Agricultural Water Management 256 (2021) 107085

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A meta-analysis on cover crop impact on soil water storage, succeeding crop yield, and water-use efficiency

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ARTICLE INFO

Handling Editor - Dr. B.E. Clothier

Keywords:
Crop yield
Cover crop management
Cover crop species
Soil water
Water use

ABSTRACT

Cover cropping is practiced to enhance soil health and sustain succeeding crop yield; however, the effect of cover crop on soil water storage, succeeding crop yield, and water-use efficiency (WUE) may not be consistent in all regions. A meta-analysis was carried out to evaluate the effect of cover crop on precipitation storage efficiency (PSE, the percent of precipitation that is stored in the soil during the fallow period), soil water storage at succeeding crop planting (SWSP), succeeding crop yield, and WUE from data collected from 117 studies across the world. Cover crop decreased PSE by 33.4% and soil water storage for the whole profile (SWSPT) at soil depth by 13.2%, but increased water storage to a depth of 30 cm (SWSP30) by 6.0% ($P < 0.05$) compared to no cover crop. Cover crop did not affect succeeding crop yield, but decreased evapotranspiration (ET) by 6.2% and increased WUE by 5.0% ($P < 0.05$) compared to no cover crop. The effect of cover crop on these parameters varied by soil and climatic conditions of various regions. Leaving cover crop residue at the soil surface or incorporating into the soil reduced PSE, SWSPT, and ET, but increased SWSP30 and WUE compared to residue removal. Maintaining cover crop biomass at 5 Mg ha^{-1} and leaving a 20-d interval between cover crop termination and succeeding crop planting, also enhanced PSE and SWSP30. Although cover crop had minimal impact on succeeding crop yield, WUE of succeeding crops can be increased with cover cropping by decreasing evapotranspiration.

1. Introduction

Cover crops are widely adopted to increase soil aggregation and carbon sequestration (Poeplau and Don, 2015), reduce nutrient leaching (Gabriel et al., 2012) and erosion (De Baets et al., 2011), and control weeds (Osipitan et al., 2019) and insects (Damien et al., 2017) compared to no cover crops. In the USA, area under cover crops increased by 6.2 million ha from 2012 to 2017 (USDA-NASS, 2017). As the Chinese government started providing subsidies to farmers for planting cover crops since 2006, area under cover crop increased by 40 million ha by 2017 (Cao et al., 2017). Cover crops showed a mixed effect on the yield of subsequent main crops (Tonitto et al., 2006; Martinez-Feria et al., 2016; Marcillo and Miguez, 2017). While legume cover crops usually have a positive effect on succeeding crop yields, cover crops have variable influence on crop yields, especially in arid and semiarid regions with limited precipitation due to water uptake by cover crops (Tonitto et al., 2006; Whish et al., 2009; Mitchell et al., 2015b). Understanding the effect of cover crops on precipitation storage efficiency (PSE), soil water storage, and succeeding main crop yield may help farmers to improve the sustainability of cropping systems by improving water management (Daryanto et al., 2018).

Cover crop transpire water for their establishment and growth,

Abbreviations: ET, evapotranspiration of the succeeding crop; PSE, precipitation storage efficiency during the fallow period; SWSH, soil water storage at harvest of the previous crop; SWSP, soil water storage at planting of the succeeding crop; SWSPT, soil water storage at planting of the succeeding crop for the whole soil profile; SWSP30, soil water storage at planting of the succeeding crop to a depth of 30 cm; WUE, water-use efficiency of the succeeding crop.

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https://doi.org/10.1016/j.agwat.2021.107085
Received 11 April 2021; Received in revised form 14 July 2021; Accepted 15 July 2021
Available online 24 July 2021
0378-3774/

thereby reducing soil water content for succeeding crop (Unger and Vigil, 1998; Blanco-Canqui et al., 2015; Sharma and Irmak, 2017). In contrast, cover crop residue accumulated at the soil surface can enhance water conservation by reducing water loss through evaporation (Delpuech and Metay, 2018) and increasing water holding and infiltration capacities (Blanco-Canqui et al., 2011; Abdollahi and Munkholm, 2014; Basche et al., 2016; Basche and DeLonge, 2019). Changes in soil water storage during cover crop growth and after cover crop termination determine PSE, and soil water storage at planting of succeeding crops (SWSP) (Nielsen et al., 2015a, 2015b; Frasier et al., 2017; Barker et al., 2018), which in turn, affect their yields (Unger and Vigil, 1998; Qi et al., 2011; Zhang et al., 2015), evapotranspiration (ET), and water use efficiency (WUE) (Daigh et al., 2014; Blanco-Canqui et al., 2015; Basche et al., 2016). Inconsistent effects of cover crop on ET and WUE have been reported in the literature (Zhang et al., 2013, 2015; Nielsen et al., 2015a, 2015b; Deng et al., 2017; Frasier et al., 2017; Xue et al., 2017). Therefore a thorough analysis of the effect of cover crop on succeeding crop yields, ET, and WUE is needed in different regions with various soil and climatic conditions.

Soil water storage and succeeding crop yields often varied with cover crop species and management practices (Fig. 1). Legume cover crops use less water than nonlegume cover crops due to lower biomass production (Zhang et al., 2013; Sharma and Irmak, 2017; Barker et al., 2018). In contrast, greater root biomass and longer growth period reduce soil water storage through increased evapotranspiration with nonlegume cover crops (Sharma and Irmak, 2017; Barker et al., 2018). Cover crop management practices, such as the interval between termination of cover crop and planting of succeeding crop, residue removal vs. residue retention, and years of cover cropping, can also affect SWSP and succeeding crop yields. Early termination of cover crop increases soil water recharge, while late termination reduces soil water storage and succeeding crop yields (Clark et al., 1997; Whish et al., 2009; Daigh et al., 2014). In addition, incorporating cover crop residue into soil can enhance SWSP, succeeding crop yield, and WUE compared to residue placement at the soil surface (Dabney, 1998; Unger and Vigil, 1998). In areas with adequate precipitation, such as in humid and subhumid regions, cover crops can have a negligible effect on SWSP (Unger and Vigil, 1998; Qi et al., 2011). In arid and semiarid regions with limited precipitation, cover cropping can reduce succeeding crop yield compared to no cover cropping by reducing SWSP (Daigh et al., 2014; Blanco-Canqui et al., 2015; Basche et al., 2016). The effect of cover crop on SWSP can also vary with soil textures because of differences in infiltration and water holding capacities (O'Dea et al., 2013; Wells et al., 2016).

