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No tillage increases soil microarthropod (Acari and Collembola) abundance at the global scale

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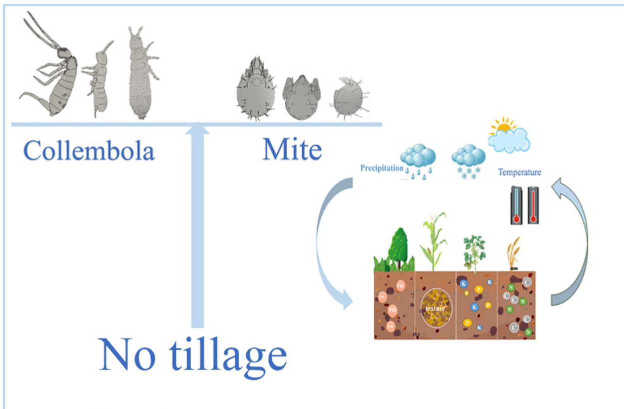
ABSTRACT



- Conservation tillage increases soil microarthropod abundance at the global scale.
- The effect of conservative tillage on microarthropods is soil texture-dependent.
- This positive effect of conservation tillage is particularly evident in nutrient-poor soil areas.
- In temperate humid regions, however, this positive effect of conservation tillage is limited.
- The effect of conservative tillage on microarthropods varies with fauna group and climate regions.

Conservation tillage is crucial for preserving soil structure and fertility. However, the effects of no tillage on the abundance of soil microarthropods (Acari and Collembola) remain unclear, with contrasting results reported. To assess the global impact of no tillage, we compiled a data set consisting of 59 publications, from which we extracted 167 observations for microarthropod abundance, 193 observations for Acari abundance, and 176 observations for Collembola abundance. Our findings revealed significant increases in soil microarthropods (27.1%), Acari (22.1%), and Collembola (32.3%) compared to conventional tillage under no tillage. The impact varied with soil texture, precipitation, and soil nutrient availability. Furthermore, to assess the impact of reduced tillage, we extracted 46 observations for microarthropod abundance, 64 observations for Acari abundance, and 27 observations for Collembola abundance. Reduced tillage also showed positive effects, with a 28.4% increase in soil microarthropods and a 53.7% increase in Acari compared to conventional tillage. Our research demonstrates the beneficial effects of no tillage and reduced tillage on soil microarthropod abundance. However, the positive effect of conservation tillage on soil microarthropods differed in magnitude Collembola and Acari. Conservation tillage should be encouraged, particularly in regions with poor soil nutrients and high precipitation, to prevent further decline in soil microarthropod abundance.

Keywords no tillage, soil microarthropod, Acari, Collembola, meta-analysis

1 Introduction

Intensification of agriculture has globally stressed ecosystems (Smith et al., 2016). However, it is crucial to acknowledge that human activities, particularly those related to land management and utilization, impose substantial pressure on soil ecosystems. Intensive soil management practices, such as extensive fertilizer and pesticide application, high-intensity soil use, and machinery-induced soil disturbance, impact the physicochemical and biological properties of the soil, including its structure, material composition, and biodiversity (Booher et al., 2012; Jiang et al., 2021), for instance, Beaumelle et al. (2023) demonstrated that pesticide

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application resulted in decreased abundance and diversity of soil fauna. Soil biodiversity is critical for soil safety and sustainable production (Kassam et al., 2009, 2010; Verhulst et al., 2010; Tittonell, 2014). These issues raise a fundamental question: How can we preserve soil biodiversity while ensuring sustainable agricultural production? This study aims to explore a potential solution—conservation tillage, particularly the no tillage system—and its impact on the abundance of soil microarthropods, including Acari and Collembola. Despite existing research focusing on the effects of no tillage on the abundance of soil microarthropods (Acari and Collembola), there remains need for a more in-depth investigation to determine whether these effects are consistent on a global scale.

Conservation tillage plays a key role in mitigating soil ecological pressure, cutting production costs, and preserving soil quality and biological activity (Sapkota, 2012; Seitz et al., 2019; Fiorini et al., 2020). Conversely, conventional tillage, while effective in suppressing the growth of annual weeds and facilitating precise seed placement (Barberi and Lo Cascio, 2001; Ehlers and Claupein, 2017), has detrimental consequences such as soil structure degradation, subsoil compaction, soil erosion, and a decline in organic content (Holland, 2004; Bulte et al., 2005). Moreover, intensive management practices associated with conventional farming can compromise the soil's water and nutrient retention capacity, exacerbating its susceptibility to compaction and surface crust formation. Such practices also result in physical disturbance and nutrient depletion, ultimately limiting the availability of food resources for soil microarthropods and disrupting the habitat of burrowing organisms (Bedano et al., 2006). In contrast, the implementation of no tillage as a conservation tillage strategy does not necessitate soil disturbance during the processes of planting and harvesting processes (Kassam et al., 2009), thereby minimizing damage to the physical structure of tillage soil, increases the organic matter content and bulk density, and preserving the soil aggregate stability (Singh et al., 2018; Coulibaly et al., 2022). However, it should be noted that the use of pesticides, herbicides, and chemicals is increased in this approach, which can have minimal impacts on soil biodiversity (Arroyo and Iturrondobeitia, 2006; Disque et al., 2019; Fiera et al., 2020; Rieff et al., 2020). Agricultural practices that alter soil physicochemical properties have implications not only for soil biodiversity but also for crop productivity (Kladivko, 2001; Mirzaei-Pashami et al., 2020).

Soil microarthropods, primarily dominated by Acari and Collembola, are crucial constituents of soil organisms. They serve as indicators of soil quality and offer valuable insights into soil properties changes (Karg, 1982; Gardi et al., 2009). Furthermore, soil microarthropods play a vital role in preserving soil ecosystem health through their influence on soil biodiversity and nutrient cycling (Filser, 2002; Kaneda and Kaneko, 2008; Zhang et al., 2021). Given the growing significance of soil microarthropods diversity in the study of soil ecosystems, the impact of conservation tillage practices on their diversity has garnered considerable attention.

