	0.019

Fig. 7 Forest plot of the change (%) in soil mineral N concentration, soil water content, and cash crop yield induced by cover cropping according to mean annual rainfall (mm). The number in parentheses represents the studies contributing to that effect size. Error bars show 95% confidence intervals (95% CIs). $P \leq 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero.



(i.e., neither a yield penalty nor benefit). The depth of soil sampling for soil mineral N determination also influenced the magnitude of the cover crop effect size, where deep sampling (>120 cm) aggregated a more positive effect (+5.8%) compared to 0–60 cm profile sampling (–20%).

3.3.3 Subsequent cash crop management

The type of subsequent cash crops also modified the relative effects induced by cover cropping. Cash crop yield increased by 20% for barley and 14.5% for rice ($P < 0.05$), but decreased by 12% for wheat, 12% for soybean, and 4% for sunflower. Sorghum and maize yields were not significantly different from zero ($P > 0.05$) (Table 2). Fertilization of both the cover crop and the cash crop also influenced the change in cash crop yield with cover cropping. High cash crop N fertilization (> 150 kg N ha⁻¹) resulted in a higher

yield increase (3–5%), while low N fertilization after cover crops (< 100 kg N ha⁻¹) led to a reduction in cash crop yield by 7–11% (Table 4, Table S4a).

4 Discussion

4.1 Environmental drivers of legacy effects of cover cropping on soil water and cash crop yields

A significant barrier to the adoption of cover cropping in water-limited environments is the potential reduction of plant-available water for the subsequent cash crop and the likelihood of yield penalty. Numerous studies have ascribed reductions in soil water at subsequent cash crop sowing to water use by cover crops during their growth, and insufficient soil water recharge/accumulation post cover crop termination to

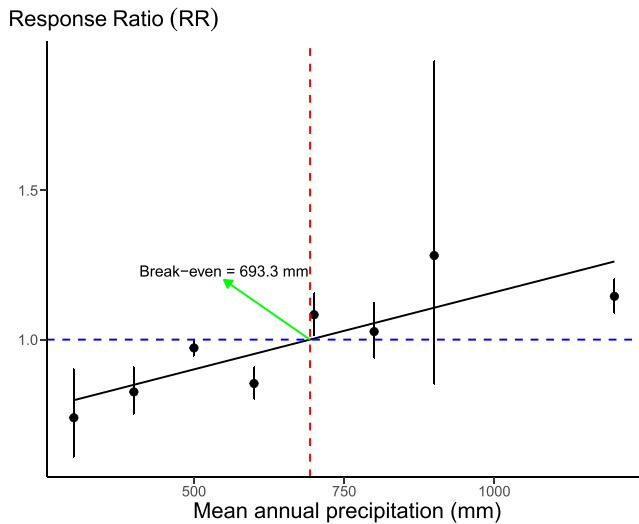


Fig. 8 Relationship of the cover cropping response ratio (*RR*) on cash crop yield and aggregated mean annual precipitation (mm). The break-even point shows the mean annual precipitation where *RR* is at unity (*RR* = 1) indicating the mean annual precipitation necessary to make benefit on the cash crop yield relative to control fallow. The fitted equation $y = 0.642 + 0.00052x$, $R^2 = 0.693$, $P = 0.01$ shows the linear regression fit. Error bars show 95% confidence intervals (95% CIs) of the *RR*.

compensate for cover crop water use (Aiken et al. 2013; Nielsen et al. 2016a; Miller et al. 2018). While cover crops have the potential to reduce water loss by evaporation and runoff through the provision of groundcover and improvement in soil physicochemical properties, improved efficiencies are not always large enough to make up for the

additional water used to grow this biomass. This risk or potential impact will likely depend on the duration of fallow periods within the rotation, cover crop choice, sowing and termination timing, tillage practice, and the subsequent cash crop management practices.