The effects of cover crop on PSE, SWSP, and main crop yield are highly site-specific and variable in regions with different soil and climatic conditions. A comprehensive study of cover crop impacts on soil water storage, and succeeding crop yield and water use across various climatic and soil conditions will provide knowledge on cover crop species and their management for maintaining soil water storage, sustaining succeeding crop yield, and enhancing efficient water use. We conducted a global meta-analysis of data reported in the literature on the impact of cover crop on PSE, SWSP, succeeding crop yields, ET, and WUE under various soil and climatic conditions. We hypothesized that cover crop would decrease PSE and SWSP, especially in arid and semi-arid areas, which would have limited effect on succeeding crop yield, ET, and WUE.The objectives of this analysis were to: (1) evaluate how cover crop species and management impact PSE, SWSP, succeeding crop yields, ET, and WUE under various soil and climatic conditions, and (2) determine if cover crop biomass and termination date relate to these parameters.

2. Materials and methods

2.1. Dataset construction

Peer-reviewed research articles published between 1980 and 2020 were searched in Web of Science, Google Scholar, and China National Knowledge Infrastructure Database to determine the cover crop effects on SWSP, PSE, succeeding crop yields, ET, and WUE. Keywords included soil water, precipitation storage efficiency, crop yield, water use efficiency, cover crop, catch crop, and green manure. The search provided 485 publications including both rainfed and irrigated systems. Since cover crops are normally not irrigated even in irrigated systems, we did not consider irrigation as a factor. All publications were screened using the following criteria for further data collection:

i. Field studies that reported soil water content, cover crops grown between the harvesting of a previous cash crop and planting of a succeeding cash crop, and cash crops with similar management practices, such as irrigation, fertilization, and tillage, were selected for the study. Studies conducted on greenhouse and pot experiments were excluded. Studies that included cover crop as an intercrop with other crops were also excluded.
ii. Data included comparison of cover crops vs. no cover crop (fallow) in a region with similar soil and climatic conditions. Studies with the no control treatment were discarded.
iii. Treatments were replicated at least three times, and mean values were shown with standard deviation (SD) or standard error (SE).
iv. In humid and subhumid regions, two to three crops could be grown in a year. In such cases, only data for those crops that were exclusively stated as cover crops were used for analysis. Data for crops used as supplemental cash crops in a year were excluded.

Subjected to these criteria, 117 studies from 99 publications from studies conducted across the world were selected for the meta-analysis (Fig. 2 and Table S1). Data for PSE, SWSP, succeeding crop yield, ET, and WUE comparing cover crop treatments with no cover crop were collected using Getdata graph digitizer 2.26 (http://getdata-graph-digitizer.com/index.php). If SE was reported, the following equation was used to calculate the standard deviation (SD):

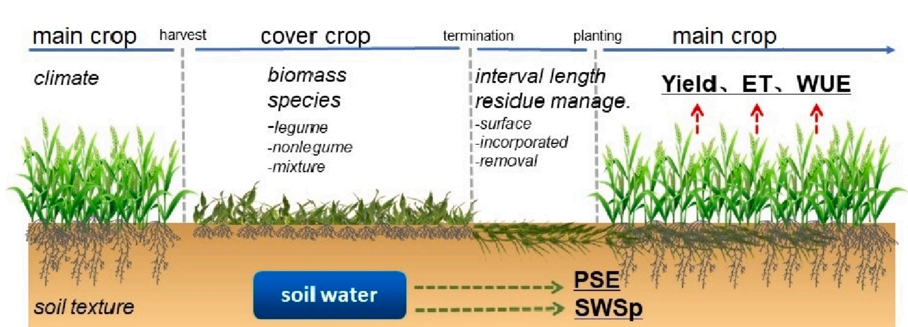

Fig. 1. Sketch map of the impact of cover species, residue management on interval between cover crop termination and succeeding crop planting on precipitation storage efficiency during the fallow period (PSE), soil water storage at planting (SWSP), succeeding crop yield, evapotranspiration (ET) and water-use efficiency (WUE) in different soil and climatic conditions of various regions.

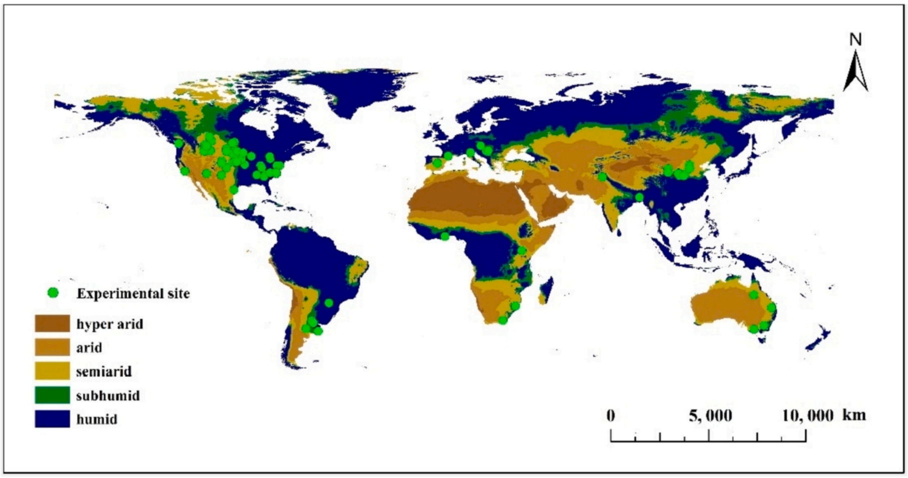

Fig. 2. Collection of data for the meta-analysis from experimental sites around the world.

$$SD = SE \times \sqrt{n} \quad (1)$$

Where "n" is the number of replicates.

The PSE (%) was calculated as:

$$PSE = (SWSP–SWSH) \times 100/Pf \quad (2)$$

where SWSP and SWSH are soil water storage (mm) at planting of the succeeding crop and at harvesting of previous crop, respectively, and Pf is the precipitation (mm) during the fallow period. The soil water storage at planting or harvest (SWSP or SWSH, mm) was calculated as:

$$SWS = \sum_{i=1}^{n} SWCi \times BDi \times Di \times 10/100 \quad (3)$$

where SWC is the soil water content (g kg^{-1}) at planting or harvest of main crop, BD is the soil bulk density (Mg m^{-3}), and D is the soil depth.