In recent years, there has been a growing research interest in farmland tillage and soil microarthropods (Yin et al., 2019; Coulibaly et al., 2022; Yu et al., 2022; Reilly et al., 2023), leading to a more comprehensive understanding of the niche and microhabitat soil microarthropods. The management of farmland tillage can have an impact on the abundance of soil microarthropods, including Acari and Collembola. According to Betancur-Corredor et al. (2023), the application of organic nitrogen fertilization has been shown to increase the abundance of soil microarthropods, including Acari and Collembola, while the application of inorganic fertilizer decreases their abundance. Additionally, research conducted by Betancur-Corredor et al. (2022) suggests that reducing the intensity of tillage can result in the increased abundance of soil Acari. Concurrently, soil microarthropods offer feedback on tillage for assessing the quality of cultivated soil (Jerez-Valle et al., 2014). Studies indicate that soil microarthropods demonstrate sensitivity to such changes in tillage management (Nadia Vignozzi et al., 2019; Yin et al., 2020). The abundance of soil microarthropods is closely associated with soil characteristics, encompassing pH, organic matter, water content, and particle size distribution (Verhulst et al., 2010; Sapkota, 2012; Xin et al., 2018). For instance, microhabitat's humidity is a significant factor affecting both the distribution and abundance of Collembola and Acari (Kardol et al., 2011; Rahgozar et al., 2019; Mirzaei-Pashami et al., 2020); soil aggregates and soil respiration affect the abundance of soil microarthropods (Machado et al., 2019; Jernigan et al., 2020); and soil organic matter and microbial carbon were significant factors in the abundance of soil Collembola and Acari (Machado et al., 2019; Coulibaly et al., 2022). Nevertheless, some studies have shown that no tillage farming has no noticeable impact on soil microarthropods, including Acari and Collembola (Zhan, 2013), and other research has reported positive on the abundance of Acari and Collembola (Dubie et al., 2011; Liu et al., 2013), as well as the negative effects on Acari and Collembola (Xin et al., 2018). The majority of studies on microarthropods in farmland soil has primarily concentrated on the impact of soil properties and farmland tillage practices. The impact of tillage on soil microarthropods may be influenced by the pre-tillage soil conditions, which have not been addressed in previous studies. The characteristics of the soil and the climate before tillage may have an impact on how no tillage affects soil microarthropods (Spedding et al., 2004; Rożen et al., 2010; Kardol et al., 2011; Santos et al., 2018). For instance, Domínguez et al.

(2010) demonstrated that the impacts of no tillage may vary depending on the soil qualities. In certain soils and climates, no tillage did not improve the physical, chemical, and biological properties of soils (Domínguez et al., 2010). Christine (1991) demonstrated that in temperate regions, no tillage led to a decrease in the abundance of soil Acari and Collembola. The increased abundance of Acari and Collembola in no tillage soils may be attributed, in part, to factors such as higher organic matter, increased water capacity, enhanced soil aggregates stability, improved water infiltration rates, greater aeration, and reduced compaction in no tillage systems (Singh et al., 2018; Jernigan et al., 2020). This phenomenon can be attributed to the enhanced distribution and availability of organic matter including organic carbon stocks, bacterial and fungal biomass, and their potential for carbon mineralization, serving as a fundamental food source (Verhulst et al., 2010; Li et al., 2020).

Thoroughly examining the interplay between soil properties, climate, and the effects of no tillage on soil microarthropods (Acari and Collembola) has been challenging due to the reliance of previous investigations on site-specific data regarding soil properties and climatic conditions (van Capelle et al., 2012; Coulibaly et al., 2022; Morugán-Coronado et al., 2022). We conducted a meta-analysis to assess the effects of no tillage farming on soil microarthropod (Acari and Collembola) and to examine the influence of soil properties and climate factors on the interplay between no tillage practices and soil microarthropods. The meta-analysis involved systematically gathering and analyzing relevant literature. We hypothesize that: (1) no tillage practices will increase the abundance of soil microarthropod (Acari and Collembola), compared to conventional tillage. Previous studies have shown the beneficial effects of no tillage practices, such as reduced soil disturbance, increased organic matter content, and improved soil moisture levels (Chivenge et al., 2007; Borgognone and Basile, 2017), which are likely to increase microarthropod abundance by improving habitat conditions and resource availability. (2) The effect of no tillage practices on soil Collembola abundance is expected to be greater compared to soil Acari. This difference can be attributed to the presence of sensory organs in soil Collembola, such as well-developed furca and slender antennae, which enable them to detect and respond to environmental changes, search for food, and avoid potential threats (Graham et al., 1994; Mitchell et al., 2017; Li et al., 2020). (3) The effect of no tillage on soil microarthropods abundance will be more pronounced in regions characterized by poor soil structure and lower nutrient availability. Previous research indicates that soil characteristics like organic matter content, texture, and pH have a stronger influence on soil fauna compared to tillage practices (Chivenge et al., 2007). In such areas, it is likely that no tillage practices will have a significant impact on soil nutrient levels, organic matter content, soil structure, and water retention (Rożen et al., 2010; Sékou, 2017; Belmonte et al., 2018; Singh et al., 2018).·

2 Materials and methods

2.1 Search strategy

Peer-reviewed literature data, obtained through a systematic literature search, were utilized to quantify the correlation between no tillage and the abundance of microarthropod, including Acari and Collembola. This study encompasses pertinent studies collected from January 1980 to April 2022, sourced from the Web of Science and CNKI (China National Knowledge Infrastructure) databases. The search was performed on April 7, 2022, utilizing the following search formulae: ((Mite* or Acarus or Acari or Acarina or Oribatida or Mesostigmata or Prostigmata) OR (Collembola or collembolan* or springtail* or Folsomia or candida or podura or snowflea or jumper)) AND (no-tillage or zero tillage or no-till or no tillage). A total of 335 papers from Web of Science and 11 papers from CNKI were identified. After removing 6 duplicates from the 346 papers, the remaining 340 papers were elected based on relevance by thoroughly reviewing their full texts and abstracts. Ultimately, this article is based on a selection of 59 articles, including 47 focused on Collembola, 46 on Acari, and 32 on microarthropods. It is important to clarify that among these articles, 13 articles included data on all three categories— Collembola, Acari, and microarthropods, while 32 articles exclusively focused on Collembola and Acari. The process of literature selection is illustrated in Fig. S1.

2.2 Inclusion and exclusion criteria

Prior to study selection, a comprehensive review of relevant literature was conducted, encompassing titles, abstracts, and full texts, to ensure conformity with the predefined criteria. With the exception of treatment variations, the experimental treatments for no tillage were required to demonstrate the presence of soil Acari, or Collembola. Furthermore, the experimental treatments were required to include conventional tillage with comparable levels of soil Acari or Collembola. Articles failing to meet these criteria were excluded from the analysis. The study areas of the 59 articles selected for meta-analysis are depicted in Table 1.

2.3 Data extraction

Most of the articles we analyzed included data on microarthropod abundance. Many of these studies

Table 1 Geographical location of the 59 articles (or source) included in the meta-analysis.

