



HAL
open science

Indicators of practice intensity unearth the effects of cropping systems on soil mesofauna

Juliette Chassain, Sophie Joimel, Antoine Gardarin, L. Vieublé-Gonod

► **To cite this version:**

Juliette Chassain, Sophie Joimel, Antoine Gardarin, L. Vieublé-Gonod. Indicators of practice intensity unearth the effects of cropping systems on soil mesofauna. *Agriculture, Ecosystems & Environment*, 2024, 362, pp.108854. 10.1016/j.agee.2023.108854 . hal-04653497

HAL Id: hal-04653497

<https://hal.science/hal-04653497v1>

Submitted on 18 Jul 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Indicators of practice intensity unearth the effects of cropping systems on soil mesofauna

Juliette Chassain 1, Sophie Joimel 1, Antoine Gardarin 2, Laure Vieubl  Gonod 1

1 Universit  Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, 91120, Palaiseau, France

2 Universit  Paris-Saclay, INRAE, AgroParisTech, UMR Agronomie, 91120, Palaiseau, France

E-mail address: juliette.chassain@outlook.fr; sophie.boulangier-joimel@agroparistech.fr;

antoine.gardarin@inrae.fr; laure.vieuble@agroparistech.fr

* Corresponding author. E-mail address: juliette.chassain@outlook.fr

Abstract

Soil organisms are impacted by a wide range of physical and chemical disturbances in intensive cropping systems. The development of cropping systems less disturbing to soil biodiversity requires to understand the consequences of various practices on soil organisms. However, most studies characterize the effects of cropping systems by distinguishing between the main types of systems (i.e. conventional, organic, conservation) without taking into account the diversity of applied practices. In this study, we aimed to describe cropping systems and their effects on soil mesofauna using indicators of practice intensity previously developed by agronomists. Mesofauna sampling was conducted in autumn 2020 and 2021 over 21 fields under conventional, conservation or organic systems, either long-established (≥ 7 years) or in transition (≤ 3 years). Primary indicators and composite indexes were computed to determine the intensity of tillage, pesticide treatments and organic inputs, and used as predictors for mesofauna density and Collembola species diversity. In 2020, mesofauna density was lower in organic than in conventional systems, and both did not differ significantly from conservation systems. In 2021, Collembola density tended to be the highest in long-established conservation systems. Transitioning organic systems had a low mesofauna density. Using composite indexes,

mesofauna density and Collembola diversity were observed to decrease under high tillage and low pesticide treatment intensity, while we found no clear effect using the organic input intensity index. Overall, practice intensity indicators and indexes were useful to explain the effects of cropping systems on soil mesofauna density and diversity. In particular, the tillage intensity index showed a major impact of tillage on soil mesofauna. However, the significance of the effects of practice intensity on mesofauna varied between years. Future studies are thus necessary to fully assess the relevance of intensity indicators and indexes in assessing the effects of cropping systems on soil biodiversity.

Keywords: Collembola, conservation agriculture, organic farming, practice intensity indicators, tillage, systems in transition

1. Introduction

The transition toward sustainable agroecosystems involves redesigning cropping systems using agroecological principles, such as enhancing soil biodiversity and ecosystem functioning (Altieri, 1989; Wezel et al., 2009). Soil organisms, and more specifically those belonging to the mesofauna, are key actors of agricultural soil functioning and associated ecosystem services as they are notably involved in litter decomposition, nutrient cycling, and climate and pest regulation (Crossley et al., 1992; Lavelle et al., 2006). Soil mesofauna includes numerous organisms ranging from 0.1 to 2 mm, mostly microarthropods, living in the surface litter and in the soil porosity (Swift et al., 1979; Lavelle and Spain, 2001). Collembola and Acari constitute a large part of soil microarthropods and play an essential role in soil organic matter decomposition (Moore et al., 1993; Chassain et al., 2021), nutrient dynamics (Mebes and Filser, 1998) and soil microstructure formation (Rusek, 1998). Collembola in particular are considered to be relevant bioindicators of soil disturbances due to their high abundance and diversity and their sensitivity to land-use change and intensity (Ponge et al., 2003; Socarrás and Izquierdo, 2014), physical soil degradation (Bispo et al., 2009) and chemicals (Cortet et al., 1999; Joimel et al., 2022). In

addition, they are a well-documented group in terms of species identification in temperate areas (Potapov et al., 2020).

Mesofauna abundance and diversity are lower in agroecosystems than in any other ecosystems (Santorufu et al., 2015; Joimel et al., 2017). Cultivated soils are characterized by regular and significant physical and chemical disturbances caused by agricultural practices. Consequently, soils of the most intensive cropping systems have been reported to have particularly low abundance and diversity of microarthropods (Winter et al., 1990; Bedano et al., 2006; Tsiafouli et al., 2015). Yet, it remains unclear if some practices are more disruptive than others within cropping systems, and how practices interact and influence soil organisms.

Alternative systems, such as systems under organic and conservation agriculture, have been developed to offset the drawbacks of intensive management. Organic farming is based on the ban of synthetic inputs (i.e. pesticides, mineral fertilizers) (Stanhill, 1990), while conservation agriculture relies on no-tillage, permanent soil cover and diversification of the crop rotation (FAO, 2022). These alternatives were both reported to benefit soil mesofauna, in particular microarthropod abundance, compared to conventional systems (Christel et al., 2021). A large part of studies are focusing on organic systems, showing benefits of organic farming on soil microarthropod abundance or richness (Doles et al., 2001; Bettiol et al., 2002; Bengtsson et al., 2005), even if no or negative effects were also reported (Schrader et al., 2006; Potapov et al., 2022). Comparatively, less studies were conducted on conservation agriculture (Christel et al., 2021), which was found to have a positive effect on soil mesofauna abundance (Ayuke et al., 2019; Menta et al., 2020; Dulaurent et al., 2022). Overall, higher densities of several soil fauna groups were previously observed in conservation than in organic systems (Henneron et al., 2015), but more studies are required to generalize the effects of these alternative systems on the abundance and diversity of soil mesofauna (Christel et al., 2021). In addition, little is known about the response of mesofauna to the transition from conventional to alternative systems or from one alternative to another (Filser et al., 1995, 2002; Jabbour, 2008; Collier et al., 2022).

Previous studies also reported effects of specific agricultural practices on soil mesofauna, in particular the impact of frequent and deep tillage (Kladivko, 2001; Miyazawa et al., 2002), pesticide treatment applications (Cortet et al., 2002; Miyazawa et al., 2002) and organic or inorganic fertilizer applications (Miyazawa et al., 2002; Reeleder et al., 2006). Reported negative effects of tillage on microarthropods (Wardle, 1995; van Capelle et al., 2012; Moradi et al., 2013) could be explained by physical disturbances of soil causing direct (e.g. physical injuries) and indirect damage (e.g. destruction of microhabitats, drying of soil surface, changes in spatial distribution of the trophic resource) to microarthropods (Kladivko, 2001; Dang et al., 2015; Tsiafouli et al., 2015). Reduced or no-tillage practices (i.e. one of the components of conservation agriculture) were reported to have a positive effect on mesofauna abundance and variable results on diversity (Brennan et al., 2006; Tabaglio et al., 2009; Betancur-Corredor et al., 2022). However, absence of or positive effects of tillage were also observed on soil mesofauna (van Capelle et al., 2012; Rieff et al., 2020). Chemical disturbances due to pesticides could have direct (e.g. survival, reproduction) and indirect (e.g. changes in the food resource) effects on soil microarthropods, especially on Collembola (Cortet et al., 2002; Joimel et al., 2022). In contrast, the effect of fertilization and organic inputs on mesofauna depend on the type of inputs and is more ambiguous (Kanal, 2004; Zhu et al., 2023). Organic inputs generally tend to increase mesofauna density, whereas mineral fertilizers may have a neutral or a negative effect (Miyazawa et al., 2002; Hu et al., 2022; Betancur-Corredor et al., 2023). Exports of crop residues, which represent another source of organic matter, were alternatively found to have negative or no effect on microarthropod density (Werner and Dindal, 1990; Brennan et al., 2006; Coulibaly et al., 2017). Lastly, crop rotation and diversification were found to have variable or no influence on microarthropod density and diversity (Osler et al., 2008; Twardowski et al., 2016; Moos et al., 2020).

Overall, the observed variability in mesofauna density and diversity is large in agricultural areas, probably due to the large panel of applied practices (Bengtsson et al., 2005). In most cases, studies on agricultural soils assessed biodiversity by comparing fields assigned to different cropping systems (i.e. conventional, integrated, organic, no-tillage, conservation) or considering only one practice (e.g.

tillage). However, the first approach conduces to a poor level of definition of applied practices, while the second gives a partial description of the studied system. In addition, tillage is often defined according to broad categories (conventional, reduced, no-tillage), thus merging practices without taking into account the parameters involved in the intensity of soil disturbances (e.g. depth or frequency of tillage). Similarly, pesticide treatments are often considered by comparing the presence/absence of treatments instead of considering separately products with different targets (e.g. herbicides, fungicides, insecticides) and application parameters (e.g. number, doses, frequency and timing).

Agronomists highlighted the usefulness of an approach by indicators describing the practices applied in cropping systems on a continuous or a semi-quantitative scale (Armengot et al., 2011; Bockstaller et al., 2015; Büchi et al., 2019). These indicators can be computed for each field using data on applied practices, preferably based on information that are easy to obtain (Büchi et al., 2019). They can be considered as both a measure of practice intensity and a measure of the related disturbances. They have the advantage to provide one value per field instead of grouping fields into systems, thus switching from a discrete to a continuous variable. In soil ecology, some authors already stated the interest of using indicators of the intensity and frequency of soil disturbances to compare the effects of different managements on soil organisms (Gareau et al., 2019; Masin et al., 2020). However, to our knowledge, this type of indicators was rarely used to assess the effects of cropping systems on soil organisms, more particularly for mesofauna. We found only one study using crop management descriptors to assess cropping system effects on microarthropods (Ferraro and Ghera, 2007a). Therefore, in our study, we used practice intensity indicators to assess the effect of physical and chemical disturbances on soil mesofauna, and to investigate whether they provide additional insight compared to defined broad categories of cropping systems.

In this context, the objectives of this study were 1) to assess if alternative cropping systems, long-established or in transition, had beneficial effects on soil mesofauna density and Collembola diversity, and 2) to test whether the use of primary indicators and composite indexes of practice intensity

(tillage, pesticide treatments, organic inputs) helps to further explain the effects of cropping systems on soil mesofauna. The study focuses on the density of total soil mesofauna, and on the species richness of Collembola due to their status of bioindicators and their relatively high density. More detailed results on the taxonomic and functional diversity of Collembola are provided in Chassain et al. (2023). We hypothesized that systems with lower physical (i.e. tillage) and chemical (i.e. pesticide treatments) disturbances, namely conservation and organic systems, could present higher density of soil mesofauna as well as a higher Collembola species diversity compared to conventional systems. We assumed that these differences may vary between long-established and transitioning alternative systems.

2. Materials and methods

2.1 Study sites

The study was conducted in autumn 2020 and 2021 over 21 fields owned by farmers located in the Paris basin, France. Climate is temperate with mean annual precipitations of 600 to 700 mm and a mean annual temperature of 11°C. In France, the year 2020 was marked by a particularly hot and dry summer (June to August), whereas summer 2021 was the coolest and rainiest since 2014. The autumn (September to November) was slightly warmer and humid in 2020 than 2021 (MeteoFrance.com). All fields were cropped with winter wheat in 2020-2021, whereas they were cropped with various crops or cover crops (e.g. rapeseed, barley, alfalfa) in 2019-2020 and in 2021-2022 (Table 1).