As soil water content was measured at different depths in various studies, we separated the data that included water content to a depth of 30 cm (SWSP30) and water content for the whole soil profile (SWSPT) depths. The PSE was selected from studies using SWSP and SWSH for the whole soil profile.

The WUE of the succeeding crop (Mg ha^{-1} mm^{-1}) was calculated as:

$$WUE = \frac{Y}{ET} \quad (4)$$

where Y is the succeeding crop yield (Mg ha^{-1}), and ET is the evapotranspiration (mm) during the growth of the succeeding crop. As the studies were carried out in the relatively level ground with < 2% slope and minimum water percolation, it was considered that water losses due surface runoff and deep drainage are negligible. The ET was calculated as:

$$ET = SWSP - SWSH + Pg + I \quad (5)$$

where Pg and I represented precipitation and irrigation during growth of the succeeding crop.

Cover crop management data included information on cover crop biomass, interval between termination of the cover crop and planting of the succeeding crop, and residue management practices (residue placement at the soil surface, residue incorporated into the soil, and residue removal) (Fig. 1). Wherever possible, we also collected data on air temperature, annual precipitation, precipitation during the fallow period, geographical information of the experimental site, and soil texture. If data on air temperature, precipitation, and soil texture were lacking, we obtained these through online search (https://www.whatsmygps.com).

The data were grouped to maximize in-group homogenization. We used the aridity index (UNEP, 1997) to classify the climatic zone. The aridity index (*AI*) for each study was calculated as:

$$AI = \frac{MAP}{MAE} \quad (6)$$

Where MAP is the mean annual precipitation and MAE the mean annual evapotranspiration at the experimental site. The climatic zone for each study was classified into hyper arid, arid, semiarid, subhumid, and humid according to aridity index value of < 0.03, 0.03–0.2, 0.2–0.5, 0.5–0.65 and > 0.65, respectively. All experimental sites were mapped using ArcGIS based on the global aridity (https://cgiarcsi.community/wp-content/uploads/2019/01/global-aridity-and-global-pet-methodology.pdf) (Fig. 2). Soil textures of study sites were grouped into five classes as sandy loam, loam, silt loam, silty clay loam, and clay loam (USDA-NRCS, https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167).

The dataset can be found in Supplementary Table S1.

2.2. Data analysis

The response ratio (RR) as the effect size was used to test cover crop effect on measured parameters (Hedges et al., 1999; Muhammad et al., 2019) and was calculated as:

$$RR = Ln\left(\frac{\text{Cover crop treatment}}{\text{No cover crop treatment}}\right) = Ln\left(\frac{X_{cc}}{X_{ncc}}\right) = Ln(X_{cc}) - Ln(X_{ncc}) \quad (7)$$

Where Xcc and Xncc represent mean values of PSE, SWSP, succeeding crop yield, ET, and WUE in cover crop and no cover crop treatments, respectively. Use of the natural log ratio ensures that equal proportionate changes occurred in the numerator and the denominator.

The error variance (V) was calculated as:

$$V = \frac{S_{cc}^2}{N_{cc}X_{cc}^2} + \frac{S_{ncc}^2}{N_{ncc}X_{ncc}^2} \quad (8)$$

Where Scc and Sncc are standard deviations and Ncc and Nncc are numbers of replications for cover crop and no cover crop treatments, respectively.

The weight (W) for each RR was calculated as:

$$W = 1/V \quad (9)$$

The unequal variances in the studies were eliminated by giving less weight to the studies with greater variance than those with smaller variance (Hedges et al., 1999). The overall mean RR (RR_{E++}) was calculated as:

$$RR_{E++} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}RR_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}} \quad (10)$$

Where "n" is the number of treatments and "m" the number of comparisons in each category. The standard error of RR_{E++} was calculated as:

$$SE(RR_{E++}) = \sqrt{\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}}} \quad (11)$$

To determine the cover crop effect on PSE, SWSP, succeeding crop yield, ET, and WUE, mean effect size and 95% bootstrapped confidence intervals (CIs) were computed by using a random model analysis with MetaWin 2.1 software (Sinaure Associate Inc., Sunderland, USA). The effect was not significant when CIs crossed zero. Statistical results showed the total heterogeneity of RR (95% CIs) among studies (Q_t), between studies (Q_b) and within studies (Q_w) (Hedges et al., 1999). The values of Q_t, Q_b, Q_w, and P among groups were summarized in Supplementary Table S2. Regression analysis was used to determine relationships among cover crop parameters, PSE, SWSP, succeeding crop yield, ET, and WUE. Statistical significance was reported at $P = 0.05$ unless otherwise mentioned. Rosenthal's fail-safe number and Spearman rank-order correlation were used to test the biasness of the publication (Rosenthal, 1991; Muhammad et al., 2021). Fail-safe number $> (5\,n + 10)$, where n is the number of observations, and/or non-significant rank-order collation indicated no publication bias (Supplementary Table S3).

3. Results

3.1. Precipitation storage efficiency and soil water storage at planting

We collected 129 paired observations for PSE, 465 for SWSPT and 152 for SWSP30, respectively. These numbers used for meta-analysis are shown on the right side of the bar in Fig. 3. Data were normally distributed with high heterogeneities as indicated by greater *Qt* values (Supplementary Fig. S1).

Cover crop, overall, decreased PSE by 33.4% compared to no cover crop (Fig. 3a). This was true for legume, nonlegume, and legume and nonlegume cover crop mixture. Cover crop reduced PSE compared to no cover crop in all climatic regions, except for the humid region. The reduction in PSE was greater in the arid and subhumid regions than in the semiarid region. Cover crop also reduced PSE compared to no cover crop in silt loam and clay loam soils, but increased in loam soil. Surface placement and incorporation of cover crop residue into the soil reduced PSE compared to residue removal. A polynomial relationship was found between RR of PSE and cover crop biomass (Fig. 4a). The PSE was maximized at cover crop biomass of around 5.0 Mg ha^{-1}. No significant relationships were found between the RR of PSE (Fig. 4b).