Articles	Latitude	Longitude	Articles	Latitude	Longitude	Articles	Latitude	Longitude
1	−37.78	−122.22	21	31.72	73.98	41	43.02	10.60
2	−34.28	138.78	22	33.96	−83.38	42	43.32	124.23
3	−33.28	−63.90	23	33.96	−83.38	43	43.54	−80.25
4	−30.00	−53.50	24	33.96	−83.38	44	43.62	−120.35
5	−29.96	−49.42	25	35.00	114.40	45	44.31	−85.60
6	−26.78	−49.10	26	35.02	114.53	46	45.13	42.06
7	−22.23	−54.82	27	35.02	114.53	47	45.44	10.99
8	−20.86	−42.80	28	35.38	−78.08	48	45.44	10.99
9	−20.38	−41.05	29	36.03	48.99	49	45.63	−122.67
10	−18.06	−49.51	30	37.72	140.38	50	46.37	−76.41
11	−11.86	−55.37	31	38.54	−76.08	51	46.31	−63.38
12	12.20	125.55	32	39.00	−76.49	52	47.43	126.63
13	20.85	−42.80	33	39.32	−5.32	53	47.43	126.63
14	23.62	104.35	34	39.96	116.23	54	47.43	126.63
15	25.45	−50.55	35	40.25	−8.32	55	51.10	17.13
16	26.35	92.83	36	40.41	−82.91	56	120.20	34.24
17	29.30	330.85	37	41.71	15.95	57	−30.33	149.78
18	29.80	76.92	38	41.87	1.15	58	36.17	97.31
19	29.80	76.92	39	42.88	143.88	59	38.38	75.58
20	29.96	−90.07	40	42.93	120.68			

incorporated both reduced tillage and no tillage treatments in their experimental designs. Therefore, we extracted this specific subset of data to acquire relevant information.

The following data were extracted and recorded: mean abundance of microarthropods, Acari, and Collembola; sample size; standard deviation and standard error for no tillage, reduced tillage, and conventional tillage soils. Additionally, we collected information on the latitude and longitude of the study area, soil texture, pH, organic matter content, soil total nitrogen content, soil phosphorus availability content, and soil potassium availability content prior to the experimental treatments. These data were extracted from tables or graphs using WebPlotDigitizer-3.8-Desktop for digitization. Visual verification was performed to ensure the accuracy of data extraction from graphs and to eliminate errors during the process. The latitude and longitude of the study area, along with its location as specified in the respective article, were directly obtained from the source material. Google Maps was utilized to determine the latitude and longitude coordinates of the study area, while ArcGIS 10.6 was employed to extract the climate data of the study area from the respective climate data layer.

Effect size metrics:

We calculated the log response ratio (*RR*, hereafter response ratio) as a measure of the effect size (Hedges et al., 1999; Lajeunesse, 2011).

$$RR = \ln R = \ln \frac{Y_{NT/RT}}{Y_{CT}}$$

$Y_{NT/RT}$: mean abundance of soil microarthropods, Acari, Collembola in each study for no tillage or reduced tillage soils. Y_{CT}: mean abundance of soil microarthropods, Acari, Collembola in each study of conventional tillage.

Meta-analyses and meta-regressions, observed effect sizes (RRs) were weighed by the inverse of the sampling variances, which were calculated as:

$$V^2(RR) = \frac{SD^2_{NT/RT}}{N_{NT/RT}\bar{Y}^2_{NT/RT}} + \frac{SD^2_{CT}}{N_{CT}\bar{Y}^2_{CT}}$$

$N_{NT/RT}$: sample size for soil microarthropods, Acari, Collembola in each study of no tillage or reduced tillage soils. N_{CT}: sample sizes for soil microarthropods, Acari, Collembola in each study of conventionally tilled soils. $\bar{Y}_{NT/RT}$: mean abundance of microarthropods, Acari, Collembola in no tillage or reduced tillage soils. $\bar{Y}_{CT}$: mean abundance of microarthropods, Acari, Collembola in conventional tillage soils. $SD_{NT/RT}$: the standard deviation for soil microarthropods, Acari, Collembola in each study of no tillage or reduced tillage soils. SD_{CT}: standard deviations for soil microarthropods, Acari and Collembola in each study of conventionally tillage soils. In cases where standard deviations are not reported in the literature, we employ the formula $SD = \sqrt{n} * SE$ (where *n* represents the sample size and *SE* represents the standard error) to convert the provided standard errors into standard deviations. This allows us to depict the data on soil microarthropods, Acari, and Collembola in conventionally tilled soils. If standard deviations and standard errors are not reported in the literature, we utilize the "Bracken 1992" method, which entails estimating the standard deviation (*SD*) by interpolating it using the coefficient of variation derived from all complete cases (Lajeunesse, 2011; Benítez-López et al., 2017). This analysis is performed using the meta gear package in R (Speidel, 1992).

The percentage increases in soil microarthropods, Acari, and collembolans for no tillage and reduced tillage soils was calculated as ($\exp(y_i) - 1) \times 100$) (Benítez-López et al., 2017). The study used the log response ratio (*RR*) as the effect value. A log response ratio (*RR*) greater than zero indicates a positive impact of the treatment on the abundance of the study subject, while a negative *RR* signifies a negative impact. A value of zero for the *RR* indicates that the treatment has no effect on the abundance of the subject under investigation. A total of 167 studies were reviewed to assess the effect of no tillage on soil microarthropods abundance, while 193 studies were screened for the impact on soil Acari abundance, and 176 studies were analyzed to explore the effect on soil Collembola abundance. Additionally, 46 studies were reviewed to investigate the effect of reduced tillage on soil microarthropods abundance, while 64 studies were analyzed for the impact on soil Acari abundance, and 27 studies were reviewed to investigate the effect on soil Collembola abundance.

2.4 Data analysis

We used the multilevel mixed effects meta-analyses to control for non-independence of different studies from the same literature. For model selection, we considered the random effects of reference, studies, and studies nested within references. Depending on the model's BIC for determining the inclusion or exclusion of random effects (Anderson and Burnham, 2004), the no tillage analysis ultimately retained a random effect structure of (1|reference/study), while reduced tillage analysis retained a random effect structure of (1|study) (Table S1).

The analysis consisted of three steps: random-effects meta-analysis, single-factor mixed-effects meta-regression analysis, and multi-factor mixed-effects meta-regression analyses. The random-effects meta-analysis assessed the overall impact of no tillage and reduced tillage practices on the abundance of soil microarthropods, Acari, and collembolans. Heterogeneity was assessed using Cochran's Q-test (QE), and the results revealed significant heterogeneity in the effects of no tillage on soil microarthropods (QE = 2455.8, $p < 0.01$), Acari (QE = 99873.8, $p < 0.01$), Collembola (QE = 13654887.1, $p < 0.01$), as well as in the effects of reduced tillage on soil microarthropods (QE = 2322.2, $p < 0.01$), Acari (QE = 17238.2, $p < 0.01$), and Collembola (QE = 257.3, $p < 0.01$), Table S2.