Among the 21 fields of the study, 12 belonged to systems established since seven to more than 20 years in conventional (Conv, n = 6 fields), organic (OA, n = 3) or conservation agriculture (CA, n = 3), and nine were in transition since 2 to 3 years from conventional to conservation (Conv-CA, n = 3), conventional to organic (Conv-OA, n = 3) or conservation to organic agriculture (CA-OA, n = 3) (Table

1). On each field, three plots were delimited for sampling, spaced from each other by 25 m and located 25 m apart from the field margins and outside of tractor traffic tracks to avoid bias.

2.2 Agricultural practices

Detailed information on the applied practices was collected by conducting an interview of farmers. Indicators of practice intensity were selected to describe the cropping system applied to each field following Büchi et al. (2019). We decided to use indicators that were easy to obtain and that contributed to differentiate cropping systems. Selected indicators belonged to four categories: soil physical disturbances (tillage), chemical crop protection (pesticide treatments), fertilization and organic inputs, and crop diversification (Table 2). Additional information on practices not included in the indicators is provided in Table S1.

As our objective was to assess the effects of practices on soil organisms, we computed 2020 and 2021 indicators by considering all practices occurring during the previous crop cycle (i.e. from the soil preparation and sowing in autumn 2019 or 2020) and until the sampling date (i.e. beginning of new crop cycle in autumn 2020 or 2021) (Fig. S1). In addition, several indicators accounted for practices applied over the last five years (2016-2020 and 2017-2021 for the first and second sampling respectively).

Primary indicators represented the intensity of practices associated to tillage (nbDTill: deep tillage, nbSTill: surface tillage, soilP: type of tillage over 5 years), pesticide treatments (nbHerb, nbFung, nbInsect: herbicide, fungicide and insecticide applications) and organic inputs (nbOrg: organic amendments, nbRes: crop residue retention, qminN: mineral nitrogen fertilizers inputs), and the crop diversification (nbCrop: crop diversity over 5 years) (Table 2).

Composite indexes were computed for tillage intensity (I_{till}) and organic input intensity (I_{org}) by an additive combination of primary indicators following Büchi et al. (2019). Primary indicators were first normalized to obtain values between 0 and 1:

$$I_{norm\ i} = \frac{(I_i - I_{min})}{(I_{max} - I_{min})}$$

where $I_{norm\ i}$ is the normalized primary indicator, I_i is the indicator value for the field i , I_{min} and I_{max} are the minimal and maximal indicator values within all fields. Then, the composite indexes were computed by an additive combination of the normalized indicators such as:

$$I_{till} = \frac{nbDTill_{norm} + nbSTill_{norm} + (1 - soilP_{norm})}{3}$$

where I_{till} is the composite index for tillage intensity and $nbDTill_{norm}$, $nbSTill_{norm}$ and $soilP_{norm}$ are respectively the normalized values of the number of deep tillage, surface tillage and average type of tillage over five years (Table 2), and:

$$I_{org} = \frac{nbOrg_{norm} + nbRes_{norm}}{2}$$

where I_{org} is the composite index for organic input intensity and $nbOrg_{norm}$ and $nbRes_{norm}$ are respectively the normalized values of the number of organic amendments (i.e. number of times organic matter was applied to the field) and of the number of times crop residues were retained over 5 years (Table 2). The composite index for pesticide treatment intensity (I_{treat}) was the sum of pesticide treatments applied over the period such as:

$$I_{treat} = nbTreat_{norm}$$

where I_{treat} is the composite index for pesticide treatment intensity and $nbTreat_{norm}$ is the normalized value of the total number of pesticide treatment applications (i.e. number of products applied over the period including herbicides, fungicides, insecticides, molluscicides and growth regulators). Each product was considered as a separated treatment even when applied together with other products. We did not consider molluscicides as an individual treatment indicator as they were rarely applied. For comparison, we calculated the treatment frequency index (TFI), a common index used by farmers and agronomists in order to assess the intensity of treatments over a crop cycle (Jørgensen and Kudsk, 2006). The TFI for each treatment was calculated as the ratio of the applied dose over the recommended dose, multiplied by the ratio of the treated surface over the field surface. The total TFI was the sum of the TFI of products applied over the crop cycle. However, as I_{treat} and TFI appeared to

be highly correlated (Spearman correlation, $cor = 0.9$, $P < 0.001$ in 2020 and 2021) and as TFI was missing for two fields, we used only Itreat for the following parts of the study. For all the indexes, a higher value indicates greater intensity of the practices in question.

2.3 Soil and mesofauna sampling

Samplings were conducted from October 19th to December 2nd in 2020 and from October 25th to November 22nd in 2021. They took place minimum one week after sowing to allow the mesofauna population to partially recover after tillage and other mechanical operations related to sowing. All samples were collected between crop rows. To limit the effect of the sampling time, we tried to sample simultaneously fields belonging to different cropping systems. However, on average, organic fields were sampled later than conventional and conservation fields as organic systems rely on late sowing to compensate for the absence of pesticide treatments.

Composite soil samples were collected at 0-10 cm depth for each plot (i.e. three sampling areas per field) by mixing eight soil cores obtained with an auger. Before analyses, samples were kept at 4°C. Soil water content was assessed by drying fresh soil at 105°C for 48h. In 2020, a fraction of sampled soils was sieved at 4 mm, air dried and analyzed for main soil characteristics by the INRAE laboratory of Arras (i.e. clay, silt, sand, organic matter, C, N, Al, Ca, Fe, K, Mg, Mn, Na and P total contents, pH, cation exchange capacity). In addition, bulk density was assessed by collecting a soil core (10 cm in diameter, 10 cm high) at 0-10 cm depth in each plot (i.e. three cores per field), which was dried (105°C, 48h) and weighed.

Mesofauna was sampled at 0-4 cm depth in each plot (i.e. three samples per field) using small soil cores (5 cm in diameter, 4 cm high). Soil cores were kept at 4°C no longer than 8 days before extraction. Mesofauna was extracted using MacFayden extractor and following the NF/ISO 23611-2 norm. A gradient of temperature from 25°C to 45°C was progressively applied to the samples during the eight days of extraction.

Mesofauna organisms were sorted under binocular into Collembola, Acari suborders and other mesofauna groups (e.g. small Myriapoda, Coleoptera and Diptera larvae, enchytraeids). Collembola were identified at the species level using phase-contrast microscope and identification keys (Bretfeld, 1999; Potapov, 2001; Hopkin, 2007). They were grouped into eco-morphological groups (euedaphic, hemiedaphic, epedaphic), which correspond to their vertical distribution in soil combined with morphological properties (Gisin, 1943). Densities of mesofauna groups were obtained by dividing abundance by the area of soil extraction (0.0025 m²). The values of the three plots were averaged to obtain one value per field.

The taxonomic diversity of Collembola was estimated by calculating the number of species, the Shannon index and the Pielou's evenness index. We calculated the ratio Acari/Collembola as a measure of disturbance. A low ratio was previously reported to be related to high disturbances as Acari were suggested to be less tolerant to disturbances than Collembola (Bachelier, 1963; Joimel et al., 2017).

2.4 Statistical analyses

A principal component analysis (PCA) was performed on primary practice indicators to assess their ability to distinguish between the different cropping systems. To further detect clusters of fields with similar practices, a Ward hierarchical clustering with bootstrapped *P*-values was conducted using primary practice indicators. Differences in practice intensity indicators between cropping systems were assessed with an analysis of variance (ANOVA) followed by a Tukey HSD post-hoc test (*P* < 0.05). The effects of practice intensity on soil mesofauna were assessed with generalized linear models (GLM) including the three intensity indexes together (i.e. *Itill*, *Itreat* and *Iorg* - continuous variables) and their interactions as explanatory variables. However, few interaction effects were observed for the three composite indexes regarding soil mesofauna (Table S2), and our dataset is considered as small for models including numerous explanatory variables. Thus, we decided to set the focus on the simplest models, looking at each intensity index or indicator separately. In addition, we considered the effects

of practice intensity on soil mesofauna for the two sampling years together and separately (for models combining the two years see Table S8; for models used for separate years see the following paragraph).

As the effects of I_{till} , I_{treat} and I_{org} on soil mesofauna were consistent when analyzing years either separately or together, we mainly examined results for the two years separately.

Effects of cropping systems, practice intensity and soil properties on soil mesofauna were assessed separately for the two sampling years and using mean values at the field level. The normality and homogeneity of variances were tested with a Shapiro-Wilk test ($\alpha > 0.05$) and a Bartlett test ($\alpha > 0.05$).

Linear models were used to assess the relations between practice intensity indexes as explanatory variables (i.e. either I_{till} , I_{treat} , I_{org} or primary indicators separately - continuous variables) and soil properties as response variables (i.e. each soil parameter separately - continuous variables).

Generalized linear models (GLM) with a quasi-Poisson family and an identity link (i.e. accounting for overdispersion of data) were used to assess the relations between cropping systems (i.e. system categories - discrete variable), practice intensity indexes (i.e. either I_{till} , I_{treat} , I_{org} or primary indicators separately - continuous variables) or soil properties (i.e. each soil parameter separately - continuous variables) as explanatory variables, and soil mesofauna density (i.e. total mesofauna, Collembola and Acari groups) or Collembola richness as response variables. GLM with a Gaussian family and an identity link were used to assess relations with Shannon or Evenness indexes as response variables. Tukey HSD post-hoc tests were performed when comparing cropping systems in order to determine significant pairwise differences.

Since the gradients of tillage and pesticide treatment intensity were correlated, we compared results with and without fields showing zero tillage or pesticide use. GLM assessing the relations between pesticide treatment intensity (I_{treat}) and soil mesofauna were performed either including or excluding all organic fields as I_{treat} was equal to zero. Similarly, GLM assessing the relations with tillage intensity (I_{till}) were performed either including or excluding fields under conservation systems for which I_{till} was equal to zero or very low.

All the analyses were performed using R software version 3.6.3 (R Development Core Team 2020) and the *stats* (R Development Core Team 2020), *ade4* (Dray and Dufour, 2007), *pvclust* (Suzuki et al., 2019), *vegan* (Oksanen et al., 2022) and *multcomp* (Hothorn et al., 2022) packages.

3. Results

3.1 Indicators of practice intensity

Mean values of primary indicators and composite indexes are presented for each system (Table 3) and for each field (Table S3, Fig. S2). As shown by the PCA based on primary indicators (Fig. 1), organic systems were clearly separated from conventional and conservation systems both of which overlapped in 2020 (total inertia: axis 1 = 41.6%, axis 2 = 19.0%) and in 2021 (axis 1 = 47.7%, axis 2 = 15.4%). This is confirmed by cluster analyses, which showed all organic fields to be part of the same cluster in both years and to be significantly separated from conservation and conventional fields, except for one conventional field in 2020 (Fig. S3). In addition, the first axis of the PCA opposed cropping systems with high use of herbicides to those with numerous tillage intervention in both years. The second axis was mainly associated with the number of times crop residues were retained over 5 years (Fig. 1).

Composite indexes *Itill*, *Itreat* and *Iorg* were significantly different between systems (Table 3). We found no significant difference between conventional and organic systems for tillage intensity (*Itill*), between conventional and conservation systems for pesticide treatment intensity (*Itreat*), nor in the three long-established systems for organic input intensity (*Iorg*) (Table 3). Organic input intensity (*Iorg*) was significantly higher in OA and CA-OA than in Conv-CA (Table 3).