Dryland climate type was an important driver of the reduction in soil water content at cash crop sowing with cover cropping compared to control fallow and was largest in continental, moderate in dry, and lowest in temperate climates. This is likely due to intrinsic differences in seasonal precipitation and temperature patterns as well as location-specific biophysical characteristics of the climate types. In continental climates, the reduction in soil water content prior to cash crop sowing is likely to represent a desirable ecosystem service, where it allows the opportunity to enhance soil water infiltration, improve drainage, and reduce excess soil water following spring rains or thaws, thus allowing earlier planting and improved crop establishment (Kahimba et al. 2008; Blanco-Canqui et al. 2015; Williams et al. 2016). Results also showed a significant reduction in soil water content in continental climates as crop yield increases which suggests the decrease in soil water content caused by cover crops is beneficial to cash crops, or alternatively, there are other yield-enhancing benefits of cover crops that outweigh the reduction in soil water content. This could likely be due to the precipitation pattern in continental climates where in-crop rainfall could compensate for cover crop water use during fallow. Nonetheless, in temperate and continental climates, cash crop

Table 3 Mean change (Δ_{mean} %) and their 95% confidence intervals (Δ_{high95} , Δ_{low95}) in soil water content, soil mineral N, and cash crop yield induced by cover cropping as moderated by cover crop functional type, cropping pattern, fertilization, termination method, and sampling depth.

** denotes significant difference from fallow control at $P < 0.01$; * denotes significant difference from fallow control at $P < 0.05$; *n* the number of studies contributing to that effect size. Where cells are blank, insufficient data were available. CC cover crop.

Moderator	Category	Soil water content				Soil mineral N concentration				Cash crop yield			
		<i>n</i>	Δ_{mean}	Δ_{low95}	Δ_{high95}	<i>n</i>	Δ_{mean}	Δ_{low95}	Δ_{high95}	<i>n</i>	Δ_{mean}	Δ_{low95}	Δ_{high95}
CC functional type	Asteraceae	6	-24.7	-53.8	22.6	3	-36.7	-75.2	61.1				
	Brassicaceae	14	-10.1	-18.7	-0.6	78	-36.1	-44.2	-26.9	91	-26.5	-41.5	-7.6
	Fabaceae	356	-16.1	-17.4	-14.7	321	-13.3	-17.6	-8.7	641	-4.9	-8.4	-1.3
	Mixture	18	-20.4	-24.2	-16.4	84	-40.1	-45.1	-34.7	182	-5.6	-9.1	-2.1
	Poaceae	143	-25.1	-31.8	-17.7	30	-58.0	-66.4	-47.5	92	-10.1	-21.9	3.6
Cover crop fertilization	Fertilized									669	-4.4*	-8.5	-0.2
	Unfertilized									267	-9.1**	-12.9	-5.0
Termination method	Chemical					230	-11.2**	-12.8	-9.7	250	-11.4**	-14.5	-8.1
	Integrated					20	-1.2	-6.8	4.8	62	12.8	-6.4	36
	Mechanical					159	-22.2**	-24.9	-19.3	621	-4.8*	-9.0	-0.4
	Frost					53	-19.2**	-23.1	-15.1				
Sampling depth	0–60 cm					123	-20.1**	-28.4	-10.8				
	60–90 cm					238	-19.3**	-23.5	-14.9				
	90–120 cm					135	-38.4**	-44.2	-32				
	> 120 cm					20	5.8	-8.7	20.9				

CC biomass production (t ha⁻¹)