Single-factor mixed-effects meta-analysis was employed to examine the relationship between 13 variables, including soil texture (a factorial variable), organic matter content, and pH value prior to tillage, and the effect size (*RR*). The 12 continuous variables were standardized using Z-scores to account for variations in magnitudes, prior to analysis. Single-factor mixed-effects meta-analyses were performed to examine the effect size of no tillage and reduced tillage for different textures. Additionally, these analyses explored the regression relationships between the 12 continuous variables and the effect size of no tillage and reduced tillage (Table S3).

To examine the relationship between the abundance effect size (*RR*) of Collembola, Acari, and microarthropods in no tillage soil and the continuous variables, a multi-factor mixed-effects meta-regression analysis model was employed. The importance of the characteristic variables was assessed using the MetaFores package in R (Lissa, 2017) (Fig. S2). The rma.mv () function of the R MetaFores package in R (Viechtbauer, 2010) and the glmulty () function of the glmulti package in R (Calcagno and de Mazancourt, 2010) were used to fit multiple models that included the five most important predictors and their interactions. Model selection was conducted procedure using maximum likelihood estimation. Model selection was performed using a small-sample modified Akaike information criterion (AICc). The relative importance value of a factor was calculated as the sum of the AICc weights of the models in which the factor was present (Terrer et al., 2021).

Assessing the robustness of the model and examining potential publication bias. Precision (1/*SE*) was utilized as a covariant in the rma.mv analysis and visualized through funnel plots and Egger tests. If there was minimal bias, the trim and fill method (Chatelain et al., 2020) was used to address it. Publication bias was evaluated using the mv function and meta residuals (Egger et al., 1997). The egger tests revealed significant publication bias for the following variables: no tillage soil microarthropods ($z = -0.98$, $p = 0.33$), Acari ($z = -1.14$, $p = 0.26$), and Collembola ($z = 0.56$, $p = 0.57$); as well as reduced tillage soil microarthropods ($z = 0.37$, $p = 0.71$), Acari ($z = -0.75$, $p = 0.44$), and Collembola ($z = 1.41$, $p = 0.16$). The model successfully passed tests for both robustness and potential publication bias, and the study's findings are accurately presented in Fig. S3. All analyses were conducted using R 4.21 software.

3 Results

3.1 Effect sizes for microarthropod (Acari, Collembola) in both no tillage and reduced tillage soils

Meta-analysis of the entire data set revealed that soil microarthropods abundance increased by 27.1% (95% confidence level: 6.2, 52.2%), soil Acari abundance increased by 22.1% (95% confidence level: 2.0, 46.2%), and soil Collembola abundance increased by 32.3% (95% confidence level: 5.1, 68.2%) in no tillage soil compared to conventional tillage. Compared to conventional tillage, soil microarthropods abundance increased by 28.4% (95% confidence: −0.2, 66.2%), soil Acari abundance increased by 53.7% (95% confidence: 20.6, 94.5%), and soil Collembola abundance was relatively reduced by 2.9% (95% confidence: −33.0, 39.3%) under reduced tillage, as shown in Fig. 1.

3.2 Impact of abiotic factors on the effect sizes of soil microarthropod (Acari, Collembola)

3.2.1 Soil microarthropods

We investigated the abundance of microarthropods in no tillage and reduced tillage soils, considering their relationship with soil properties (Table S3). The impact of no tillage on microarthropods abundance was significantly influenced by soil texture ($p < 0.01$). Specifically, when the soil texture was silty loam, no tillage practices result in significantly higher microarthropods abundance compared to conventional tillage ($p < 0.01$), Fig. 2A. Concerning the influence soil pH on soil microarthropods abundance under no tillage practices, it was observed that no tillage enhanced microarthropods abundance within the pH range of 5.1−8.3, with a decreasing effect as pH increases (Fig. 3C). Similarly, the effect of available phosphorus (P) content on microarthropods abundance in no tillage soils revealed that the influence of no tillage on microarthropods abundance increased as available soil P content decreased (Fig. 3D).

We evaluated the association between microarthropods abundance in no tillage and reduced tillage soils and climatic factors (Table S3). The analysis of mean annual precipitation revealed a positive trend between the effects of no tillage on soil microarthropods abundance and increasing annual precipitation. The impact of no tillage on microarthropods abundance varied depending on average annual precipitation. For areas with mean annual precipitation above 400 mm, no tillage practices had a more pronounced effect, resulting in increased microarthropod abundance compared to conventional tillage. Conversely, in areas with mean annual precipitation below 400 mm, no tillage practices led to a decrease in microarthropod abundance (Fig. 3B). Furthermore, the analysis of the precipitation of driest month demonstrated a positive trend between the effects of no tillage on microarthropods abundance and higher precipitation of driest month (Fig. 3A).

3.2.2 Soil Acari

The abundance of soil Acari in no tillage soils was significantly affected by soil texture ($p < 0.01$). Specifically, in sandy clay loam soil, the abundance of soil Acari was significantly higher in no tillage compared to conventional tillage ($p < 0.01$), Fig. 2C.

We investigated the correlation between no tillage practices and soil Acari abundance, taking into account the influence of climatic factors (Table S3). The analysis of the mean annual precipitation and no tillage effects on soil Acari abundance revealed a trend of increasing soil Acari abundance with annual precipitation. The impact of no tillage on soil Acari abundance depended on the level of mean annual

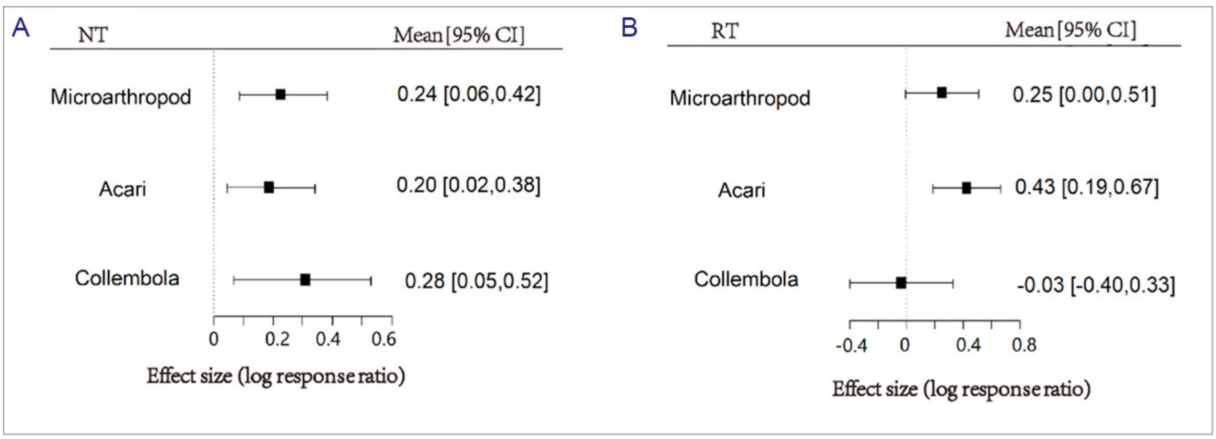

Fig. 1 Effects of no tillage and reduced tillage practices on microarthropod, Acari, and Collembola abundance: A Meta-analysis of weighted-mean effect sizes and 95% confidence intervals. NT and RT represent no tillage and reduced tillage, respectively. The grey dashed line represents the null effect (0); the small black squares denote weighted effect sizes with values outside the brackets; the lines extending from the small black squares indicate 95% confidence intervals with values enclosed in brackets.