Tillage intensity was higher in organic fields than in most conventional fields in both years (Fig. S2). Primary indicators of tillage practices, *nbDTill*, *nbSTill* and *soilP*, followed a similar trend to that observed for *Itill* (Table 3). Pesticide treatment intensity varied over a large range of values for conventional and conservation systems (Fig. S2). Primary indicators of pesticide treatments, *nbHerb*,

nbFung and nbInsect, followed a similar trend to that observed for Itreat (Table 3). Organic input intensity was higher in OA and CA-OA than in most conventional and conservation fields (Fig. S2). Primary indicators showed organic amendments (nbOrg) to be significantly more numerous in long-established organic systems than in conventional and conservation systems in both years, and a trend for more mineral nitrogen inputs (qminN) in conventional than in long-established conservation systems in 2021 (Table 3, Fig. S2).

Regarding transitioning systems, all intensity indexes were similar between Conv and Conv-CA, whereas Itreat was higher in Conv than in Conv-OA and in CA than in CA-OA in both years (Table 3). In addition, nbOrg was lower in Conv than in Conv-OA in both years (Table 3).

3.2 Soil properties and effects of abiotic parameters on soil mesofauna

Field soils were silty or clayey, with a pH ranging from 5.6 to 8.1 and a bulk density between 1.1 and 1.5 g.cm⁻³ at 0-10 cm depth (Table 1). We observed no significant difference in soil properties at 0-10 cm depth between cropping systems (Table S4) and few effects of practice intensity on soil properties (Table S5). Increases in tillage intensity (Itill) and organic input intensity (Iorg) were associated to a decrease in the soil C/N ratio (Table S5). In addition, organic input intensity had a positive effect on the CEC, and Ca and Mg contents (Table S5).

Soil mesofauna density was not significantly related to the soil water content (GLM, $P > 0.05$) nor to the crop type in 2021 (GLM, $P > 0.05$). In addition, measured soil properties had few effects on mesofauna density, and each effect was observed either in 2020 or in 2021 (Table S6).

3.3 Effects of cropping systems and practice intensity on mesofauna density

Mesofauna density was on average lower in 2020 ($20\,462 \pm 22\,286 \text{ ind.m}^{-2}$) than in 2021 ($32\,249 \pm 22\,440 \text{ ind.m}^{-2}$) with a large variability between fields (Fig. 2). Very few organisms were collected in organic systems in 2020, in particular in Conv-OA (Fig. 2).

Total mesofauna and Acari (total, Oribatida, Gamasida) densities were significantly lower in OA and Conv-OA than in Conv in 2020, but we observed no significant difference between systems in 2021 (Fig. 2a and b, Table 4). Collembola density was significantly higher in Conv and Conv-CA than in Conv-OA in 2020, and in CA than in CA-OA systems in 2021 (Fig. 2c) corresponding to effects observed on hemiedaphic species (Table 4). In addition, Collembola density tended to be higher in CA than in Conv in 2021 ($P = 0.09$). Euedaphic species (i.e. species associated to the upper mineral layer of soil) were less present but their density was significantly higher in Conv than in Conv-OA in 2020, and in OA than in CA-OA in 2021 (Table 4). Epedaphic species (i.e. species associated to the soil surface and litter layer) density did not differ significantly between systems. The ratio Acari/Collembola was significantly higher in CA-OA than in other systems, except Conv-OA, in 2021 (Table 4).

Tillage intensity (I_{till}) and pesticide treatment intensity (I_{treat}) demonstrated significant effects on soil mesofauna density (Fig. 2, Table 5). An increase in I_{till} was related to a decrease in total mesofauna and Collembola (epedaphic) densities in both years (Fig. 2, Table 5a and b) and of Acari (total, Gamasida) in 2020 only (Fig. 2, Table 5a). Primary indicators of tillage, nbDTill, nbSTill and soilP, impacted the density of many mesofauna groups in both years (Table 5). Inversely, all mesofauna groups had a significantly higher density as I_{treat} increased in 2020 (Fig. 2, Table 5a). Among primary indicators, nbHerb was significantly related to the largest number of mesofauna groups (Table 5a). Epedaphic Collembola represented the only group for which density was significantly impacted by I_{till} and I_{treat} in both years (Table 5a and b). In contrast, we found no clear effect of organic matter input intensity (I_{org}) on mesofauna parameters. A decrease in nbOrg and an increase in qminN had a positive effect on Acari and Collembola densities in 2020 (Table 5a). An increase in nbRes had a positive effect on Gamasida and epedaphic Collembola densities in 2020 (Table 5a). Overall, total mesofauna and Acari densities responded to the same primary indicators.

We observed similar effects of *Itill* on soil mesofauna either including or excluding fields under conservation systems (Table S7). Besides, *Itreat* effects were similar either including or excluding fields under organic systems for Collembola density, whereas we observed no effect of *Itreat* on Acari density when excluding organic fields (Table S7).

Effects of *Itill*, *Itreat* and *Iorg* on soil mesofauna density were consistent when analyzing years either separately (Table 5) or together (Table S8). When the two years were analyzed together, the interaction between *Itill* and year was significant for epedaphic Collembola density and the interaction between *Itreat* and year was significant for Gamasida (Table S8).

3.4 Effects of cropping systems and practice intensity on Collembola species richness

A total of 30 and 43 Collembola species were collected in 2020 and 2021 respectively. Collembola species collected in each system are reported in Table S9. Collembola species richness and Shannon index were significantly higher in Conv, CA and Conv-CA than in Conv-OA in 2020, but we observed no difference between systems in 2021 (Table 4).

Collembola species richness significantly decreased as tillage intensity (*Itill*) increased in 2020, with a similar trend in 2021, and increased as pesticide treatment intensity (*Itreat*) increased in 2020 only (Table 5). Organic input intensity (*Iorg*) had no effect on Collembola species richness (Table 5). However, in 2020, species richness increased as *nbOrg* decreased (Table 5a). Shannon index followed a similar trend to that observed for species richness. Pielou's evenness index increased as *Itreat* decreased in 2020 (Table 4). All diversity values are reported at the field level in Table S10.

We observed similar effects of *Itill* and *Itreat* on Collembola richness either including or excluding fields under conservation and organic systems respectively (Table S7). In addition, *Itill* and *Itreat* had significant effects on Collembola richness when analyzing years together, with a significant interaction between *Itreat* and year (Table S8).

4. Discussion

4.1 Limited influence of soil properties on the relations between practice intensity and soil mesofauna

Agricultural practices have been reported to impact soil properties more than microarthropods (Reilly et al., 2023). Reduced tillage can notably increase SOC content (Dupla et al., 2022), mostly in the upper soil layer (Dimassi et al., 2014; Nunes et al., 2020). However, in our study, practice intensity had little effects on soil properties, and despite a decrease in soil C/N as tillage (*Itill*) and organic input intensity (*Iorg*) increased, we found no effect on SOC or TN content. A positive effect of organic inputs on SOC could be observed when applied over a longer time span than in our study (e.g. 10 years) (Dupla et al., 2022). Various soil properties can also vary with the number of crops or cover-crops in the rotation (Ferraro and Ghera, 2007b; Dupla et al., 2022), but we did not observe such effect.

Many soil properties can influence soil mesofauna, especially microarthropods (Mantoni et al., 2021). Previous studies mostly reported an influence of soil organic matter, C and N content (Kautz et al., 2006; Potapov et al., 2017) and pH (van Straalen and Verhoef, 1997; Martins da Silva et al., 2016). However, soil mesofauna density and diversity were poorly explained by soil properties at 0-10 cm depth in our study. We found only few effects for different groups and these were not observed in both years. This could be partly due to the low variability of soil properties between fields and could be different under more variable conditions.

4.2 Relevance of practice intensity indicators to assess the effects of cropping systems on soil mesofauna

Intensity indicators confirmed that at least part of the observed variability in the effects of cropping systems on soil mesofauna could be explained by the diversity of applied practices. Indeed, primary indicators (e.g. *nbOrg*) and composite indexes of the intensity of tillage (*Itill*), pesticide treatments

(Itreat) and organic inputs (Iorg) revealed a gradient of practice intensity with a high variability of practices even within categories of cropping systems (i.e. tillage in conventional and organic systems, pesticide treatments in conventional and conservation systems). It is also noteworthy that primary indicators of practice intensity allowed differentiating cropping systems in our study as in Büchi et al. (2019), thus showing the robustness of this approach for comparing cropping systems including both long-established and transitioning systems.

Composite indexes and primary indicators allowed to observe the effects of practices on mesofauna density and Collembola species diversity (e.g. significant negative effect of Itill on mesofauna density in both years), which were hidden when fields were grouped into system categories. Mesofauna density and diversity were associated to Itill and Itreat, while no clear relation was observed with Iorg. However, effects of organic inputs on soil mesofauna could be observed using primary indicators of organic amendments (nbOrg) and in a lower extent of residue retention (nbRes). Effects were also observed when using an indicator of inorganic inputs (qminN). This illustrated that organic and inorganic inputs can have opposite effects on soil mesofauna (Kanal, 2004; Betancur-Corredor et al., 2023; Zhu et al., 2023), and that primary indicators could currently be more relevant than a composite index to describe organic input and fertilization effects on soil organisms.

4.3 Effects of cropping systems on soil mesofauna: systems *versus* practice intensity

Mesofauna density and Collembola diversity were observed to vary between the different cropping systems categories. In particular, mesofauna density tended to be higher in conservation than in conventional systems in 2021, especially for Collembola. This is in agreement with reported benefits of conservation systems compared to conventional systems regarding mesofauna (Brennan et al., 2006; Coulibaly et al., 2022; Dulaurent et al., 2022). The trend observed in our study could be associated with a low tillage intensity in conservation systems, whereas the limited significance could be related to the lack of difference for other practices between conservation and conventional fields.

Our results did not point toward benefits of organic agriculture on soil mesofauna density and diversity, contrary to several previous studies (Hole et al., 2005; Christel et al., 2021). They showed a lower mesofauna density in long-established organic than in conventional systems in 2020, and no difference in 2021. These negative or neutral effects of organic systems on soil mesofauna compared to conventional systems were previously reported, especially for Collembola (Alvarez et al., 2001; Filser et al., 2002), and could be explained by higher disturbances related to tillage in organic systems (Mazzoncini et al., 2010). In line with this, we observed that all organic fields had a high tillage intensity, while this was more contrasted for conventional systems. The variability of the effects of organic systems on soil mesofauna could also be associated with a larger annual variability of mesofauna density in organic systems than in the other systems. Indeed, we observed very low mesofauna densities in all organic fields in 2020, and high variability between fields in 2021. Contrary to results reported for other soil organisms (Henneron et al., 2015), mesofauna density and Collembola diversity were not significantly different between long-established organic and conservation systems. However, despite the absence of significant difference, we observed on average more Collembola in long-established conservation than organic systems in both years.

The use of practice intensity indicators to characterize cropping systems revealed that mesofauna density and Collembola species richness were higher under lower physical disturbances (i.e. tillage intensity) but not under lower chemical disturbances (i.e. pesticide treatment intensity) contrary to our original hypothesis. This was consistent with the average higher density observed in conservation than in organic systems, the first being commonly associated to the absence of tillage and high pesticide treatment intensity, and the latter to the absence of treatments and high tillage intensity. Similar effects of tillage and pesticide treatment intensity were observed when removing conservation or organic systems respectively, showing that these effects were not only associated to system categories (i.e. tillage effect associated to conservation systems and pesticide effects to organic systems). However, cautions should still be observed when considering the effects of pesticide treatment intensity on Acari as these were only observed when including organic fields in the analyses.

Overall, indicators and indexes were useful to determine the factors explaining changes in soil mesofauna density and diversity within all fields, including intermediate cropping systems that could not be correctly attributed to arbitrary system categories.