All cover crop species and mixtures also exhibited lower SWSPT, with an overall decline of 13.2% for cover crop compared to no cover crop (Fig. 3b). The SWSPT was lower with cover cropping than without in arid, semiarid, and subhumid regions, but not in the humid region (Fig. 3b). Cover crop also reduced SWSPT in sandy loam, loam, silt loam, and clay loam soils, with little effect in silty clay loam soil. All residue management practices reduced SWSPT, and no significant differences were found among cover crop residues being incorporated into the soil, surface placed and removed out. The relationship between RR of SWSPT and cover crop biomass was not significant (Fig. 4a). However, the RR of SWSPT was maximized at an interval of 20 d between cover crop termination and succeeding crop planting.

In contrast to that for SWSPT, cover crop overall increased SWSP30 by 6.0% compared to no cover crop, especially for nonlegumes and legumes, but not for the mixture (Fig. 3c). The SWSP30 increased with cover cropping compared to no cover cropping in semiarid and humid regions, but minimum impact in arid and subhumid regions. However, SWSP30 due to cover crop vs. no cover crop was greater in silt loam, loam, and silt clay loam.Residue incorporation into the soil increased, but residue removal decreased SWSP30 compared to surface placement of the residue. The RR of SWSP30 increased linearly with increased cover crop biomass (Fig. 4a), but not correlated with the interval between cover crop termination and succeeding crop planting.

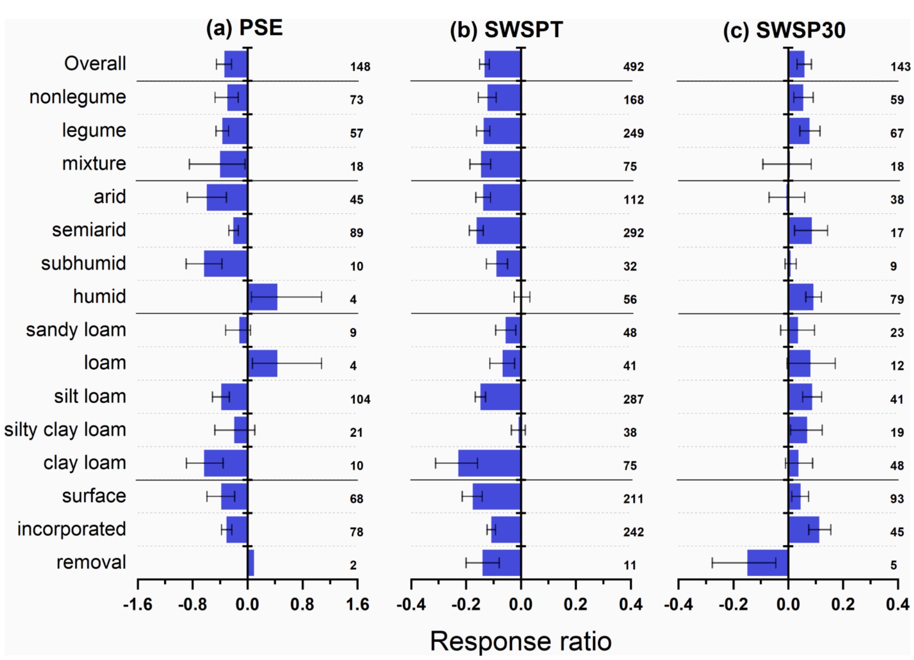

Fig. 3. Response ratio of cover crop compared to no cover crop with bootstrapped 95% confidence interval on precipitation storage efficiency during the fallow period (PSE) and soil water storage at succeeding crop planting for the whole profile (SWSPT) and to a depth of 30 cm (SWSP30) for cover crop species, climatic zones, soil textures, and residue management. Numbers on the right side of the bar for each category of the parameters are numbers of data used for meta-analysis.

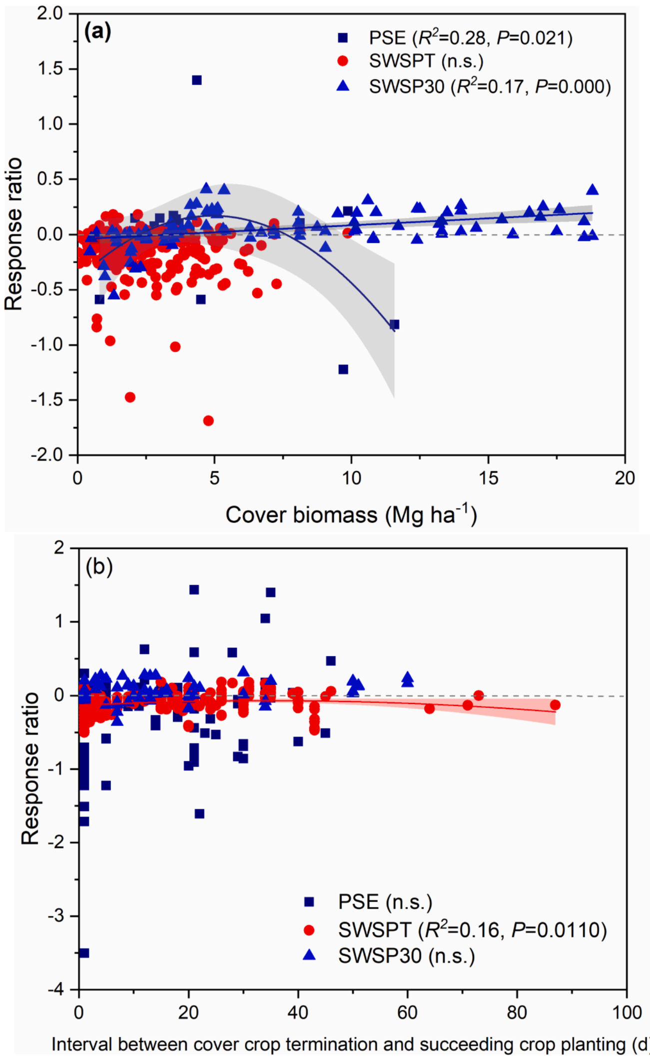

Fig. 4. Relationship between the response ratio of cover crop compared to no cover crop, (a) cover crop biomass, and (b) and the interval between cover crop termination and planting of succeeding crop for precipitation storage efficiency during the fallow period (PSE), soil water storage at succeeding crop planting for the whole profile (SWSPT) and to a depth of 30 cm (SWSP30).