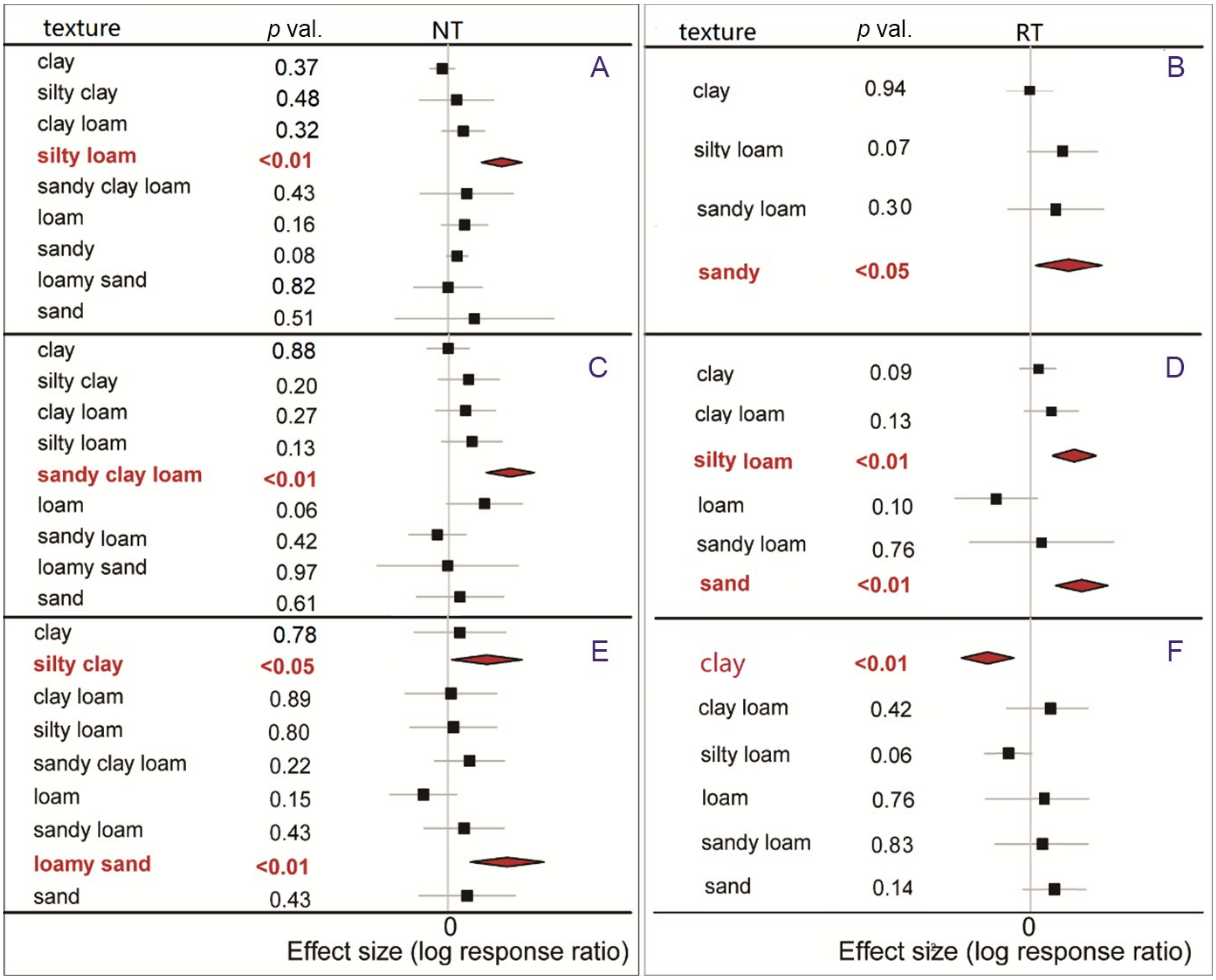

Fig. 2 Impact of soil texture on microarthropod, Acari, and Collembola abundance in no tillage and reduced tillage soils. The comparison between no tillage (NT) and reduced tillage (RT) is illustrated on the left and right, respectively; A and B represent soil microarthropods; C and D represent soil Acari; E and F represent soil Collembola.

precipitation. In wetter areas, no tillage had a greater effect, resulting in higher soil Acari abundance compared to conventional tillage. Conversely, in areas with a mean annual precipitation below 300 mm, no tillage led to a decrease in soil Acari abundance, whereas it increased in areas with a mean annual precipitation above 300mm, as compared to conventional tillage (Fig. 4A). Moreover, the impact of no tillage on soil Acari abundance was more pronounced in locations with higher precipitation of driest month, while it was relatively lower in areas with lower precipitation of the driest month (Fig. 4B). These findings highlight the stronger influence of no tillage practices on soil Acari abundance in areas with higher levels of both mean annual precipitation and precipitation of the driest month.

We conducted a comprehensive analysis to examine the impact of reduced tillage on soil Acari abundance (Table S3). Texture was found to significantly affect value (*RR*) of Acari abundance in reduced tillage soils ($p < 0.01$). For chalk loam and sandy soils, reduced tillage significantly increased soil Acari abundance compared to conventional tillage (Fig. 2D). The analysis of soil pH and the effect of reduced tillage on soil Acari abundance revealed that within the pH range of 5.8−6.7, reduced tillage led to increased soil Acari abundance. Additionally, we investigated the relationship between soil available phosphorus (P) and potassium (K) levels and the effect of reduced tillage on Acari abundance. The results revealed a significant relationship, indicating that lower levels of available P and available K were linked to a greater increase in Acari abundance in reduced tillage soils (available P: $p < 0.01$; available K: $p < 0.05$).

Reduced tillage practices resulted in increased soil Acari abundance compared to conventional tillage in regions with higher mean annual temperature (Table S3). We explored the association between mean annual temperature and the effect of reduced tillage on soil Acari abundance ($p < 0.05$).