In the literature, tillage was often the main factor impacting soil mesofauna (Ferraro and Ghera, 2007a; Coudrain et al., 2016; Coulibaly et al., 2017), while pesticides were designated as a second order factor of influence on microarthropods (Cortet et al., 2002). In our study, we surprisingly found pesticide treatments to be positively related to soil mesofauna, including Collembola and Acari. Ferraro and Ghera (2007a) observed similar results for Acari, while they reported negative effects on Collembola. Pesticide treatments could have both direct and indirect effects on soil organisms, the latter being most probably at the origin of the positive effect we observed. The main pesticides used in the studied field crops were herbicides, which caused an increase in dead weed biomass at the soil surface, providing more food for decomposers (Wardle et al., 1999). Herbicides are also known to be used as an energy source by some species of micro-organisms (Neher, 1995; Vieublé Gonod et al., 2006; Walder et al., 2022). This process could lead to an increase in microbial biomass and grazing activity of microarthropods (Hendrix and Parmelee, 1985), but must be treated with cautions as the quantity of herbicides applied to the field (i.e. few g or L.ha⁻¹) represents a relatively little quantity of carbon. Pesticide treatments could also decrease the pool of predators, thus increasing the number of mesofauna preys (Bengtsson et al., 2005). Moreover, we observed that the number of pesticide treatments, especially herbicides, was inversely related to the number of tillage interventions (Pearson correlation from -0.62 to -0.42). This illustrated that cropping systems rely on an equilibrium between tillage and pesticide treatments to manage weeds and pests. Therefore, the observed positive effect of pesticide treatment intensity could be partly associated with the positive effect of a lower number of tillage interventions.

Practices related to fertilization and organic inputs had variable effects on mesofauna density. We observed a negative effect of organic amendments (nbOrg) and a positive effect of mineral nitrogen inputs (qminN) on microarthropod density, which contrasts with previous studies (Miyazawa et al.,

2002; Betancur-Corredor et al., 2023). Organic amendments tended to increase in line with tillage interventions, because tillage is often used to bury organic matter. Thus, the negative relation between organic matter inputs and soil mesofauna could also be related to the negative effects of tillage. In addition, we observed that mesofauna density was related to organic amendments in 2020, when all fields were cropped with wheat, but not in 2021, when fields were cultivated with various crops. In line with this, previous studies have shown that different wheat varieties had a similar influence on mesofauna density (Salmon et al., 2021), while fertilization had less effect on mesofauna than crop type (Bandyopadhyaya et al., 2002; Gergócs et al., 2022). However, contrary to previous studies (Menta et al., 2020), we observed no effect of crop type on soil mesofauna.

4.4 Effects observed on soil mesofauna during the transition toward alternative systems

Long-established and transitioning alternative systems had similar mesofauna density and Collembola species richness, in particular regarding conservation systems. This suggests rapid changes in mesofauna communities after conversion. However, in transitioning organic systems, the mesofauna density remained low in both years and tended to be lower than in long-established organic systems. Collembola species richness was particularly low in transitioning organic systems in 2020, but this was mostly explained by the very low abundance of Collembola in the samples. We suggest that a transitory negative effect on mesofauna has occurred during the first years of the transition to organic systems, thus contradicting previously reported increase in Collembola and Acari densities during this transition (Werner and Dindal, 1990; Filser et al., 2002; Schrader et al., 2006). In particular, the decrease in Collembola density could be related to an increase in competition or predation by other organisms following the transition to organic agriculture (Filser et al., 2002), which could be caused by increased tillage and lower pesticide treatment intensity.

Systems in transition from conservation to organic agriculture presented a very high Acari/Collembola ratio in both years, significant in 2020 only, which could indicate that they provided a better

environment for soil mesofauna. However, it was mainly due to a very low Collembola density in both years and suggested that this transition may cause important changes in the soil mesofauna community. To our knowledge, no other study was conducted on the effects of the transition from conservation to organic systems on soil biodiversity. More research is required to assess changes occurring at a longer term and on other groups of soil organisms.

4.5 Limitations and perspectives on the use of practice intensity indicators in ecology

Primary indicators and composite indexes enabled us to better consider the variability of practices within different cropping systems. Nevertheless, these could still be improved to better understand the effects of practices on soil organisms. For instance, the overall fertilization and organic input effect on mesofauna depends on the nature of the applied fertilizers or residues (i.e. mineral or organic nature of fertilizers, type and composition of fertilizers or residues) and the doses and frequency of application (Weil and Kroontje, 1979; Miyazawa et al., 2002; Song et al., 2016). Tillage and pesticide treatment indexes could also rely on further information. In particular, few studies were conducted on the effect of the timing of tillage on soil fauna nor on the duration of recovery after tillage (Schmidt and Curry, 2001; Roger-Estrade et al., 2010). Gathering more information on agricultural practices requires high data collection effort, which is complex to handle, but could be of importance for the development of future cropping systems.

Our results were based on a limited number of samples. However, while the number of fields seemed low when comparing different cropping systems, it was satisfactory when using continuous intensity indicators and regressions. Indicators could thus represent a solution to overpass the limitations inherent to many ecological studies (i.e. time and labor constraints).

Taking into account the interactions between the three composite indexes did not reveal any combined effects on mesofauna density. This could be due to the relatively small number of samples, and we cannot exclude the possibility that interactions between different practices may influence

mesofauna. For instance, combination of tillage and organic matter inputs were reported to benefit soil organisms (Jabbour et al., 2016), in particular Acari (Miyazawa et al., 2002). Therefore, we encourage future studies to assess conjointly the effect of different practices on soil biodiversity.

A large inter-annual variability in mesofauna density and diversity was observed in our study, as previously reported for microarthropods (Tabaglio et al., 2009; Gergócs et al., 2022). These variations could be partly due to climatic conditions (Taylor et al., 2004; Salmon et al., 2021), whose effects could be more or less significant depending on the cropping system (Meyer et al., 2021). Seasonal variability was reported to be even larger than variability between years (Berg and Bengtsson, 2007) and could be especially important regarding Collembola in transitioning systems (Werner and Dindal, 1990). Therefore, long-term studies with several sampling times throughout the year are required to assess more precisely the effects of practice intensity on soil mesofauna.

5. Conclusion

Conventional, organic and conservation agriculture differ broadly in terms of tillage, pesticide treatments and organic inputs, but the great variability observed *in situ* within each of these practices made difficult to compare cropping systems and to study their effects on soil biodiversity. Taking into account the intensity of various practices *via* composite indexes seemed relevant to better understand the effects of cropping systems on soil organisms, especially mesofauna, with the long-term objective to develop alternative and agroecological systems relying on strong soil biodiversity. Composite indexes for tillage intensity and pesticide treatment intensity revealed effects of these practices on mesofauna density and diversity, while the composite index for organic input intensity considered in our study appeared to be less adapted to understand effects of associated practices on soil mesofauna. Future studies, focusing on different groups of soil organisms and different seasons, are necessary to further assess the potential of intensity indicators for investigating the effects of cropping systems on

soil biodiversity. This will ultimately help the development of sustainable cropping systems relying on strong soil biodiversity and functioning.

Acknowledgements

This work was supported by INRAE, AgroParisTech and the Office Français de la Biodiversité.

We would like to thank Swann Felin and Baptiste Coupery for their great work throughout the sampling campaigns, and Marine Chombart, Véronique Etievant, Antoine Bamière, Grigorios Andronidis, Sékou Coulibaly and Tania De Almeida for their additional help. Justine Pigot and Aude Barbottin have contributed to the collection of valuable data on agricultural practices by conducting farmer's interviews. We also thank all the farmers involved this study. Silhouette images of soil organisms were taken from phylopic.org.

References

- Altieri, M.A., 1989. Agroecology: A new research and development paradigm for world agriculture. *Agric. Ecosyst. Environ.* 27, 37–46.
- Alvarez, T., Frampton, G.K., Goulson, D., 2001. Epigeic Collembola in winter wheat under organic, integrated and conventional farm management regimes. *Agric. Ecosyst. Environ.* 83, 95–110. [https://doi.org/10.1016/S0167-8809\(00\)00195-X](https://doi.org/10.1016/S0167-8809(00)00195-X)
- Armengot, L., José-María, L., Blanco-Moreno, J.M., Bassa, M., Chamorro, L., Sans, F.X., 2011. A novel index of land use intensity for organic and conventional farming of Mediterranean cereal fields. *Agron. Sustain. Dev.* 31, 699. <https://doi.org/10.1007/s13593-011-0042-0>
- Ayuke, F.O., Kihara, J., Ayaga, G., Micheni, A.N., 2019. Conservation agriculture enhances soil fauna richness and abundance in low input systems: Examples from Kenya. *Front. Environ. Sci.* 7, 97.
- Bachelier, G., 1963. *La vie animale dans les sols*. ORSTOM, Paris.
- Bandyopadhyaya, I., Choudhuri, D.K., Ponge, J.-F., 2002. Effects of some physical factors and agricultural practices on Collembola in a multiple cropping programme in West Bengal (India). *Eur. J. Soil Biol.* 38, 111–117. [https://doi.org/10.1016/S1164-5563\(01\)01114-1](https://doi.org/10.1016/S1164-5563(01)01114-1)
- Bedano, J.C., Cantú, M.P., Doucet, M.E., 2006. Soil springtails (Hexapoda: Collembola), symphylans and pauropods (Arthropoda: Myriapoda) under different management systems in agroecosystems of the subhumid Pampa (Argentina). *Eur. J. Soil Biol.* 42, 107–119. <https://doi.org/10.1016/j.ejsobi.2005.11.004>
- Bengtsson, J., Ahnström, J., Weibull, A.-C., 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *J. Appl. Ecol.* 42, 261–269. <https://doi.org/10.1111/j.1365-2664.2005.01005.x>
- Berg, M.P., Bengtsson, J., 2007. Temporal and spatial variability in soil food web structure. *Oikos* 116, 1789–1804. <https://doi.org/10.1111/j.0030-1299.2007.15748.x>

- Betancur-Corredor, B., Lang, B., Russell, D.J., 2023. Organic nitrogen fertilization benefits selected soil fauna in global agroecosystems. *Biol. Fertil. Soils* 59, 1–16. <https://doi.org/10.1007/s00374-022-01677-2>
- Betancur-Corredor, B., Lang, B., Russell, D.J., 2022. Reducing tillage intensity benefits the soil micro- and mesofauna in a global meta-analysis. *Eur. J. Soil Sci.* 73, e13321. <https://doi.org/10.1111/ejss.13321>
- Bettiol, W., Ghini, R., Galvão, J.A.H., Ligo, M.A.V., Mineiro, J.L. de C., 2002. Soil organisms in organic and conventional cropping systems. *Sci. Agric.* 59, 565–572. <https://doi.org/10.1590/S0103-90162002000300023>
- Bispo, A., Cluzeau, D., Creamer, R., Dombos, M., Graefe, U., Krogh, Ph., Sousa, Jp., Peres, G., Rutgers, M., Winding, A., Römbke, J., 2009. Indicators for monitoring soil biodiversity. *Integr. Environ. Assess. Manag.* 5, 717. <https://doi.org/10.1897/IEAM-2009-064.1>
- Bockstaller, C., Feschet, P., Angevin, F., 2015. Issues in evaluating sustainability of farming systems with indicators. *Ol. Corps Gras Lipides* 22, 1. <https://doi.org/10.1051/ocl/2014052>
- Brennan, A., Fortune, T., Bolger, T., 2006. Collembola abundances and assemblage structures in conventionally tilled and conservation tillage arable systems. *Pedobiologia* 50, 135–145. <https://doi.org/10.1016/j.pedobi.2005.09.004>
- Bretfeld, G., 1999. Synopses on Palaearctic Collembola, Volume 2: Symphypleona, Synopses on Palaearctic Collembola. Senckenberg Museum of Natural History, Goerlitz.
- Büchi, L., Georges, F., Walder, F., Banerjee, S., Keller, T., Six, J., van der Heijden, M., Charles, R., 2019. Potential of indicators to unveil the hidden side of cropping system classification: Differences and similarities in cropping practices between conventional, no-till and organic systems. *Eur. J. Agron.* 109, 125920. <https://doi.org/10.1016/j.eja.2019.125920>
- Chassain, J., Vieublé Gonod, L., Chenu, C., Joimel, S., 2021. Role of different size classes of organisms in cropped soils: What do litterbag experiments tell us? A meta-analysis. *Soil Biol. Biochem.* 162, 108394. <https://doi.org/10.1016/j.soilbio.2021.108394>