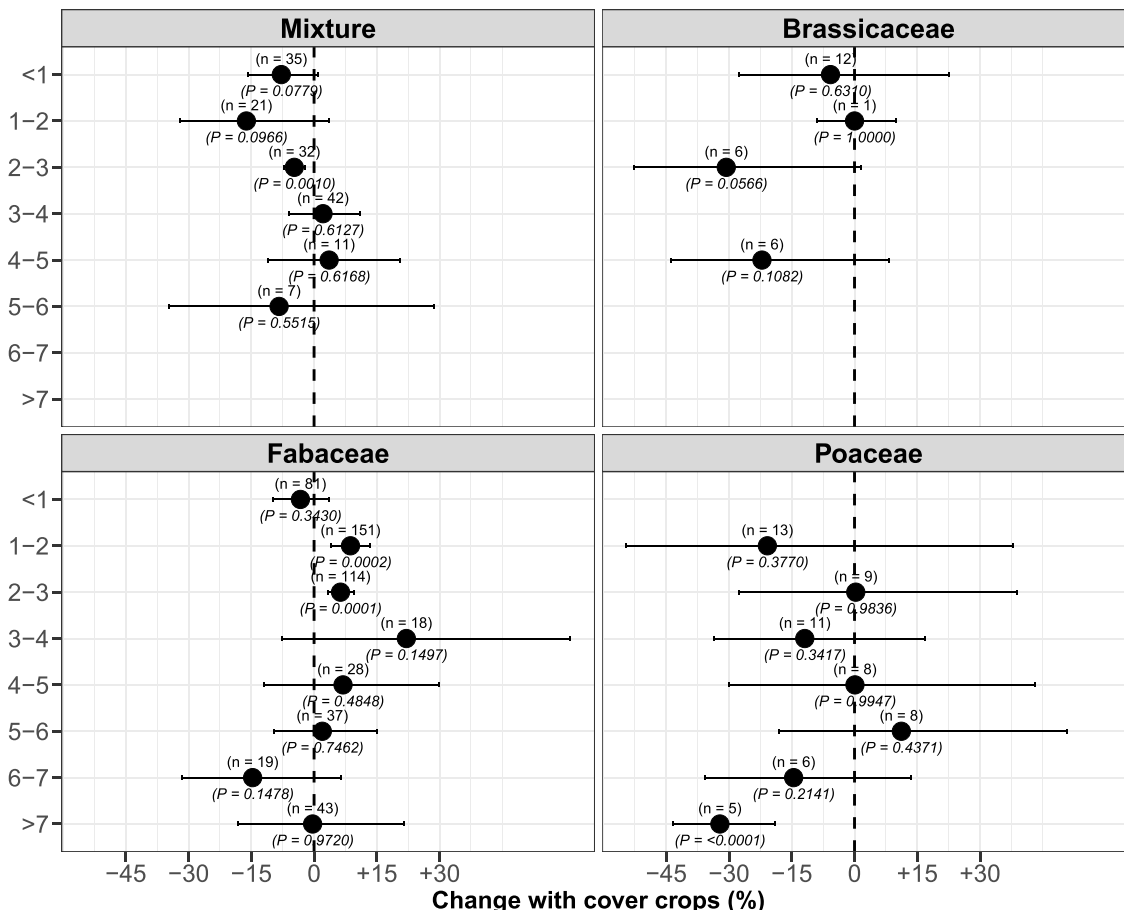


Fig. 9 Forest plot of the relative change (%) in cash crop yield induced by cover cropping according to the cover crop’s functional type and the level of biomass production interaction. The number in parentheses represents

the number of studies contributing to that effect size. Error bars show 95% confidence intervals (95% CIs). $P \leq 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero.

yield response following cover crops was variable, with both yield increases and reductions. In the semi-arid continental climate of the Loess Plateau, China, for example, summer cover crops were reported to increase wheat yields by 13% and WUE by 28%, and also maintained the soil water balance across the 6 years of study (Zhang et al. 2016). Aiken et al. (2013), in eight 3-year crop sequences in the semi-arid drylands of the central High Plains, USA, found that replacing the control fallow period with cover crops reduced wheat yields by 31%. Maize yield following cover crops was reduced by 10% in the same environment (Nielsen et al. 2016b). In a tropical climate, where precipitation is largely unimodal, cash crop yield increased by 15% with cover cropping compared to control fallows. This is likely because there is a distinct wet and dry season in this climate type, with the total annual rainfall of the studies included in this meta-analysis being over 1000 mm. However, it is important to note that data for tropical dryland climates accounted for only 3% of the total dataset, indicating that either limited cover cropping studies were conducted or satisfied the criteria for inclusion in this study.