3.2. Succeeding crop yield

Data for succeeding crop yield (418 paired observations shown on the right of bars in Fig. 5) were heterogeneous and normally distributed across studies (Supplementary Fig. S1). Cover crop, overall, did not affect succeeding crop yield (Fig. 5a). The effect of cover crop species on succeeding crop yield was also not significant, although legume and the mixture of legume and nonlegume cover crops tended to increase succeeding crop yield, but nonlegume cover crop tended to decrease it. The succeeding crop yield decreased with cover crop relative to no cover crop in the semiarid region, but increased it in the subhumid and humid regions. Compared to no cover crop, cover crop decreased succeeding crop yield in sandy loam soil, but increased in clay loam soil. Cover crop residue removal reduced succeeding crop yield, but residue placed at the surface or incorporated into the soil had no effect on succeeding crop yield.

The RR of succeeding crop yield increased linearly with increased cover crop biomass (Fig. 6a). Similarly, the RR of succeeding crop yield increased with increased interval between cover crop termination and succeeding crop planting (Fig. 6b). The RR of succeeding crop yield was also linearly related to RR of SWSPT (Fig. 7).

3.3. Evapotranspiration and water-use efficiency

As with succeeding crop yield, data for succeeding crop ET and WUE (188 and 148 paired observations shown on the right of bars in Fig. 5) were heterogeneous and normally distributed across studies (Supplementary Fig. S1). Cover crop decreased ET of succeeding crop, irrespective of the species, with an overall decrease of 6.2% compared to no cover crop (Fig. 5b). Cover crop decreased ET compared to no cover crop in arid, semiarid, and humid regions, but had no effect in the subhumid region. Cover crop also decreased ET compared to no cover crop in silt loam and silty clay, but not in other soil textures. Surface placement or incorporation of cover crop residue into the soil decreased ET, but residue removal increased ET. The RR of ET declined with increased cover crops biomass (Fig. 6a), but increased with increased interval between cover crop termination and succeeding crop planting (Fig. 6b). The RR of ET was linearly related to the RR of SWSPT (Fig. 7).

Cover crop significantly increased WUE of succeeding crop by 5.0% compared to no cover crop (Fig. 6c). The increase was contributed primarily by legume cover crop, with limited effect of nonlegume and mixture of legume and nonlegume cover crops. Cover crop increased succeeding crop WUE compared to no cover crop in the semiarid, subhumid, and humid regions. Similarly, cover crop increased succeeding crop WUE in silt loam, silt clay loam, and clay loam soils, but decreased it in sandy loam soil. Cover crop residue placed at the surface increased, but residue removal reduced succeeding crop WUE. The RR of WUE was linearly related to RR of SWSPT (Fig. 7).

4. Discussion

4.1. Effect of cover crop on soil water storage

The reduction in PSE due to cover crop compared to no cover crop (Fig. 3a) was probably attributable to water uptake by cover crop during its growth. This probably resulted in reduced SWSPT for all cover crop species compared to no cover crop (Fig. 3b). Extraction of water by cover crop roots to enhance aboveground biomass may have reduced PSE and SWSPT. The increased SWSP30 for all cover crop species, except for the cover crop mixture (Fig. 3c), could be the result of soil water recharge at the surface layer following precipitation, followed by reduction in evaporation due to residue accumulated at the soil surface. The change in soil water storage with cover cropping is a result of the balance between soil water depletion due to cover crop evapotranspiration and water conservation from enhanced shading and residue accumulation after cover crop termination (Mitchell et al., 2015b). Cover crops use water for their growth, but the residues after their termination enhance soil water conservation (Dabney, 1998; Unger and Vigil, 1998), and increase water holding capacity by enhancing soil organic matter (Poeplau and Don, 2015), porosity (Villamil et al., 2006), hydraulic conductivity (Blanco-Canqui et al., 2011), and aggregation (Sainju et al., 2003; Villamil et al., 2006) compared to no cover crop. Daryanto et al. (2018) reported that cover crop increased topsoil (0–5 cm) water content by 5%, while not affecting water content to a depth of 60 cm.

Soil water extraction by cover crop compared to no cover crop also probably reduced PSE and SWSPT in arid, semiarid, and subhumid regions (Fig. 3a and b) where precipitation is limited and ET exceeds precipitation. This was not the case in the humid region where increased precipitation compared to ET increased PSE, resulting in the nonsignificant effect of cover crop on SWSPT. However, precipitation during cover crop growth and soil water recharge in the surface layer may have resulted in increased SWSP30 in semiarid and humid regions or no change in arid and subhumid regions (Fig. 3c). Soil water depletion due to cover crop should be carefully examined, especially in arid and semiarid regions, as it can substantially reduce subsequent crop yield.

Depletion of soil water by cover crop also may have reduced PSE and SWSPT in all soil textures (Fig. 3a and b), except for PSE in loam soil where the limited number of observations (n = 4) showed an increased