- Chassain, J., Joimel, S., Vieublé Gonod, L., 2023. Collembola taxonomic and functional diversity in conventional, organic and conservation cropping systems. *Eur. J. Soil Biol.* 118, 103530. <https://doi.org/10.1016/j.ejsobi.2023.103530>
- Christel, A., Maron, P.-A., Ranjard, L., 2021. Impact of farming systems on soil ecological quality: a meta-analysis. *Environ. Chem. Lett.* 19, 4603–4625. <https://doi.org/10.1007/s10311-021-01302-y>
- Coller, E., Oliveira Longa, C.M., Morelli, R., Zanoni, S., Cersosimo Ippolito, M.C., Pindo, M., Cappelletti, C., Ciutti, F., Menta, C., Zanzotti, R., Ioriatti, C., 2022. Soil communities: Who responds and how quickly to a change in agricultural system? *Sustainability* 14, 383. <https://doi.org/10.3390/su14010383>
- Cortet, J., Gillon, D., Joffre, R., Ourcival, J.-M., Poinot-Balaguer, N., 2002. Effects of pesticides on organic matter recycling and microarthropods in a maize field: use and discussion of the litterbag methodology. *Eur. J. Soil Biol.* 38, 261–265. [https://doi.org/10.1016/S1164-5563\(02\)01156-1](https://doi.org/10.1016/S1164-5563(02)01156-1)
- Cortet, J., Vauflery, A.G.-D., Poinot-Balaguer, N., Gomot, L., Texier, C., Cluzeau, D., 1999. The use of invertebrate soil fauna in monitoring pollutant effects. *Eur. J. Soil Biol.* 35, 115–134. [https://doi.org/10.1016/S1164-5563\(00\)00116-3](https://doi.org/10.1016/S1164-5563(00)00116-3)
- Coudrain, V., Hedde, M., Chauvat, M., Maron, P.-A., Bourgeois, E., Mary, B., Léonard, J., Ekelund, F., Villenave, C., Recous, S., 2016. Temporal differentiation of soil communities in response to arable crop management strategies. *Agric. Ecosyst. Environ.* 225, 12–21. <https://doi.org/10.1016/j.agee.2016.03.029>
- Coulibaly, S.F.M., Aubert, M., Brunet, N., Bureau, F., Legras, M., Chauvat, M., 2022. Short-term dynamic responses of soil properties and soil fauna under contrasting tillage systems. *Soil Tillage Res.* 215, 105191. <https://doi.org/10.1016/j.still.2021.105191>

- Coulibaly, S.F.M., Coudrain, V., Hedde, M., Brunet, N., Mary, B., Recous, S., Chauvat, M., 2017. Effect of different crop management practices on soil Collembola assemblages: A 4-year follow-up. *Appl. Soil Ecol.* 119, 354–366. <https://doi.org/10.1016/j.apsoil.2017.06.013>
- Crossley, D.A., Mueller, B.R., Perdue, 1992. Biodiversity of microarthropods in agricultural soils: relations to processes. *Agric. Ecosyst. Environ.* 40, 37–46.
- Dang, Y.P., Moody, P.W., Bell, M.J., Seymour, N.P., Dalal, R.C., Freebairn, D.M., Walker, S.R., 2015. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: II. Implications for agronomy, soil and environment. *Soil Tillage Res.* 152, 115–123. <https://doi.org/10.1016/j.still.2014.12.013>
- Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.-P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. *Agric. Ecosyst. Environ.* 188, 134–146. <https://doi.org/10.1016/j.agee.2014.02.014>
- Doles, J.L., Zimmerman, R.J., Moore, J.C., 2001. Soil microarthropod community structure and dynamics in organic and conventionally managed apple orchards in Western Colorado, USA. *Appl. Soil Ecol.* 18, 83–96. [https://doi.org/10.1016/S0929-1393\(01\)00143-3](https://doi.org/10.1016/S0929-1393(01)00143-3)
- Dray, S., Dufour, A.-B., 2007. The ade4 Package: Implementing the duality diagram for ecologists. *J. Stat. Softw.* 22, 1–20. <https://doi.org/10.18637/jss.v022.i04>
- Dulaurent, A.-M., Houben, D., Honvault, N., Faucon, M.-P., Chauvat, M., 2022. Beneficial effects of conservation agriculture on soil fauna communities in Northern France (preprint). In Review. <https://doi.org/10.21203/rs.3.rs-1882824/v1>
- Dupla, X., Lemaître, T., Grand, S., Gondret, K., Charles, R., Verrecchia, E., Boivin, P., 2022. On-farm relationships between agricultural practices and annual changes in organic carbon content at a regional scale. *Front. Environ. Sci.* 10. <https://doi.org/10.3389/fenvs.2022.834055>
- FAO, 2022. Conservation Agriculture. <https://www.fao.org/conservation-agriculture/> (accessed 23 March 2023)

- Ferraro, D.O., Ghera, C.M., 2007a. Exploring the natural and human-induced effects on the assemblage of soil microarthropod communities in Argentina. *Eur. J. Soil Biol.* 43, 109–119. <https://doi.org/10.1016/j.ejsobi.2006.11.006>
- Ferraro, D.O., Ghera, C.M., 2007b. Quantifying the crop management influence on arable soil condition in the Inland Pampa (Argentina). *Geoderma* 141, 43–52. <https://doi.org/10.1016/j.geoderma.2007.04.025>
- Filser, J., Fromm, H., Nagel, R.E., Winter, K., 1995. Effects of previous intensive agricultural management on microorganisms and the biodiversity of soil fauna. *Plant Soil* 170, 123–129.
- Filser, J., Mebes, K.-H., Winter, K., Lang, A., Kampichler, C., 2002. Long-term dynamics and interrelationships of soil Collembola and microorganisms in an arable landscape following land use change. *Geoderma, Land use and sustainability: FAM Research Network on Agroecosystems* 105, 201–221. [https://doi.org/10.1016/S0016-7061\(01\)00104-5](https://doi.org/10.1016/S0016-7061(01)00104-5)
- Gareau, T.P., Voortman, C., Barbercheck, M., 2019. Carabid beetles (Coleoptera: Carabidae) differentially respond to soil management practices in feed and forage systems in transition to organic management. *Renew. Agric. Food Syst.* 1–18. <https://doi.org/10.1017/S1742170519000255>
- Gergócs, V., Flórián, N., Tóth, Z., Szili-Kovács, T., Mucsi, M., Dombos, M., 2022. Crop species and year affect soil-dwelling Collembola and Acari more strongly than fertilisation regime in an arable field. *Appl. Soil Ecol.* 173, 104390. <https://doi.org/10.1016/j.apsoil.2022.104390>
- Gerson, U., 2014. Pest control by mites (Acari): present and future. *Acarologia* 54, 371–394. <https://doi.org/10.1051/acarologia/20142144>
- Gisin, H., 1943. *Okologie und Lebensgemeinschaften der Collembolen im schweizerischen Exkursionsgebiet Basels.*
- Hendrix, P.F., Parmelee, R.W., 1985. Decomposition, nutrient loss and microarthropod densities in herbicide-treated grass litter in a Georgia piedmont agroecosystem. *Soil Biology and Biochemistry* 17, 421–428. [https://doi.org/10.1016/0038-0717\(85\)90003-3](https://doi.org/10.1016/0038-0717(85)90003-3)

- Henneron, L., Bernard, L., Hedde, M., Pelosi, C., Villenave, C., Chenu, C., Bertrand, M., Girardin, C., Blanchart, E., 2015. Fourteen years of evidence for positive effects of conservation agriculture and organic farming on soil life. *Agron. Sustain. Dev.* 35, 169–181.
<https://doi.org/10.1007/s13593-014-0215-8>
- Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V., Evans, A.D., 2005. Does organic farming benefit biodiversity? *Biol. Conserv.* 122, 113–130.
<https://doi.org/10.1016/j.biocon.2004.07.018>
- Hopkin, S.P., 2007. *A Key to the Collembola (Springtails) of Britain and Ireland*. Field Studies Council, Shrewsbury.
- Hopkin, S.P., 1997. *Biology of the Springtails: (Insecta: Collembola)*. OUP Oxford.
- Hothorn, T., Bretz, F., Westfall, P., Heiberger, R.M., Schuetzenmeister, A., Scheibe, S., 2022. multcomp: Simultaneous inference in general parametric models.
- Hu, J., Zhou, S., Tie, L., Liu, Xiong, Liu, Xing, Zhao, A., Lai, J., Xiao, L., You, C., Huang, C., 2022. Effects of nitrogen addition on soil faunal abundance: A global meta-analysis. *Glob. Ecol. Biogeogr.* 31, 1655–1666. <https://doi.org/10.1111/geb.13528>
- Jabbour, R., 2008. *Management effects on epigeal arthropods and soil-dwelling communities during the transition to organic agriculture*. The Pennsylvania State University.
- Jabbour, R., Pisani-Gareau, T., Smith, R.G., Mullen, C., Barbercheck, M., 2016. Cover crop and tillage intensities alter ground-dwelling arthropod communities during the transition to organic production. *Renew. Agric. Food Syst.* 31, 361–374.
<https://doi.org/10.1017/S1742170515000290>
- Jagers Op Akkerhuis, G., Ley, F.D., Zwetsloot, H., Ponge, J.-F., Brussaard, L., 2010. Soil microarthropods (Acari and Collembola) in two crop rotations on a heavy marine clay soil. *Rev. D'Ecologie Biol. Sol* 25, 175–202.