3.2.3 Soil Collembola

We explored the correlation between soil properties and the effect size of Collembola abundance in no tillage soils

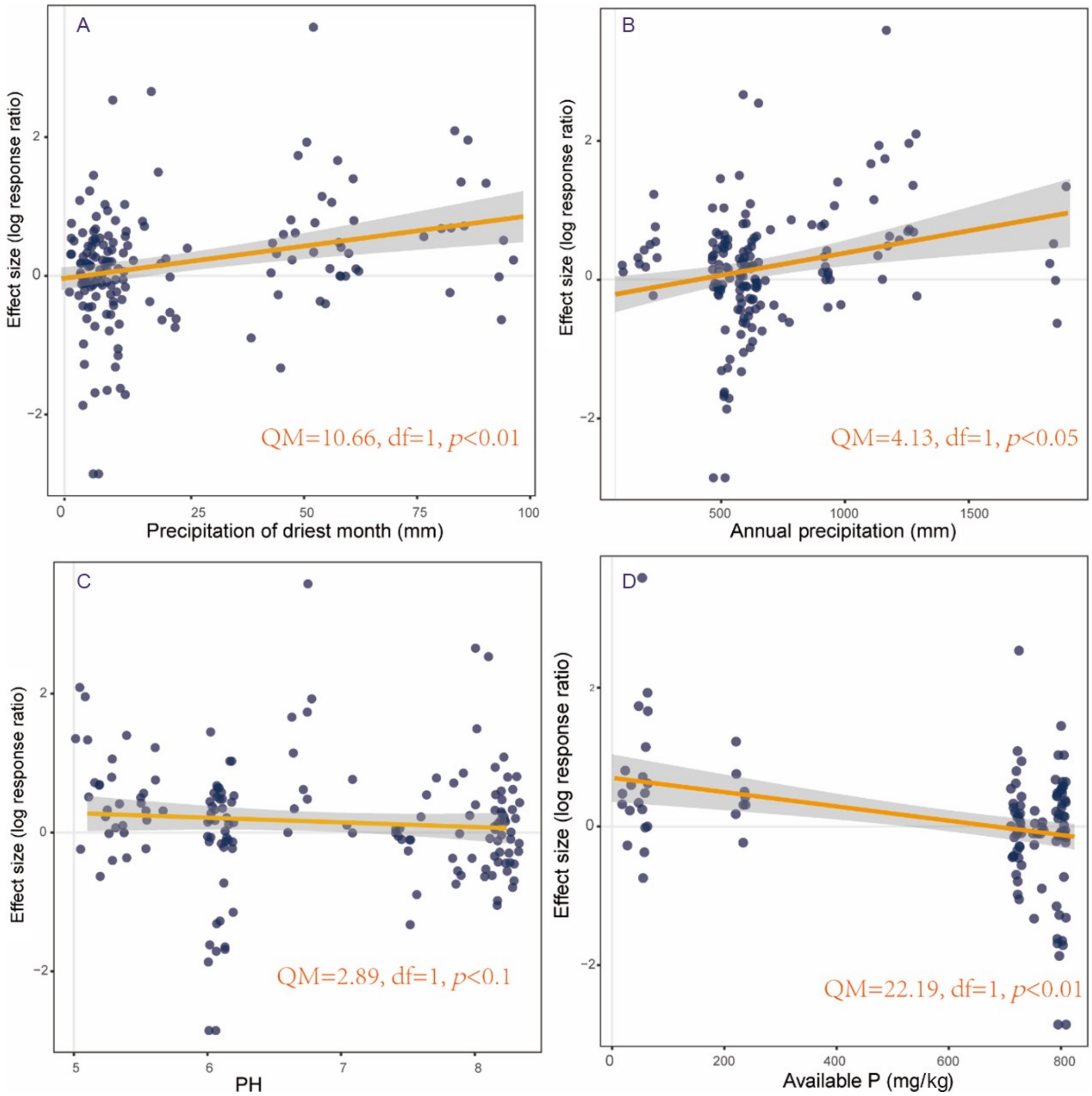

Fig. 3 Variation in effect sizes of microarthropod abundance in no tillage soils across different environmental factors. A to D indicate, respectively, the effect of precipitation of driest month, annual precipitation, soil pH and available P on the effect size of microarthropod abundance in no tillage soils.

(Table S3). Soil texture significantly influenced the effect size (*RR*) of Collembola abundance in no tillage soils ($p < 0.05$), with positive effects observed in silty clay and loamy sandy soils (Fig. 2E). The relationship between soil total nitrogen (N) content, organic matter content, and the effect of no tillage on soil Collembola abundance revealed that the effect size (RR) of no tillage was larger in soils with lower total N content and organic matter content. Specifically, no tillage increased soil Collembola abundance when the organic matter content ranged from 8 g kg^{-1} to 32 g kg^{-1} or when the total N content of the soil was less than 3.5g kg^{-1} (Fig. 5).

The impact of soil texture on the effect size (RR) of Collembola abundance in reduced tillage soils was found to be significant ($p < 0.10$) (Table S3). Specifically, for clay soils, reduced tillage led to a significant decrease in soil Collembola abundance compared to conventional tillage (Fig. 2F). The effect of reduced tillage on soil Collembola abundance increased with the increase of soil total nitrogen (N) content (Table S3). The relationship between mean annual temperature, maximum temperature, and the effect of reduced tillage on soil Collembola abundance revealed that the effect size (*RR*) of reduced tillage was greater in soils with lower mean annual temperature and maximum temperature (Table S3). These findings indicate that implementing reduced tillage practices can enhance soil Collembola abundance, particularly in colder regions.

3.3 The impact of temperature, precipitation, and their interaction on soil microarthropod (Acari, Collembola) abundance in no tillage management

The examination of microarthropod (Acari, Collembola) abundance in no tillage soils revealed a several significant