This meta-analysis identified differences in cash crop yield response to cover cropping based on soil type and climate interaction. For example, following cover crops on Vertisols in dry climates, cash crop yield was increased by over 50%, while in temperate climates on similar soil type, cash crop yields were reduced by over 25%. This may be attributable to differences in precipitation patterns between dry and temperate regions. In temperate regions where rainfall is winter-dominant, precipitation coincides with the cash crop growing season (Stewart 2016). Consequently, cover crops grown during summer are reliant upon stored soil moisture, elevating the risk of depleting soil moisture reserves for the subsequent cash crop. This increases the dependence of the cash crop on highly variable in-crop rainfall. In contrast, in a dry climate where rainfall is summer dominant and cash crops are predominantly winter-grown, summer cover cropping is likely to enhance rainfall capture, soil water storage, and fallow efficiency and offer greater potential to generate increases in subsequent cash crop yield (Deng et al. 2020). This suggests that interactions between

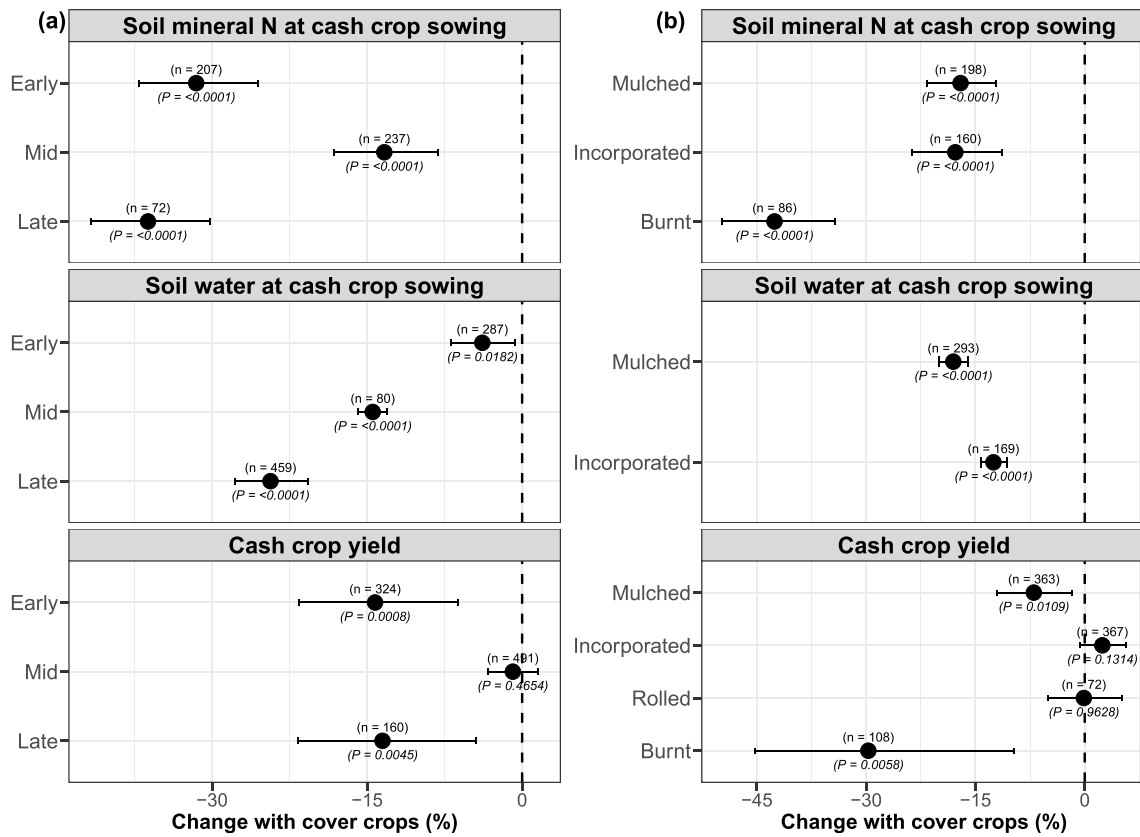


Fig. 10 Forest plot of the change (%) in soil mineral N concentration, soil water content, and cash crop yield induced by cover cropping according to (a) cover crop termination time and (b) post-termination cover crop residue fate. The number in parentheses represents the number of studies

contributing to that effect size. Error bars show 95% confidence intervals (95% CIs). $P \leq 0.05$ indicates that the mean change (%) with cover cropping was significantly different from zero.

climates and soil types must be considered when managing cover cropping to maximize the ecosystem services and minimize disservices.