- Joimel, S., Chassain, J., Artru, M., Faburé, J., 2022. Collembola are Among the Most Pesticide-Sensitive Soil Fauna Groups: A Meta-Analysis. *Environ. Toxicol. Chem.* 41, 2333–2341.
<https://doi.org/10.1002/etc.5428>
- Joimel, S., Schwartz, C., Hedde, M., Kiyota, S., Krogh, P.H., Nahmani, J., Pérès, G., Vergnes, A., Cortet, J., 2017. Urban and industrial land uses have a higher soil biological quality than expected from physicochemical quality. *Sci. Total Environ.* 584–585, 614–621.
<https://doi.org/10.1016/j.scitotenv.2017.01.086>
- Jørgensen, L.N., Kudsk, P., 2006. Twenty years' experience with reduced agrochemical inputs: effects on farm economics, water quality, biodiversity and environment. Presented at the HGCA conference, Grantham UK.
- Kanal, A., 2004. Effects of fertilisation and edaphic properties on soil-associated Collembola in crop rotation. *Agron. Res.* 2, 153–168.
- Kautz, T., López-Fando, C., Ellmer, F., 2006. Abundance and biodiversity of soil microarthropods as influenced by different types of organic manure in a long-term field experiment in Central Spain. *Appl. Soil Ecol.* 33, 278–285. <https://doi.org/10.1016/j.apsoil.2005.10.003>
- Kladivko, E.J., 2001. Tillage systems and soil ecology. *Soil Tillage Res.* 61, 61–76.
[https://doi.org/10.1016/S0167-1987\(01\)00179-9](https://doi.org/10.1016/S0167-1987(01)00179-9)
- Kreuzer, K., Bonkowski, M., Langel, R., Scheu, S., 2004. Decomposer animals (Lumbricidae, Collembola) and organic matter distribution affect the performance of *Lolium perenne* (Poaceae) and *Trifolium repens* (Fabaceae). *Soil Biol. Biochem.* 36, 2005–2011.
<https://doi.org/10.1016/j.soilbio.2004.05.019>
- Lavelle, P., Decaëns, T., Aubert, M., Barot, S., Blouin, M., Bureau, F., Margerie, P., Mora, P., Rossi, J.-P., 2006. Soil invertebrates and ecosystem services. *Eur. J. Soil Biol.*, ICSZ 42, S3–S15.
<https://doi.org/10.1016/j.ejsobi.2006.10.002>
- Lavelle, P., Spain, A.V. (Eds.), 2001. Soil Organisms, in: *Soil Ecology*. Springer Netherlands, Dordrecht, pp. 201–356. https://doi.org/10.1007/0-306-48162-6_3

- Mantoni, C., Pellegrini, M., Dapporto, L., Del Gallo, M.M., Pace, L., Silveri, D., Fattorini, S., 2021. Comparison of soil biology quality in organically and conventionally managed agro-ecosystems using microarthropods. *Agriculture* 11, 1022. <https://doi.org/10.3390/agriculture11101022>
- Martins da Silva, P., Carvalho, F., Dirilgen, T., Stone, D., Creamer, R., Bolger, T., Sousa, J.P., 2016. Traits of collembolan life-form indicate land use types and soil properties across an European transect. *Appl. Soil Ecol.* 97, 69–77. <https://doi.org/10.1016/j.apsoil.2015.07.018>
- Masin, C., Rodríguez, A.R., Zalazar, C., Godoy, J.L., 2020. Approach to assess agroecosystem anthropic disturbance: Statistical monitoring based on earthworm populations and edaphic properties. *Ecol. Indic.* 111, 105984. <https://doi.org/10.1016/j.ecolind.2019.105984>
- Mazzoncini, M., Canali, S., Giovannetti, M., Castagnoli, M., Tittarelli, F., Antichi, D., Nannelli, R., Cristani, C., Bàrberi, P., 2010. Comparison of organic and conventional stockless arable systems: A multidisciplinary approach to soil quality evaluation. *Appl. Soil Ecol.* 44, 124–132. <https://doi.org/10.1016/j.apsoil.2009.11.001>
- Mebes, K.-H., Filser, J., 1998. Does the species composition of Collembola affect nitrogen turnover? *Appl. Soil Ecol.* 9, 241–247. [https://doi.org/10.1016/S0929-1393\(97\)00051-6](https://doi.org/10.1016/S0929-1393(97)00051-6)
- Menta, C., Conti, F.D., Lozano Fondón, C., Staffilani, F., Remelli, S., 2020. Soil arthropod responses in agroecosystem: implications of different management and cropping systems. *Agronomy* 10, 982. <https://doi.org/10.3390/agronomy10070982>
- Meyer, S., Kundel, D., Birkhofer, K., Fließbach, A., Scheu, S., 2021. Soil microarthropods respond differently to simulated drought in organic and conventional farming systems. *Ecol. Evol.* 11, 10369–10380. <https://doi.org/10.1002/ece3.7839>
- Miyazawa, K., Tsuji, H., Yamagata, M., Nakano, H., Nakamoto, T., 2002. The effects of cropping systems and fallow managements on microarthropod populations. *Plant Prod. Sci.* 5, 257–265. <https://doi.org/10.1626/pps.5.257>

- Moore, J.C., DeRuiter, P.C., Hunt, H.W., 1993. Soil invertebrate/micro-invertebrate interactions: disproportionate effects of species on food web structure and function. *Vet. Parasitol.* 48, 247–260. [https://doi.org/10.1016/0304-4017\(93\)90160-O](https://doi.org/10.1016/0304-4017(93)90160-O)
- Moos, J.H., Schrader, S., Paulsen, H.M., 2020. Minor changes in collembolan communities under different organic crop rotations and tillage regimes. *Landbauforsch. J. Sustain. Org. Agric. Syst.* 113–128. <https://doi.org/10.3220/LBF1611932809000>
- Moradi, J., Besharati, H., Bahrami, H.A., Karimi, M., 2013. A 2-year study of soil tillage and cattle manure application effects on soil fauna populations under *Zea Mays* cultivation, in western Iran (Sanandaj). *Environ. Earth Sci.* 70, 799–805. <https://doi.org/10.1007/s12665-012-2169-y>
- Neher, D.A., 1995. Biological diversity in soils of agricultural and natural ecosystems, in: *Exploring the Role of Diversity in Sustainable Agriculture*. American Society of Agronomy, Madison, WI, pp. 55–72.
- Nunes, M.R., Karlen, D.L., Veum, K.S., Moorman, T.B., Cambardella, C.A., 2020. Biological soil health indicators respond to tillage intensity: A US meta-analysis. *Geoderma* 369, 114335. <https://doi.org/10.1016/j.geoderma.2020.114335>
- Oksanen, J., Simpson, G.L., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O’Hara, R.B., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., Caceres, M.D., Durand, S., Evangelista, H.B.A., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M.O., Lahti, L., McGlenn, D., Ouellette, M.-H., Cunha, E.R., Smith, T., Stier, A., Braak, C.J.F.T., Weedon, J., 2022. *vegan: Community Ecology Package*.
- Osler, G.H.R., Harrison, L., Kanashiro, D.K., Clapperton, M.J., 2008. Soil microarthropod assemblages under different arable crop rotations in Alberta, Canada. *Appl. Soil Ecol.* 38, 71–78. <https://doi.org/10.1016/j.apsoil.2007.09.003>

- Ponge, J.F., Gillet, S., Dubs, F., Fedoroff, E., Haese, L., Sousa, J.P., Lavelle, P., 2003. Collembolan communities as bioindicators of land use intensification. *Soil Biol. Biochem.* 35, 813–826.
[https://doi.org/10.1016/S0038-0717\(03\)00108-1](https://doi.org/10.1016/S0038-0717(03)00108-1)
- Potapov, A.M., Beaulieu, F., Birkhofer, K., Bluhm, S.L., Degtyarev, M.I., Devetter, M., Goncharov, A.A., Gongalsky, K.B., Klarner, B., Korobushkin, D.I., Liebke, D.F., Maraun, M., Mc Donnell, R.J., Pollierer, M.M., Schaefer, I., Shrubovych, J., Semenyuk, I.I., Sendra, A., Tuma, J., Tůmová, M., Vassilieva, A.B., Chen, T., Geisen, S., Schmidt, O., Tiunov, A.V., Scheu, S., 2022. Feeding habits and multifunctional classification of soil-associated consumers from protists to vertebrates. *Biol. Rev.* brv.12832. <https://doi.org/10.1111/brv.12832>
- Potapov, A.M., Bellini, B.C., Chown, S.L., Deharveng, L., Janssens, F., Kováč, Ľ., Kuznetsova, N., Ponge, J.-F., Potapov, M., Querner, P., Russell, D., Sun, X., Zhang, F., Berg, M.P., 2020. Towards a global synthesis of Collembola knowledge: challenges and potential solutions. *Soil Org.* 92, 161–188. <https://doi.org/10.25674/so92iss3pp161>
- Potapov, A.M., Goncharov, A.A., Semenina, E.E., Korotkevich, A.Y., Tsurikov, S.M., Rozanova, O.L., Anichkin, A.E., Zuev, A.G., Samoylova, E.S., Semenyuk, I.I., Yevdokimov, I.V., Tiunov, A.V., 2017. Arthropods in the subsoil: Abundance and vertical distribution as related to soil organic matter, microbial biomass and plant roots. *Eur. J. Soil Biol.* 82, 88–97.
<https://doi.org/10.1016/j.ejsobi.2017.09.001>
- Potapov, M., 2001. Synopses on Palaearctic Collembola, Volume 3: Isotomidae, Synopses on Palaearctic Collembola. Senckenberg Museum of Natural History, Goerlitz.
- Potapov, M.B., Bokova, A.I., Janion-Scheepers, C., Kuznetsova, N.A., Merk, M.S., Panina, K.S., Potapov, A.M., Saraeva, A.K., 2022. Organic farming and moderate tillage change the dominance and spatial structure of soil Collembola communities but have little effects on bulk abundance and species richness. *SOIL Org.* 94, 99–110.
<https://doi.org/10.25674/so94iss2id173>

- Reeleder, R.D., Miller, J.J., Ball Coelho, B.R., Roy, R.C., 2006. Impacts of tillage, cover crop, and nitrogen on populations of earthworms, microarthropods, and soil fungi in a cultivated fragile soil. *Appl. Soil Ecol.* 33, 243–257. <https://doi.org/10.1016/j.apsoil.2005.10.006>
- Reilly, K., Cavigelli, M., Szlavecz, K., 2023. Agricultural management practices impact soil properties more than soil microarthropods. *Eur. J. Soil Biol.* 117, 103516. <https://doi.org/10.1016/j.ejsobi.2023.103516>
- Rieff, G.G., Natal-da-Luz, T., Renaud, M., Azevedo-Pereira, H.M.V.S., Chichorro, F., Schmelz, R.M., Sá, E.L.S. de, Sousa, J.P., 2020. Impact of no-tillage versus conventional maize plantation on soil mesofauna with and without the use of a lambda-cyhalothrin based insecticide: A terrestrial model ecosystem experiment. *Appl. Soil Ecol.* 147, 103381. <https://doi.org/10.1016/j.apsoil.2019.103381>
- Roger-Estrade, J., Anger, C., Bertrand, M., Richard, G., 2010. Tillage and soil ecology: Partners for sustainable agriculture. *Soil Tillage Res.* 111, 33–40. <https://doi.org/10.1016/j.still.2010.08.010>
- Rusek, J., 1998. Biodiversity of Collembola and their functional role in the ecosystem. *Biodivers. Conserv.* 7, 1207–1219. <https://doi.org/10.1023/A:1008887817883>
- Salmon, S., Vittier, T., Barot, S., Ponge, J.-F., Ben Assoula, F., Lusley, P., 2021. Responses of Collembola communities to mixtures of wheat varieties: A trait-based approach. *Pedobiologia* 87–88, 150755. <https://doi.org/10.1016/j.pedobi.2021.150755>
- Santorufu, L., Cortet, J., Nahmani, J., Pernin, C., Salmon, S., Pernot, A., Morel, J.L., Maisto, G., 2015. Responses of functional and taxonomic collembolan community structure to site management in Mediterranean urban and surrounding areas. *Eur. J. Soil Biol.* 70, 46–57. <https://doi.org/10.1016/j.ejsobi.2015.07.003>
- Schmidt, O., Curry, J.P., 2001. Population dynamics of earthworms (Lumbricidae) and their role in nitrogen turnover in wheat and wheatclover cropping systems. *Pedobiologia* 45, 174–187. <https://doi.org/10.1078/0031-4056-00078>