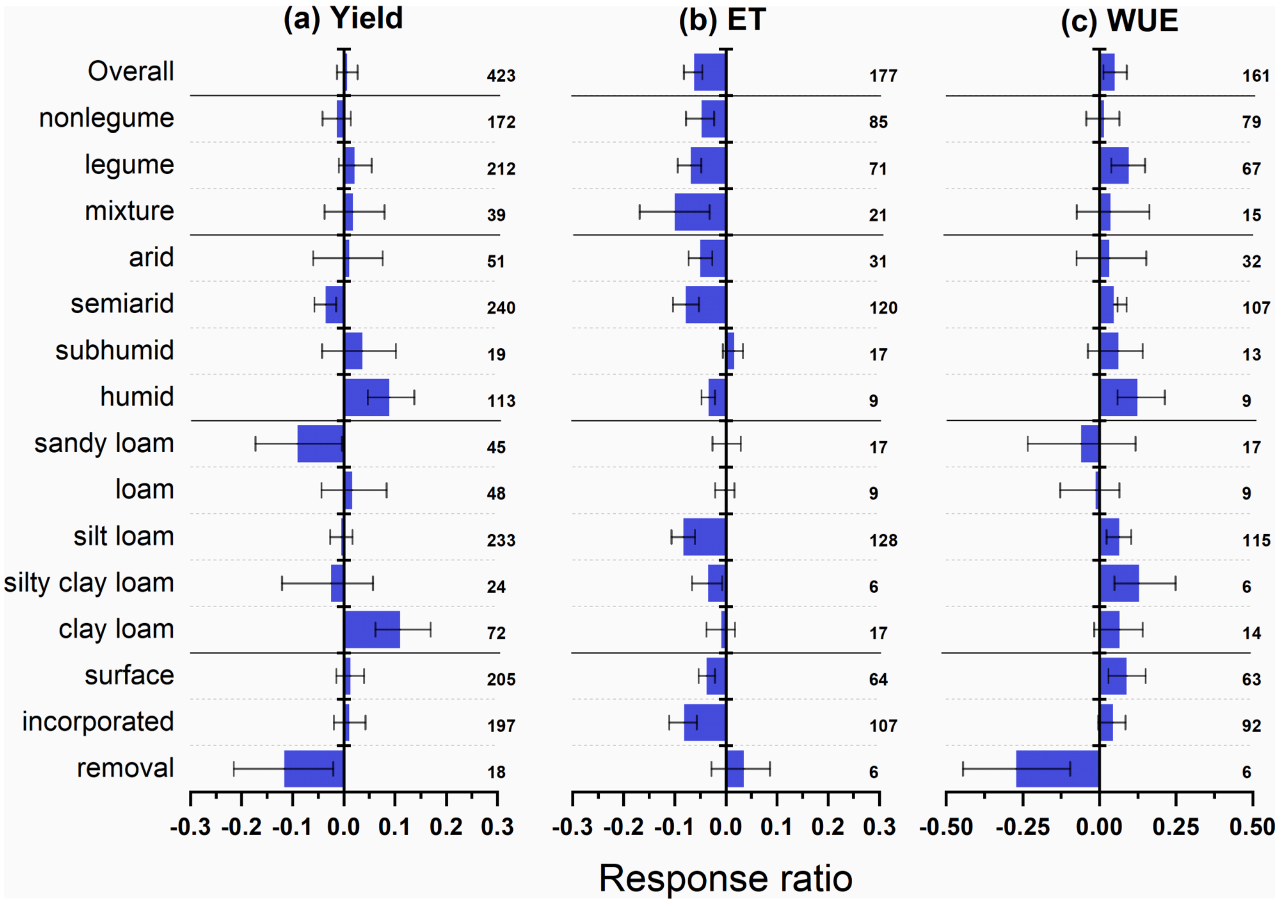

Fig. 5. Response ratio of cover crop compared to no cover crop with bootstrapped 95% confidence interval on succeeding crop yield, evapotranspiration (ET), and water-use efficiency (WUE) for cover crop species, climatic zones, soil textures, and residue management. Numbers on the right side of the bar for each category of the parameters are numbers of data used for meta-analysis.

in PSE due to cover crop compared to no cover crop. Soil water recharge following precipitation, however, may have increased SWSP30 due to cover crop compared to no cover crop in all soil textures (Fig. 3c). Increased water extraction by cover crop compared to water conservation by cover crop residue probably increased PSE and SWSPT with surface placement and incorporated residue into the soil (Fig. 3a and b). Residue retention either at the soil surface or through incorporation into the soil clearly increased SWSP30 by increasing soil water conservation from the mulch effect of residue, while residue removal diminished SWSP30 (Fig. 3c).

Cover crop biomass can affect PSE and SWSP30 in various ways. Increased shading from enhanced cover crop biomass can reduce evaporation and therefore maintain SWSP30 (Blanco-Canqui et al., 2015; Mitchell et al., 2015a, 2015b). In contrast, greater water extraction from increased cover crop biomass can reduce PSE and SWSP (Unger and Vigil, 1998). The positive linear relationship between RR of cover crop and cover crop biomass for PSE (Fig. 4a) suggests that increased shading effect from cover crop biomass probably enhanced PSE. Positive relationship between RR of SWSP30 and cover crop biomass also occurred to a biomass of 5 Mg ha^{-1}, above which the RR declined with further increase in biomass. This suggests that cover crop biomass should not be accumulated to more than 5 Mg ha^{-1} in order to maintain soil water in surface layers and succeeding crop yield, as dryland crop yield depends on surface soil water storage at planting SWSP30 (Unger and Vigil, 1998; Nielsen et al., 2015b). Barker et al. (2018) observed no difference in SWSPT to a depth of 1.2 m in the spring and SWSP30 in the winter following cover crops compared to no cover crop, when the biomass was < 1.75 Mg ha^{-1} in Nebraska.

Timing of cover crop termination can influence SWSPT by reducing water extraction by cover crop. Early termination reduces cover crop biomass, but increases SWSPT by increasing soil water recharge during the fallow period following precipitation by increasing the interval between cover crop termination and succeeding crop planting. In contrast, late termination can enhance cover crop biomass, but reduces SWSPT by extracting soil water by cover crop. This result (Fig. 4b) demonstrates that 20 d is the appropriate interval between cover crop termination and succeeding crop planting to maximize SWSPT. Although SWSPT increased from 0 to 20 d interval, it declined after 20 d probably because of increased water loss from evaporation. Some researchers (Clark et al., 1997; Whish et al., 2009; Daigh et al., 2014) reported that 14-d interval between cover crop termination and succeeding crop planting can be used to enhance SWSPT. Increasing the interval to $>$ 4 wk can reduce soil water storage (Clark et al., 1997) towing to increased surface evaporation.