While there was a general trend in reduction of soil water content at cash crop sowing in all climate types, there were lower soil water penalties where annual water input exceeded

Table 4 Mean change (Δ_{mean} %) and their 95% confidence intervals (Δ_{high95} , Δ_{low95}) in soil water content, soil mineral N, and cash crop yield induced by cover cropping as moderated by tillage practices, cash crop species, and N fertilizer applied to cash crops. ** denotes significant difference from control fallow (control) at $P < 0.01$; * denotes significant difference from control fallow (control) at $P < 0.05$; n is the number of studies contributing to that effect size. Where cells are blank, insufficient data were available.

Moderator	Category	Soil mineral N			Cash crop yield				
		n	Δ_{mean}	Δ_{low95}	Δ_{high95}	n	Δ_{mean}	Δ_{low95}	Δ_{high95}
Tillage	Reduced	80	-43.1**	-50.7	-34.4	132	-27.3**	-40.7	-10.9
	No-till	287	-20.6**	-25.1	-15.8	502	-10.3**	-13.8	-6.5
	Conventional	149	-20.3**	-26	-14.2	372	2.9	-0.8	6.7
Cash crop type	Barley					30	24.1**	20.2	28.2
	Maize					56	1.2	-3.5	6.1
	Rice					27	14.5**	9	20.3
	Sorghum					67	12.6	-1.2	28.4
	Soybean					30	-11.6*	-19.6	-2.9
	Sunflower					30	-3.9*	-7.3	-0.4
N applied to cash crop (kg N ha ⁻¹)	Wheat					766	-11.5**	-15.1	-7.8
	0–50					689	-6.8**	-11.1	-2.3
	50–100					250	-10.8**	-14.8	-6.6
	100–150					28	-5.4	-11.2	0.8
	150–200					27	2.8	-1.6	7.4
>200					12	4.7	-3	13	

693 mm. This is likely because cover crop water use has a greater likelihood of being replenished through less variable precipitation compared with drier conditions. This indicates the challenge of integrating cover crops in areas with annual precipitation below 693 mm given the risk of water use by cover crops and thus, compromising cash crop productivity. Where annual water input exceeded 693 mm, cover cropping led to either a neutral or positive change in cash crop yield relative to fallow control. Thus, there is a greater opportunity of integrating cover crops to provide ecosystem services in these higher rainfall environments because cover crop water use is more likely to be replenished by improved water infiltration, reduced evaporation and runoff due to residue groundcover, and greater soil water storage with an increase in soil organic matter (Blanco-Canqui et al. 2015).

4.2 Cover crop management legacies

Some practices to minimize the potential negative effects of cover crops on soil water content and subsequent cash crop yield include early cover crop termination, careful selection of cover crop functional type, and management of cover crop residues post-termination. As observed in this meta-analysis, early termination of cover crops reduced the impact of cover crops on depleting soil water content compared with late termination. In line with previous research, early termination reduces cover crop transpiration without greatly reducing biomass and groundcover, and so maintains greater soil water content for the following cash crop (Wunsch et al. 2017; Blanco-Canqui 2018). Daryanto et al. (2018) posited that where cover crop biomass production comes at the expense of soil water depletion, cover crop species selection and flexibility in cover crop termination timing should be based on the average precipitation input during the fallow periods. For example, late termination is needed to accumulate significant biomass and N that can provide groundcover and minimize N losses but comes at the expense of high soil water use. In contrast, early termination can lower water use but significantly lowers biomass production, limiting the benefits of groundcover. Consistent with previous research in water-limited environments (Wunsch et al. 2017; Blanco-Canqui 2018), early termination was found to reduce cover crop transpiration and therefore maintain greater soil water content for the following cash crop. Crop modeling by Whish et al. (2009) validated these field observations and predicted that crop yields would only be adversely affected if cover crops were terminated early with herbicide after achieving 50% groundcover.

Cover crop choice was shown to have a large influence on the cover cropping effect size on subsequent cash crop yield compared to control fallows. Both legume and non-legume cover crops reduced cash crop yields. Previous studies have shown similar and divergent results. For example, in the humid temperate Argentine Pampas, legume cover crops were found to

increase maize yield by 7%, but yield was decreased by 8% when the cover crop species was a non-legume (Alvarez et al., 2017). Similarly, a global meta-analysis of cotton yield revealed that cover crops increased cottonseed and lint yield by 6% and 5%, respectively, and that such effects were more pronounced with legume rather than non-legume cover crops (Toler et al., 2019). We found lower yield reduction with mixtures than with monocultures; however, no superiority of monoculture over mixtures were found in the case of soil water at cash crop sowing and on subsequent cash crop yield. The greater reduction in cash crop yield reported in some studies has been attributed to higher water use by mixtures compared with monocultures (Wortman et al. 2012; Reese et al. 2014; Nielsen et al. 2016b).