- Schrader, S., Kiehne, J., Anderson, T., Paulsen, H.-M., Rahmann, G., 2006. Development of collembolans after conversion towards organic farming, in: Atkinson, C., Younie, D. (Eds.), *What Will Organic Farming Deliver?* AAB Office, Warwick, UK, pp. 181–184.
https://doi.org/10.1/ABB06_Collembolans.pdf
- Sjursen, H., Holmstrup, M., 2004. Direct measurement of ammonium excretion in soil microarthropods. *Funct. Ecol.* 18, 612–615.
- Socarrás, A., Izquierdo, I., 2014. Evaluation of agroecological systems through biological indicators of the soil quality: edaphic mesofauna. *Pastos Forrajes* 37, 109–114.
- Song, L., Liu, J., Yan, X., Chang, L., Wu, D., 2016. Euedaphic and hemiedaphic Collembola suffer larger damages than epedaphic species to nitrogen input. *Environ. Pollut.* 208, 413–415.
<https://doi.org/10.1016/j.envpol.2015.10.008>
- Stanhill, G., 1990. The comparative productivity of organic agriculture. *Agric. Ecosyst. Environ.* 30, 1–26. [https://doi.org/10.1016/0167-8809\(90\)90179-H](https://doi.org/10.1016/0167-8809(90)90179-H)
- Suzuki, R., Terada, Y., Shimodaira, H., 2019. pvclust: Hierarchical clustering with P-values via multiscale bootstrap resampling.
- Swift, M.J., Heal, O.W., Anderson, J.M., 1979. *Decomposition in terrestrial ecosystems*. Blackwell, Oxford.
- Tabaglio, V., Gavazzi, C., Menta, C., 2009. Physico-chemical indicators and microarthropod communities as influenced by no-till, conventional tillage and nitrogen fertilisation after four years of continuous maize. *Soil Tillage Res.* 105, 135–142.
<https://doi.org/10.1016/j.still.2009.06.006>
- Taylor, A.R., Schröter, D., Pflug, A., Wolters, V., 2004. Response of different decomposer communities to the manipulation of moisture availability: potential effects of changing precipitation patterns. *Glob. Change Biol.* 10, 1313–1324. <https://doi.org/10.1111/j.1365-2486.2004.00801.x>

- Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., de Ruiter, P.C., van der Putten, W.H., Birkhofer, K., Hemerik, L., de Vries, F.T., Bardgett, R.D., Brady, M.V., Bjornlund, L., Jørgensen, H.B., Christensen, S., Hertefeldt, T.D., Hotes, S., Gera Hol, W.H., Frouz, J., Liiri, M., Mortimer, S.R., Setälä, H., Tzanopoulos, J., Uteseny, K., Pižl, V., Stary, J., Wolters, V., Hedlund, K., 2015. Intensive agriculture reduces soil biodiversity across Europe. *Glob. Change Biol.* 21, 973–985. <https://doi.org/10.1111/gcb.12752>
- Twardowski, J.P., Hurej, M., Gruss, I., 2016. Diversity and abundance of springtails (Hexapoda: Collembola) in soil under 90-year potato monoculture in relation to crop rotation. *Arch. Agron. Soil Sci.* 62, 1158–1168. <https://doi.org/10.1080/03650340.2015.1131270>
- Foster, G.R., Toy, T.E., Renard, K.G., 2003. Comparison of the USLE, RUSLE1.06c, and RUSLE2 for application to highly disturbed lands. Proceedings of the first interagency conference on research in watersheds, Washington, DC: US Department of Agriculture, Agricultural Research Service, pp. 154–160.
- van Capelle, C., Schrader, S., Brunotte, J., 2012. Tillage-induced changes in the functional diversity of soil biota – A review with a focus on German data. *Eur. J. Soil Biol.* 50, 165–181. <https://doi.org/10.1016/j.ejsobi.2012.02.005>
- van Straalen, N.M., Verhoef, H.A., 1997. The Development of a Bioindicator System for Soil Acidity Based on Arthropod pH Preferences. *J. Appl. Ecol.* 34, 217–232. <https://doi.org/10.2307/2404860>
- Vieublé Gonod, L., Martin-Laurent, F., Chenu, C., 2006. 2,4-Dimpycton bacterial communities, and the activity and genetic potential of 2,4-Ddegrading communities in soil. *FEMS Microbiol. Ecol.*, 58, 529–537. <https://doi.org/10.1111/j.1574-6941.2006.00159.x>
- Walder, F., Schmid, M.W., Riedo, J., Valzano-Held, A.Y., Banerjee, S., Büchi, L., Bucheli, T.D., van der Heijden, M.G.A., 2022. Soil microbiome signatures are associated with pesticide residues in arable landscapes. *Soil Biol. Biochem.* 174, 108830. <https://doi.org/10.1016/j.soilbio.2022.108830>

- Wardle, D.A., 1995. Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices, in: *Advances in Ecological Research*. Elsevier, pp. 105–185. [https://doi.org/10.1016/S0065-2504\(08\)60065-3](https://doi.org/10.1016/S0065-2504(08)60065-3)
- Wardle, D.A., Nicholson, K.S., Bonner, K.I., Yeates, G.W., 1999. Effects of agricultural intensification on soil-associated arthropod population dynamics, community structure, diversity and temporal variability over a seven-year period. *Soil Biol. Biochem.* 31, 1691–1706. [https://doi.org/10.1016/S0038-0717\(99\)00089-9](https://doi.org/10.1016/S0038-0717(99)00089-9)
- Weil, R.R., Kroontje, W., 1979. Organic matter decomposition in a soil heavily amended with poultry manure. *J. Environ. Qual.* 8, 584–588. <https://doi.org/10.2134/jeq1979.00472425000800040029x>
- Werner, M.R., Dindal, D.L., 1990. Effects of conversion to organic agricultural practices on soil biota. *Am. J. Altern. Agric.* 5, 24–32. <https://doi.org/10.1017/S0889189300003192>
- Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., David, C., 2009. Agroecology as a science, a movement and a practice. A review. *Agron. Sustain. Dev.* 29, 503–515. <https://doi.org/10.1051/agro/2009004>
- Winter, J.P., Voroney, R.P., Ainsworth, D.A., 1990. Soil microarthropods in long-term no-tillage and conventional tillage corn production. *Can. J. Soil Sci.* 70, 641–653. <https://doi.org/10.4141/cjss90-067>
- Zhu, Y., Bian, H., Ju, C., Xu, C., Zhou, Y., Zhang, H., Xu, X., 2023. Fertilization alters the abundance but not the diversity of soil fauna: A meta-analysis. *Glob. Ecol. Biogeogr.* 32, 482–494. <https://doi.org/10.1111/geb.13641>

Table 1. Cropping system, location, crop and soil properties (0-10 cm depth) for the 21 fields of the study. Age corresponds to the number of years since conversion to the current system in 2020.

System	Field	Region	Age	Crop 2019-2020	Crop 2020-2021	Crop 2021-2022	Clay	Silt	Sand	SOM	pH	BD
							g.kg ⁻¹	g.kg ⁻¹	g.kg ⁻¹	g.kg ⁻¹		
Conv	A5	Eure-et-Loir	20	rapeseed	wheat	barley	206	448	52	24.5	6.8	1.3
	A9	Yvelines	20	faba.	wheat	rapeseed	208	402	187	18.5	6.8	1.3
	A10	Eure-et-Loir	20	rapeseed	wheat	alfalfa	220	442	47	20.9	7.2	1.3
	A12	Yvelines	20	rapeseed	wheat	cover	221	352	164	23.3	7.4	1.3
	A16	Essonne	20	rapeseed	wheat	mustard	284	338	67	24.2	8.1	1.4
	A21	Eure-et-Loir	20	rapeseed	wheat	barley	340	226	238	32.9	8.0	1.2
CA	A2	Essonne	17	faba.	wheat	cover	210	381	119	33.5	6.3	1.3
	A8	Essonne	7	rapeseed	wheat	mustard	193	364	183	24.0	5.6	1.5
	A17	Yvelines	10	barley	wheat	rapeseed	228	349	203	36.4	8.1	1.2
Conv-CA	A1	Eure-et-Loir	3	rapeseed	wheat	wheat	151	474	56	19.5	6.8	1.3
	A14	Yvelines	3	barley	wheat	cover	175	385	120	32.0	6.8	1.2
	A15	Yvelines	3	faba.	wheat	wheat	193	395	92	28.1	7.0	1.4
OA	A3	Essonne	20	alfalfa	wheat	wheat	158	409	196	17.5	6.5	1.4
	A4	Yvelines	19	triticale, peas	wheat	bare	426	237	93	34.4	7.9	1.1
	A11	Yvelines	20	rapeseed	wheat	cover	253	350	120	27.0	7.3	1.2
Conv-OA	A7	Yvelines	2	cover	wheat	rye	172	481	63	22.3	6.6	1.2
	A18	Yvelines	3	alfalfa, wheat	wheat	bare	196	455	68	23.9	6.8	1.2
	A19	Yvelines	2	grass	wheat	clover	280	264	262	23.8	7.7	1.3
CA-OA	A6	Essonne	2	lentil	wheat	bare	277	378	29	21.0	6.6	1.3
	A13	Yvelines	2	maize	wheat	rye, lentil	248	412	75	33.4	6.9	1.2
	A20	Eure-et-Loir	2	triticale, faba.	wheat	cover	204	407	49	16.9	7.5	1.4

faba.: faba beans, Conv: conventional agriculture, CA: conservation agriculture, OA: organic agriculture, Conv-CA: transition from conventional to conservation (≤ 3 years), Conv-OA: transition from conventional to organic (≤ 3 years), CA-OA: transition from conservation to organic (≤ 3 years), SOM: soil organic matter, BD: bulk density.

1 Table 2. Primary indicators and composite indexes of practice intensity used to characterize cropping
 2 systems. Composite indexes are given in bold. Time represents the time span in which data were
 3 collected to compute the indicator, either one year (1 y) from beginning of the previous cropping cycle
 4 until the sampling date, or five years (5 y) to account for the crop succession temporal scale. Indexes
 5 are adapted from Büchi et al. (2019).

Category	Name	Time	Content
(a) Soil physical disturbances (tillage)	nbDTill	1 y	Number of deep tillage (i.e. ploughing, > 15 cm depth)
	nbSTill	1 y	Number of surface tillage (i.e. all shallow tillage activities < 15 cm depth such as mechanical weeding, stubble incorporation, stones removal, seedbed preparation and rolling)
	soilP	5 y	Type of tillage in the last 5 years, calculated as the average of annual tillage weight (plough = 0.5, reduced tillage = 3, no-till = 5)
	Itill		Average of standardized tillage indicators
(b) Chemical crop protection (pesticide treatments)	nbHerb	1 y	Number of herbicide treatments
	nbFung	1 y	Number of fungicide treatments
	nbInsect	1 y	Number of insecticide treatments
	Itreat		Total number of pesticide treatments: herbicides, fungicides, insecticides, molluscicides and growth regulators
	TFI		Treatment frequency index comprising herbicides, fungicides, insecticides, molluscicides and seed treatments applied during the crop cycle (from sowing to harvest)
(c) Fertilization and organic inputs	nbOrg	5 y	Number of organic amendments in the last 5 years
	nbRes	5 y	Number of times crop residues were retained in the last 5 years
	lorg		Average of standardized indicators of organic matter inputs
	qminN	1 y	Quantity of mineral nitrogen fertilizers inputs (kg N.ha ⁻¹)
(d) Crop diversification	nbCrop	5 y	Number of different crops in the last 5 years

6

7

8 Table 3. Primary indicators and composite indexes of practice intensity in different cropping systems in 2020 and 2021. Values are means \pm standard deviations.
 9 Normalized values are presented for Itill, Itreat and Iorg. Different lower-case letters and bold values indicate significant differences between systems (ANOVA,
 10 $P < 0.05$).