4.2. *Effect of cover crop on succeeding crop yield*

The overall nonsignificant effect of cover crop on succeeding crop yield (Fig. 5a) can be explained by soil water and nutrient availability. Legume cover crops have been known to enhance succeeding crop yields by supplying N compared to non-legumes or no cover crop, but nonlegume cover crops can reduce yields (Gabriel and Quemada, 2011; Alvarez et al., 2017; Marcillo and Miguez, 2017; Daryanto et al., 2018). This was also observed for slightly but not significantly greater succeeding crop yield with legume and mixture of legume and nonlegume cover crops compared to no cover crop. Legumes can fix N from the atmosphere, and rapid mineralization of the N-rich residues can enrich soil inorganic N to meet N demand of succeeding crops (Daryanto et al.,

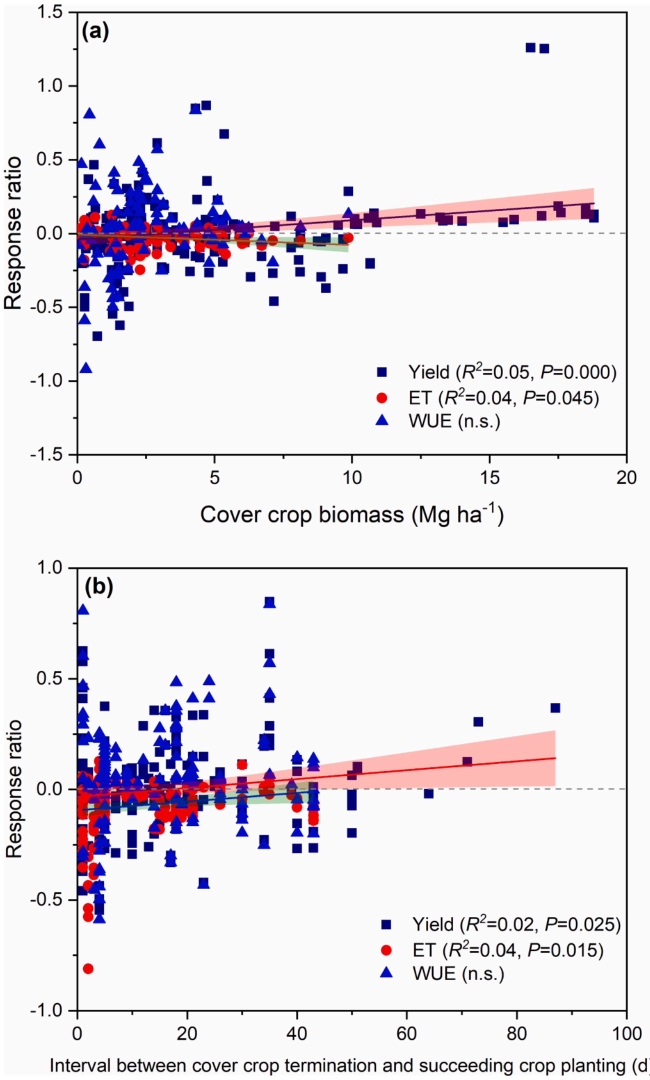

Fig. 6. Relationship between the response ratio of cover crop compared to no cover crop on (a) cover crop biomass (b) and the interval between cover crop termination and planting of succeeding crop for succeeding crop yield, evapotranspiration (ET), and water-use efficiency (WUE).

2018). In contrast, the slightly negative succeeding crop yield with nonlegume cover crop compared to no cover crop was probably resulting from greater water extraction by cover crop due to increase biomass, followed by soil N immobilization by nonlegume cover crop residue due to its greater C/N ratio. Nonlegume cover crops produce greater above- and belowground biomass and have higher C/N ratio than legume cover crops (Kuo et al., 1997). The overall result was the nonsignificant effect of cover crop on succeeding crop yield, as data were pooled from legume, nonlegume, and legume and nonlegume mixture, and no cover crop for analysis.

The nonsignificant or negative effect of RR of cover crop on succeeding crop yield in arid and semiarid regions (Fig. 5a) can be attributed to reduced soil water storage due to water extraction by cover crops and limited precipitation in these regions, as precipitation following cover crop termination may not be enough to recharge soil water and sustain succeeding crop yield (Unger and Vigil, 1998). Studies in arid and semiarid regions have reported that cover crops reduced succeeding crop yields by depleting soil water compared to no cover crop (Lyon et al., 2007; Kramberger et al., 2009; Nielsen et al., 2015b). It may be possible that cover crop residue accumulated at the soil surface conserved soil water, resulting in the nonsignificant effect of cover crop

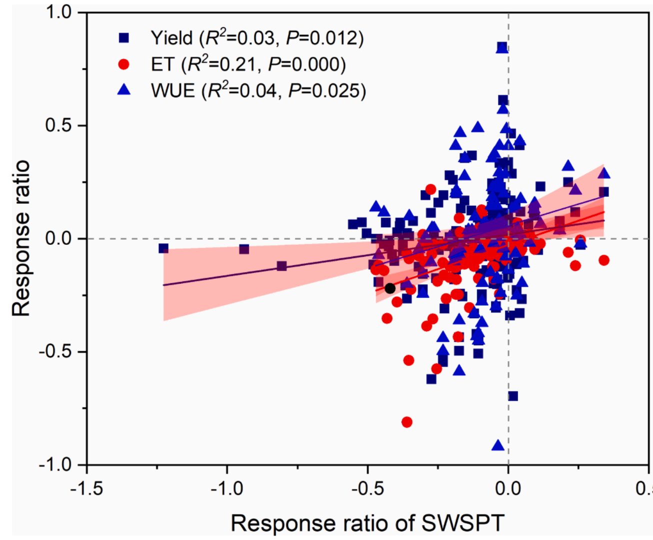

Fig. 7. Relationship between the response ratio of cover crop compared to no cover crop and soil water storage at planting of the succeeding crop (SWSPT) for succeeding crop yield, evapotranspiration (ET), and water-use efficiency (WUE).

on SWSP30 in the arid region or increased value in the semiarid region (Fig. 3b), although SWSPT was lower with cover crop than without (Fig. 3c). Because most of the root growth occurs in the surface soil layer, soil water stored in the surface layer may be more important for crop growth than water stored in the entire soil profile. As a result, there was no significant effect of cover crop on succeeding crop yield in the arid and semiarid regions. In subhumid and humid regions where precipitation is abundant, extraction of soil water by cover crop probably has limited effect on soil water recharge, resulting in increased succeeding crop yield in these regions (Ewing et al., 1991; Unger and Vigil, 1998). Increased SWSPT due to cover crop compared to no cover crop increased succeeding crop yield (Fig. 7).

Differences in water holding capacity of soils probably affected the RR of cover crop on succeeding crop yield among soil textures (Fig. 5a) (Unger and Vigil, 1998; Blanco-Canqui and Ruis, 2020). Cover crop may have extracted most of the water from coarse-textured soil due to its lower water holding capacity, resulting in reduced succeeding crop yield with cover crop compared to no cover crop in sandy loam soil (Unger and Vigil, 1998). Furthermore, coarse-textured soils may also have more water lost through evaporation and deep percolation more rapidly than fine-textured soils, affecting succeeding crop yield. The reverse may be true in fine-textured (clay loam) soil where its greater water holding capacity may have limited water extraction by cover crop, resulting in increased soil water availability for succeeding crop and enhancing its yield.