The result of the meta-analysis indicates that the benefit of cover cropping in enhancing cash crop yield, soil water content, and soil mineral N concentration at cash crop sowing is related to the amount of biomass produced by cover crops. High biomass production by grasses and brassicas led to significant reductions in soil water and soil mineral N, and increased yield penalties. However, high biomass production by legumes did not increase the risk of yield penalties. This suggests that greater cover crop biomass production comes with concomitant increases in soil N uptake. The legacy effects on the subsequent cash crop depend on the quality of the cover crop residue, the rate of residue decomposition, and the synchrony between cover crop residue N release and uptake by the cash crop (Justes 2017). The groundcover residue produced by Poaceae, which has longer residence times due to higher C/N ratios than legume and brassica residues, may allow soils to recover moisture more efficiently during the cash crop phase. In contrast, Brassicas and legumes with rapid residue decomposition do not allow for in-crop recovery of soil moisture, but are likely to increase soil mineral N (Daryanto et al. 2018). The burning of cover crop residues consistently reduced cash crop yield. This is likely due to reduced soil fertility benefits because of nutrient loss via burning and reduced groundcover for soil water conservation (Oikeh et al. 2008).

The inconsistencies in relative soil water content and cash crop yield response to cover cropping indicate the complexity of cover crop management, and caution is needed in recommending or promoting cover crops in low rainfall drylands compared with higher rainfall regions where most cover crops research has been conducted. As observed in this meta-analysis, cover crops are not universally beneficial in terms of generating ecosystem services. Furthermore, biophysical and crop management factors such as climate, soil type, cover crop management, and their interaction, must be incorporated into the cropping system design to optimize the ecosystem services of cover cropping and minimize ecosystem disservices. Ultimately, the goal and the ecosystem services intended to be derived from cover cropping should dictate the selection of cover crop functional types and management practices. For example, where the goal is to minimize N leaching, growing grass or brassica cover crops with late termination might be appropriate to maximize N

uptake into cover crop biomass. In contrast, where rainfall is more limited and N leaching is less of a risk, early to mid-termination of grass cover crops may be more appropriate to minimize cover crop evapotranspiration while enhancing groundcover, subsequent rainfall capture, and fallow efficiency.

4.3 Cover crop legacies on soil mineral nitrogen availability

This meta-analysis showed that cover crops significantly reduced soil mineral N stock at cash crop sowing compared with control fallows, with smaller magnitude of reduction in deep soil layers (> 90cm) likely due to less utilization of deep layer soil N. The mechanism of this reduction has been attributed to cover crop N uptake and accumulation in their biomass, and reduction of N in percolating water flux (Kaspar et al. 2012; White et al. 2017; Norberg and Aronsson 2019). The potential of cover crops to scavenge and accumulate excess nutrients such as N is an important approach for reducing nutrient losses, improving nutrient recycling within cropping systems, and reducing risks of denitrification losses as N₂O (Daryanto et al. 2018; Abdalla et al. 2019). Tonitto et al. (2006) found that cover crops can reduce N leaching by up to 70% compared to control fallows. Couédel et al. (2018) also reported that cover crops reduce N leaching by 59% relative to fallows. The reduction in soil mineral N by cover crops indicates their potential to be used as a catch crop to reduce N leaching if properly designed in cropping systems. However, where soil mineral N is insufficient, cover crops could increase the risk of nutrient limitations in the subsequent crop. Hence, N capture and retention by cover crops is beneficial in highly fertilized systems where there is often excess N, but in limited N contexts, this could be problematic.