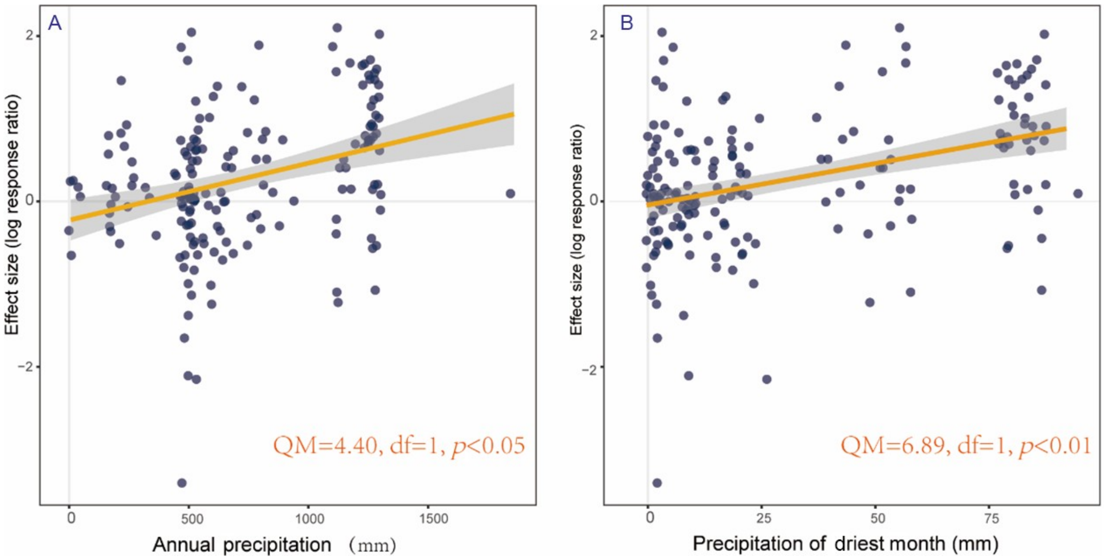

Fig. 4 Effect size of Acari abundance in no tillage soils under different annual precipitation and precipitation of driest month. A indicates annual precipitation, B indicates precipitation of driest month.

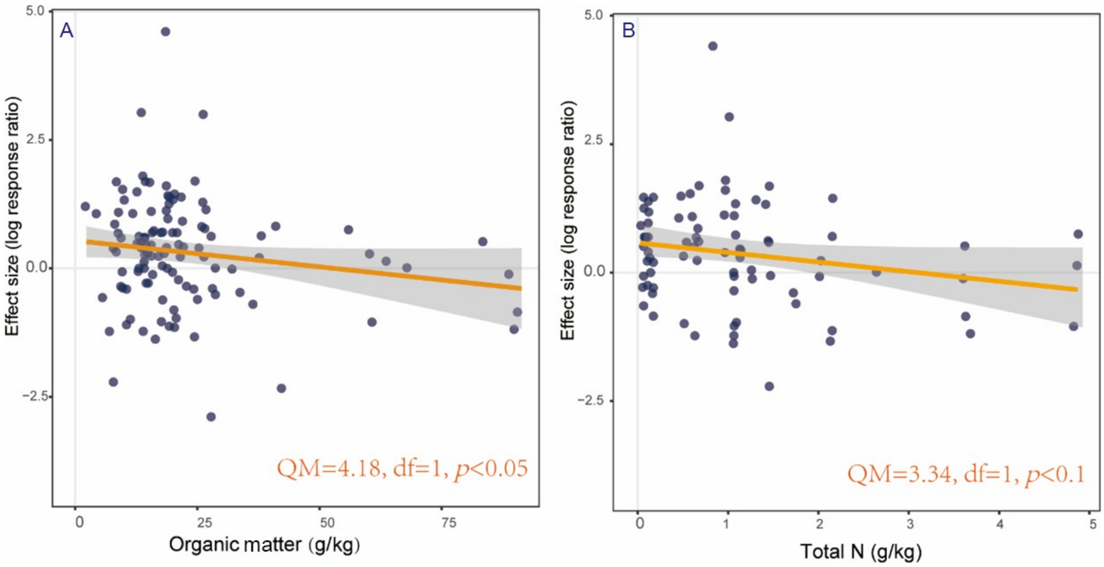

Fig. 5 Effect size of Collembola abundance in no tillage soils under different soil organic matter and soil total N. A indicates soil organic matter, B indicates soil total N.

factors that influence the effect size (Table S4). The microarthropod abundance in no tillage soils was found to be influenced by several significant factors, including annual precipitation, annual precipitation and precipitation of driest month interaction, precipitation of driest month and annual precipitation interaction, annual precipitation and maximum temperature of warmest month interaction, and maximum temperature of warmest month and minimum temperature of coldest month interaction. Similarly, Acari abundance in no tillage soils was influenced by significant factors, such as precipitation of driest month, annual mean temperature and maximum temperature of warmest month interaction. Finally, Collembola abundance in no tillage soils was influenced by various significant factors, including maximum temperature of warmest month and annual precipitation interaction, maximum temperature of warmest month and precipitation of driest month interaction, maximum temperature of warmest month and annual mean temperature interaction, maximum temperature of warmest month and soil pH interaction. The estimated parameter sizes for each of these models are provided in Table S5.

4 Discussion

4.1 Abundance of microarthropod in no tillage and reduced tillage soils

Our results from the meta-analysis support hypothesis (1) as it reveals a significant increase in soil microarthropod abundance under both no tillage and reduced tillage conditions. Soil Collembola and Acari in the soil tillage layer are known to be sensitive to changes in soil moisture, food resources, and habitat disturbance (Rebek et al., 2002; Menta et al., 2020; Yin et al., 2020). No tillage systems result in the accumulation of plant residues on the soil surface, which increasing microbial carbon content (Li et al., 2020; Morugán-Coronado et al., 2022). These systems also promote a higher abundance of soil surface fungi (Morugán-Coronado et al., 2022), which contribute to the formation of bio-pores and aggregates through fungal mycelium (Treonis et al., 2010; Li et al., 2020). The quantity of bio-pores and the stability of aggregates are crucial factors determining the habitat and stability of soil microarthropods. Soil Acari are highly responsive to fluctuations in the soil microenvironment (Minor et al., 2004). However, some microarthropods may perish during tillage, leading to a decline in soil faunal abundance (Verhulst et al., 2010; Tsiafouli et al., 2015). Moisture levels in microhabitats play a crucial role in the abundance, distribution, and diversity of Acari and Collembola (Siepel, 1996; Rahgozar et al., 2019; Mirzaei-Pashami et al., 2020). For instance, Oseto et al. (1987) provided evidence that Collembola in conventionally tilled soil exhibit higher vulnerability to moisture-induced stress. Adopting reduced tillage or no tillage practices improves moisture content in the tillage layer of dryland regions (Sékou, 2017), leading to increased abundance of Acari and Collembola in the soil and overall soil faunal abundance. Moreover, our findings are not consistent with those of van Capelle et al. (2012) which investigated the effects of conservation tillage on soil organisms using data from German agroecosystems over a 60-year period. However, the study included four studies conducted in temperate climates that employed ANOVA analysis and reported a decline in Acari and Collembola abundance in no tillage soils (van Capelle et al., 2012). Therefore, our meta-analysis approach collecting data at the global scale from diverse climate types, provides a more comprehensive understanding of conservation tillage on soil biodiversity.