Retaining cover crop residue either through surface placement or incorporation into the soil probably enhanced soil water conservation and nutrient supply, thereby resulting slightly, but nonsignificantly, in increased succeeding crop yield with the residue placed at the soil surface or incorporated into the soil (Fig. 5a). In contrast, reduced soil water conservation and nutrient input resulting from residue removal may have reduced succeeding crop yield with this treatment. Retention of cover crop residue in the soil is critical for conserving soil water and increasing succeeding crop yield (Unger and Vigil, 1998; Chalise et al., 2019). Cover crop residue incorporated into the soil, regardless of species, can increase nutrient supply and support succeeding crop yield compared to residue removal (Poeplau and Don, 2015).

4.3. *Cover crop effect on succeeding crop water use*

The lower ET of the succeeding crop for all cover crop species compared to no cover crop (Fig. 5b) was probably due to reduced SWSPT (Fig. 3b). It may be possible that increased water extraction by cover crop reduced SWSPT and therefore ET. The negative ET response for cover crop compared to no cover crop was observed in all climatic zones, except nonsignificant in the subhumid region (Fig. 5b). This result also parallels with lower SWSPT in all climatic regions where SWSPT for cover crop compared to no cover crop was lower or not significant in all regions (Fig. 3b). Similarly, reduced ET for cover crop compared to no cover crop also occurred in silt loam and silty clay loam soils where SWSPT were lower or not significantly different (Fig. 3b). Enhanced soil water conservation due to cover crop residue retention in the soil, whether at the surface or incorporated, may have reduced SWSPT (Fig. 3b) and therefore ET (Fig. 5b). Residue removal from the soil, however, increased ET with cover crop compared to no cover crop, although it reduced SWSPT (Fig. 3b). Increased water lost through evaporation due to residue removal may have increased ET. Residue cover in the soil often reduces soil temperature, consequently reducing evaporation (Dabney, 1998; Gabriel et al., 2014). There was a strong positive relationship between ET and SWSPT (Fig. 7), suggesting that ET reduces as SWSPT decreases.

A negative linear relationship also occurred between RR of cover crop and cover crop biomass for ET (Fig. 6a). It is likely that increased cover crop biomass occurred at the expense of SWSPT, thereby reducing ET. In contrast, a positive linear relationship occurred between RR of cover crop and the interval between termination of cover crop and planting of succeeding crop for ET (Fig. 6b). Increased water loss through evaporation during the fallow period probably increased ET as the interval between cover crop termination and succeeding crop planting increased.

Lack of a significant effect of cover crop on succeeding crop yield, but reduced ET, resulted in the nonsignificant effect of overall cover crop as well as nonlegume and mixed cover crops in WUE (Fig. 5). An exception, however, occurred for legume cover crop where WUE was greater (Fig. 5c). A small increase in succeeding crop yield, but reduced ET, may have increased WUE for legume cover crop. Similarly, increased succeeding crop yield, but reduced ET, may have increased WUE for cover crop compared to no cover crop in subhumid and humid regions. The nonsignificant effect of cover crop on succeeding crop WUE in arid and semiarid regions was due to the limited effect on crop yield and ET. Reduction in succeeding crop yield, but nonsignificant effect of cover crop compared to no cover crop on ET, also reduced WUE in sandy loam soil. Similarly, nonsignificant succeeding crop yield, but reduced ET, decreased WUE due to cover crop compared to no crop for residue placed at the surface or incorporated into the soil. In contrast, reduced succeeding crop yield, but increased ET, reduced WUE for residue removal. The positive relationship between RR of WUE and RR of SWSPT (Fig. 7) suggests that soil water storage at planting may play an important role in WUE.

4.4. Limitations

Although no publication bias was found in this meta-analysis (Supplementary Table S3), limited data available for PSE, SWSP, succeeding crop yield, ET, and WUE in certain climatic zones and soil texture as well as residue management practices may have resulted in inconclusive results. For example, RR of cover crop for PSE was greater in loam, but lower in all other soil textures (Fig. 3). Residue removal increased PSE, but reduced SWSPT and SWSP30. Similarly, succeeding crop yield and ET in response to cover crop compared to no cover crop were lower, but WUE was greater for silty clay loam soil (Fig. 5). This resulted in the reduced reliability of interpretation for certain parameters in some soil and climatic conditions and residue management Practices. Increased data availability, however, will enhance the meta-analysis of these data in the future.

5. Conclusions

Cover crop reduced PSE, SWSPT, and ET compared to no cover crop, but had limited effect on succeeding crop yield and WUE. The effect of cover crop on PSE, SWSPT, SWSP30, succeeding crop yield, ET and WUE varied in regions with various soil and climatic conditions and residue management practices. Cover crop usually had positive effects on PSE, SWSP30, succeeding crop yield and WUE in the humid region and fine-textured soil, and residue retention in the soil. Maintaining cover crop biomass to 5 Mg ha^{-1} and the interval between cover crop termination and succeeding crop planting to 20 d also had positive effect on SWSPT and succeeding crop yield. One approach to enhance SWSP, succeeding crop yield, and WUE is to choose cover crops that require less water to grow, such as broadleaf types (USDA-ARS, 2018), especially in arid and semiarid regions. There should be at least a 3 week interval between cover crop termination and planting of succeeding crop so that soil water can be recharged during the fallow period. Leaving cover crop residue on the soil surface can increase soil water storage thanks to reduced ET, resulting in enhanced crop yield and WUE. Removal of cover crop residue from the soil is undesirable because it reduces SWSP30 and SWSPT, promotes ET, and decreases succeeding crop yield and WUE.

Declaration of Competing Interest

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

Acknowledgements

Authors appreciate Prof. Charles P. West and Dr. Andrea Basche for reviewing and editing the earlier version of the paper. The study was supported by the Chinese Academy of Sciences “Light of West China” Program for Introduced Talent in the West, the National Natural Science Foundation of China (Grant No. 31570440, 31270484), and the Key International Scientific and Technological Cooperation and Exchange Project of Shaanxi Province, China (Grant No. 2020KWZ-010).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2021.107085.

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