There was also variation in soil mineral N responses to cover cropping with cover crop functional type. We found a greater reduction in soil mineral N with grasses and brassicas. This is likely due to their N scavenging properties associated with rapid growth and biomass accumulation (Justes 2017). These non-legumes reduced N leaching by 56% compared to control fallows due to rapid N uptake and accumulation, greater soil microbial immobilization, and reduction in leachate and drainage volume (Thapa et al. 2018). Legume and brassica monocultures will likely have relatively rapid N release from residues due to their inherent low C/N ratios, whereas grass monocultures may exhibit relatively low N mineralization rates due to high residue loads with high C/N ratios (Daryanto et al. 2018). This has consequences for system N retention and recycling, where low C/N ratio residues may carry a greater risk of N loss, whereas high C/N ratio residues have a greater risk of N immobilization (Williams et al. 2018; Thapa et al. 2021a, 2022). Interestingly, mixtures led to a greater reduction in soil mineral N than monoculture cover crops. This may be due to greater biomass and N accumulation in mixtures than in monocultures. Because cover crop

mixtures usually comprise different functional types with contrasting root architectures, they may have the potential to exploit more soil mineral N across the soil profile than a monoculture cropping pattern (De Notaris et al. 2018). Several studies have demonstrated that a mixture of cover crops of different functional types is also more efficient in providing N supply and N retention services (Kramberger et al. 2014; White et al. 2017). Kaspar and Bakker (2015) reported that some mixtures could reduce soil mineral N availability due to uptake during cover crop growing season or N immobilization during residue decomposition.

The magnitude and direction of the reduction in soil mineral N at cash crop sowing observed in this meta-analysis also varied with crop management practices. When cover crops were terminated by natural cause (frost), it led to significant soil mineral N reductions than when terminated by herbicides. Rosa et al. (2021) reported similar findings, where cover crops were frost killed in late spring in semi-arid USA and led to reductions in soil nitrate at 10–20-cm depth by 26% relative to control fallow. In a continental climate in France, frost-terminated cover crops led to lower total N at cash crop sowing compared to termination by herbicide or mechanical termination by rolling (Romdhane et al. 2019). No significant N fertilizer replacement benefit of adding legume cover crops on the subsequent cash crop was observed. This could be partly due to the rapid N-mineralization of legume residues releases N into the mineral N pool which could potentially be lost by denitrification and leaching before crop uptake and assimilation. Therefore, designing cover crop mixtures with complementary plant traits may effectively provide soil mineral N ecosystem services in dryland cropping systems.

5 Conclusions

This meta-analysis has shown that using cover crops for fallow replacement resulted in +15%, +4%, -12%, and -11% change in subsequent cash crop yield in tropical, continental, dry, and temperate climates, respectively, relative to control fallow. The magnitude of this change and the frequency of negative impact on the legacy of soil water and mineral N reductions on subsequent cash crop yield varied significantly with climate and soil types, and crop management practices. Although there was high variability in the crop response to cover cropping, the frequency of studies with increased yield (ecosystem service) in high precipitation areas underscores the importance of cover crops in these cropping systems. In contrast, the use of cover crops in more water-constrained areas posed penalties for soil water available for subsequent crops and cash crop yield risk (ecosystem disservices). Hence, the complexity of cover crop management must be considered when designing a cropping system that integrates cover crops to optimize the ecosystem services and minimize ecosystem

disservices. Considering the high variability in crop response to cover cropping through soil water and mineral N and cash crop yield, further quantitative assessment of the influence of climate patterns on cash crop yield response to cover cropping is warranted. This will provide a basis for understanding the implication of variation in, for example, precipitation pattern, e.g., whether summer or winter dominant rainfall and how this interacts with soil type and cropping system. The results of this meta-analysis highlight the need for a quantitative synthesis of the relative risks and opportunities to use cover crops for fallow replacements in dryland cropping systems. To resolve this, field-scale experiments should be complemented with long-term simulation studies that can extrapolate understanding of the dynamics of the cover crop management over longer time scales and under a wide range of climatic and soil conditions. This will allow the development of best management practices for cover crops in dryland cropping systems that minimize yield penalties and maximize the ecosystem services provided by cover crops.

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Availability of data and material The datasets generated during and/or analyzed during the current study are available in the Figshare repository at <https://doi.org/10.6084/m9.figshare.16684219>.

Code availability The codes analyzed during the current study are available from the corresponding author on reasonable request.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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