Our analysis supports hypothesis (2) that no tillage practices have a stronger impact on soil Collembola abundance compared to soil Acari abundance. This difference can likely be attributed to the presence of sensory organs in soil Collembola, including well-developed springing mechanisms and slender antennae, which enable them to detect and respond to environmental changes, forage for food, and avoid potential threats (Graham et al., 1994; Mitchell et al., 2017). Additionally, competition for resources and living space among soil Collembola and Acari, both being microarthropod in the soil, may contribute to the observed variations (Wang et al., 2019).

Furthermore, our findings demonstrate that no tillage and reduced tillage practices have distinct effects on the abundance of soil microarthropods, specifically Acari and Collembola. No tillage practices lead to increased abundance of both Acari and Collembola, while reduced tillage primarily promotes Acari abundance without significant effects on Collembola. This discrepancy can be attributed to the shared objective of reducing soil damage caused by frequent tillage in traditional agriculture and preserving the ecological integrity of the land (Hobbs et al., 2008; Borgognone and Basile, 2017), and the competition between Acari and collembolans is relevant (Wang et al., 2019). However, no tillage practices outperform reduced tillage in maintaining soil structure stability, reducing soil moisture evaporation, and enhancing the overall ecological environment (Borgognone and Basile, 2017).

4.2 The impact of abiotic factors on microarthropod abundance in no tillage and reduced tillage soils

Our hypothesis (3) states that the effect of no tillage on soil microarthropod abundance will be more pronounced in regions characterized by poor soil structure and lower nutrient availability, based on previous research indicating the stronger influence of soil characteristics on soil fauna compared to tillage factors (van Capelle et al., 2012). For instance, in a meta-analysis conducted by Betancur-Corredor et al. (2023), it was found that organic nitrogen fertilizers increased the density of soil springtails. Overall, organic fertilization had a positive impact on the majority of taxonomic groups compared to inorganic fertilization. Similarly, studies have indicated that nitrogen addition resulted in an overall negative impact on soil fauna, with no significant effects observed on the abundance of Collembola and Acari (Hu et al., 2022), however, the effects of nitrogen fertilization on soil fauna were dependent on the rate of nitrogen application, soil texture, and climatic conditions (Betancur-Corredor et al., 2023). Our analysis confirms that the effect of no tillage practices on soil Collembola abundance is greater in regions with low soil organic matter and total nitrogen content. Similarly, in areas with low available phosphorus content, the effect of no tillage practices on soil microarthropod abundance is more pronounced. Additionally, in regions with low available phosphorus and potassium content, reduced tillage practices have a greater impact on soil Acari abundance. The abundance of soil fauna is closely related to soil characteristics (Filser et al., 2000). Singh et al. (2018) also observed an increase in Acari and Collembola abundance in no tillage soils, attributes to factors such as enhanced moisture content, increased water infiltration rates, improved aeration, and reduced soil compaction in no tillage agricultural systems. In regions characterized by poor soil structure and lower nutrient availability, it is highly likely that the adoption of no tillage practices will have a more pronounced influence on soil nutrient levels, organic matter content, soil structure, and water retention (Rożen et al., 2010; Sékou, 2017; Belmonte et al., 2018; Singh et al., 2018).

Our research findings align with the conclusions drawn in the review by Corredor et al. (2022), which indicates that soils with coarser textured have a positive impact on the abundance of Acari and Collembola. van Capelle et al. (2012) demonstrated the dependency of tillage practices' impact on soil texture (Betancur-Corredor et al., 2023). Soil texture plays a crucial role in determining the distribution and physical structure of the three soil phases, i.e., liquid, gas, and solid, as evidenced by previous studies (Zhu et al., 2018; Nadia Vignozzi et al., 2019). Furthermore, the spatial distribution of pore sizes within the soil, controlled by soil texture, significantly affects the microhabitat of soil microarthropods (Coulibaly et al., 2022). Due to their limited ability to dig tunnels or pits in the soil, Collembola and Acari are highly sensitive to environmental stress caused by small pores (Beylich et al., 2010). Machado et al. (2019) reported a strong correlation between Collembola abundance and soil microporosity (pore size > 0.08 mm) and soil biopores (pore size > 1.0 mm). Clayey soils, which have a high proportion of small pores and are less aerated and permeable, pose a significant challenge to the survival of these soil microarthropods.

Our research findings indicate that no tillage practices have a greater positive impact on soil microarthropods and Acari abundance in regions with high precipitation compared to conventional tillage. Reduced tillage practices also result in a significant increase in Acari abundance in these areas. Soil microarthropod abundance is affected by climate and altitude (Domínguez et al., 2010; Murvanidze et al., 2019; Mirzaei-Pashami et al., 2020), and humidity in the microhabitat plays a crucial role in Acari diversity and abundance (Siepel, 1996; Rahgozar et al., 2019). The bulk density of untilled topsoil is generally higher than conventionally tilled soil, and multiple tilling operations can lead to soil compaction and damage (Kracht and Schrader, 1997; Schrader and Lingnau, 1997). No tillage practices help regulate soil moisture by reducing surface runoff and improving soil structure and pore channels, leading to increased water content in arid and semi-arid areas and decreased water content in humid areas (Rożen et al., 2010). Conversely, conventional tillage, with its loose topsoil, allows surface water to enter the soil layer more quickly but restricts water drainage due to compaction, leading to saturated pores in the tilled layer and adversely affecting microarthropods, Acari, and Collembola residing in larger pores (Machado et al., 2019). Overall, conservation tillage management should consider the local environmental conditions to maximize the promotion of soil biodiversity and overall soil health.

5 Conclusion

The meta-analysis results demonstrate the positive effects of no tillage and reduced tillage practices on the abundance of soil microarthropods, including Acari and Collembola. However, it is important to note that the impacts of these practices vary among Acari and Collembola, necessitating careful consideration and differentiation. No tillage promotes the abundance of Acari and Collembola, while reduced tillage specifically benefits Acari. The effectiveness of tillage management strategies relies on specific soil properties and climatic conditions. No tillage has a significant effect on microarthropod and Acari abundance in loamy soil, whereas it has a stronger impact on the Collembola abundance in sandy and clayey soil. In nutrient-poor soil areas, both no tillage and reduced tillage have a greater effect on relies microarthropod (Acari, Collembola), whereas their impact is relatively limited in temperate humid regions. Therefore, it is crucial to select the appropriate intensity of these practices, taking into account the diverse climatic and soil conditions.

Data availability

The authors affirm that additional primary data supporting the results of this study can be found in this article and its supplementary materials. Furthermore, supplementary data further supporting the findings of this research can be obtained from the corresponding author upon reasonable request.

Code availability

Upon request, the corresponding authors can provide the custom codes used for all analyses.

Conflict of interest

The authors declare no conflicts of interest.

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Electronic supplementary material

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