	2020						2021					
	Conv	CA	Conv-CA	OA	Conv-OA	CA-OA	Conv	CA	Conv-CA	OA	Conv-OA	CA-OA
nbDTill	0.7 \pm 0.8	0	0	1.7 \pm 0.6	1.7 \pm 0.6	1.0 \pm 1.0	0.7 \pm 0.8	0	0	1.3 \pm 0.6	1.3 \pm 0.6	0.3 \pm 0.6
nbSTill	5.3 \pm 3.1	0.7 \pm 1.2	0.3 \pm 0.6	6.3 \pm 2.5	3.7 \pm 1.2	7.0 \pm 4.6	4.0 \pm 2.5 abc	0 c	0.3 \pm 0.6 bc	7.7 \pm 1.2 ab	7.0 \pm 2.7 abc	8.3 \pm 5.9 a
soilP	2.0 \pm 1.0 bc	4.9 \pm 0.2 a	3.8 \pm 0.4 ab	1.3 \pm 1.3 c	1.5 \pm 1.0 bc	2.3 \pm 0.8 bc	2.0 \pm 1.1 bc	4.9 \pm 0.2 a	4.1 \pm 0.6 ab	1.3 \pm 1.3 c	1.5 \pm 1.0 c	2.3 \pm 0.8 bc
Itill	0.5 \pm 0.2 ab	0.0 \pm 0.1 c	0.1 \pm 0.0 bc	0.7 \pm 0.3 a	0.6 \pm 0.1 a	0.6 \pm 0.2 ab	0.4 \pm 0.2 ab	0 b	0.1 \pm 0.1 b	0.7 \pm 0.1 a	0.6 \pm 0.2 a	0.4 \pm 0.1 ab
nbHerb	5.2 \pm 1.9 a	6.3 \pm 4.0 a	5.3 \pm 0.6 a	0 b	0 b	0 b	7.8 \pm 1.2 a	6.0 \pm 2.7 a	6.3 \pm 3.5 a	0 b	0 b	0 b
nbFung	0.8 \pm 0.4	0.3 \pm 0.6	1.0 \pm 1.0	0	0	0	1.8 \pm 0.4 b	1.7 \pm 1.5 bc	3.3 \pm 0.6 a	0 c	0 c	0 c
nbInsect	1.3 \pm 1.0 ab	0 b	2.3 \pm 0.6 a	0 b	0 b	0 b	0.8 \pm 0.8	0.7 \pm 1.2	2.0 \pm 2.0	0	0	0
Itreat	0.7 \pm 0.2 a	0.6 \pm 0.4 a	0.8 \pm 0.0 a	0 b	0 b	0 b	0.8 \pm 0.1 a	0.6 \pm 0.3 a	0.8 \pm 0.3 a	0 b	0 b	0 b
TFI	5.0 \pm 1.4 a	3.1 \pm 1.9 a	6.4 \pm 0.0 a	0 b	0 b	0 b	9.4 \pm 1.6 a	5.9 \pm 4.2 ab	6.6 \pm 0.0 ab	0 b	0 b	0.3 \pm 0.5 b
nbOrg	0.8 \pm 1.0 c	0.7 \pm 0.6 c	1.0 \pm 1.0 bc	5.0 \pm 1.7 a	3.3 \pm 0.6 ab	2.3 \pm 0.6 bc	0.8 \pm 1.0 c	0.7 \pm 0.6 c	1.0 \pm 1.0 bc	5.0 \pm 1.7 a	3.3 \pm 0.6 ab	3.0 \pm 1.0 abc
nbRes	4.7 \pm 0.8	5.0 \pm 0.0	2.7 \pm 2.1	4.0 \pm 1.7	2.7 \pm 1.2	5.0 \pm 0.0	4.7 \pm 0.8	5.0 \pm 0.0	2.7 \pm 2.1	4.0 \pm 1.7	2.7 \pm 1.2	4.7 \pm 0.6
Iorg	0.5 \pm 0.1 ab	0.6 \pm 0.0 ab	0.3 \pm 0.2 b	0.8 \pm 0.2 a	0.5 \pm 0.2 ab	0.7 \pm 0.0 a	0.5 \pm 0.1 ab	0.6 \pm 0.0 ab	0.3 \pm 0.2 b	0.8 \pm 0.2 a	0.5 \pm 0.2 ab	0.7 \pm 0.2 a
qminN	129 \pm 67	109 \pm 95	69 \pm 70	0	0	0	198 \pm 41 a	130 \pm 40 b	187 \pm 24 ab	0 c	0 c	0 c
nbCrop	3.2 \pm 0.8	3.3 \pm 0.6	3.7 \pm 0.6	3.7 \pm 0.6	3.0 \pm 1.0	3.3 \pm 0.6	3.5 \pm 1.1	3.7 \pm 0.6	3.7 \pm 0.6	3.7 \pm 0.6	3.7 \pm 1.2	3.7 \pm 0.6

11 Conv, CA and OA: conventional, conservation and organic agriculture, Conv-CA, Conv-OA and CA-OA: transitioning systems (initial-recent system), nbDTill: nb of deep tillage, nbSTill: nb of surface
 12 tillage, soilP: type of tillage (5 y), Itill: tillage intensity index, nbHerb: nb of herbicides, nbFung: nb of fungicides, nbInsect: nb of insecticides, Itreat: pesticide treatment intensity index, TFI:
 13 treatment frequency index, nbOrg: nb of organic amendments (5 y), nbRes: nb of times crop residues were retained (5 y), Iorg: organic input intensity index, qminN: quantity of mineral nitrogen
 14 (kg N.ha⁻¹), nbCrop: nb of crops (5 y).
 15

16 Table 4. Effects of cropping systems on the density of mesofauna groups (10^2 ind.m^{-2}), the ratio Acari/Collembola and the Collembola diversity in studied
 17 cropping systems in 2020 and 2021. Values are means \pm standard deviations. Different lower-case letters and bold values indicate significant differences
 18 between cropping systems according to the results of GLM ($P < 0.05$).

	2020						2021					
	Conv	CA	Conv-CA	OA	Conv-OA	CA-OA	Conv	CA	Conv-CA	OA	Conv-OA	CA-OA
Acari density												
Actinidida	1 \pm 2	6 \pm 7	13 \pm 23	1 \pm 0	0 \pm 1	7 \pm 3	4 \pm 5	0 \pm 1	6 \pm 11	0 \pm 1	0 \pm 1	9 \pm 8
Gamasida	28 \pm 17 a	34 \pm 24 ab	15 \pm 12 ab	10 \pm 7 ab	5 \pm 2 b	9 \pm 8 ab	22 \pm 13	34 \pm 10	22 \pm 11	44 \pm 47	18 \pm 12	32 \pm 11
Oribatida	280 \pm 305 a	192 \pm 91 ab	67 \pm 56 ab	30 \pm 28 b	24 \pm 8 b	73 \pm 48 ab	113 \pm 109	197 \pm 43	207 \pm 95	188 \pm 201	94 \pm 61	214 \pm 126
Collembola density												
Epedaphic	29 \pm 32 a	45 \pm 29 a	50 \pm 57 a	10 \pm 2 a	5 \pm 5 a	18 \pm 16 a	45 \pm 58	157 \pm 117	96 \pm 50	30 \pm 13	28 \pm 15	18 \pm 3
Euedaphic	8 \pm 8 a	3 \pm 3 ab	4 \pm 4 ab	1 \pm 1 ab	0 \pm 1 b	3 \pm 2 ab	3 \pm 5 ab	4 \pm 4 ab	8 \pm 9 ab	21 \pm 20 a	2 \pm 2 ab	0 \pm 0 b
Hemiedaphic	17 \pm 12 a	20 \pm 12 a	21 \pm 7 a	8 \pm 8 ab	1 \pm 1 b	5 \pm 2 ab	28 \pm 26 ab	166 \pm 104 a	78 \pm 80 ab	84 \pm 94 ab	28 \pm 30 ab	9 \pm 3 b
Other organisms	6 \pm 5 a	3 \pm 1 ab	4 \pm 3 ab	2 \pm 1 ab	0 \pm 1 b	2 \pm 1 ab	4 \pm 7	6 \pm 2	6 \pm 6	6 \pm 3	3 \pm 3	2 \pm 4
Ratio A/C density	5.5 \pm 4.0	4.0 \pm 1.7	1.3 \pm 0.3	2.1 \pm 0.8	6.2 \pm 5.1	7.9 \pm 10.3	2.4 \pm 1.0 b	1.1 \pm 0.9 b	1.7 \pm 0.9 b	1.4 \pm 0.8 b	3.9 \pm 3.9 ab	9.2 \pm 5.3 a
Collembola diversity												
Richness	8.0 \pm 3.0 a	9.7 \pm 4.9 a	10.3 \pm 2.1 a	5.7 \pm 0.6 ab	2.7 \pm 0.6 b	6.3 \pm 2.1 ab	7.7 \pm 4.1	13.3 \pm 1.2	12.3 \pm 3.1	13.3 \pm 4.2	9.0 \pm 1.7	8.0 \pm 1.0
Shannon	1.7 \pm 0.5 a	1.8 \pm 0.5 a	1.9 \pm 0.2 a	1.5 \pm 0.2 ab	0.9 \pm 0.2 b	1.6 \pm 0.3 ab	1.5 \pm 0.5	1.9 \pm 0.2	1.7 \pm 0.2	2.0 \pm 0.5	1.8 \pm 0.1	1.8 \pm 0.2
Evenness	0.8 \pm 0.1	0.8 \pm 0.0	0.8 \pm 0.1	0.9 \pm 0.0	0.9 \pm 0.1	0.9 \pm 0.1	0.8 \pm 0.2	0.7 \pm 0.1	0.7 \pm 0.0	0.8 \pm 0.2	0.8 \pm 0.1	0.9 \pm 0.1

19 Conv, CA and OA: conventional, conservation and organic agriculture; Conv-CA, Conv-OA and CA-OA: transitioning systems (initial-recent system); Ratio A/C: ratio Acari/Collembola.
 20
 21
 22
 23

Table 5. Effects of practice intensity on the density of mesofauna groups and Collembola diversity in (a) 2020 and (b) 2021. *t*-values and *P*-values were obtained using GLM for each intensity index or indicator separately. *t*-values indicate an increase (positive *t*-values) or a decrease (negative *t*-values) in density as practice intensity increases. Bold values indicate significant effects (*P* < 0.05 *, < 0.01 **, < 0.001 ***). Primary indicators having a significant (*P* < 0.05) positive (+) or negative (-) effect on mesofauna variables are reported.

	ltill		ltreat		lorg		Primary indicators
	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>	<i>t</i>	<i>P</i>	
(a) 2020							
Acari density							(+) nbHerb, qminN ; (-) nbDTill, nbOrg
Actinidida	-1.81	0.086	0.86	0.401	2.08	0.051	(-) nbFung
Gamasida	-3.99	<0.001***	3.84	0.001**	0.36	0.723	(+) soilP, nbHerb, nbRes, qminN ; (-) nbDTill, nbOrg
Oribatida	-1.96	0.065	2.15	0.044*	-0.11	0.913	(+) nbHerb, qminN ; (-) nbDTill
Collembola density							(+) soilP, nbHerb, qminN ; (-) nbDTill, nbSTill, nbOrg
Epedaphic	-3.36	0.003**	3.27	0.004**	-0.16	0.878	(+) soilP, nbHerb, nbRes, qminN ; (-) nbDTill, nbSTill, nbOrg
Euedaphic	-0.31	0.759	2.29	0.034*	-0.72	0.477	(+) nbInsect, qminN
Hemiedaphic	-2.97	0.008**	4.00	<0.001***	-1.43	0.169	(+) soilP, nbHerb ; (-) nbDTill
Other organisms	-1.01	0.325	3.53	0.002**	0.87	0.392	(+) nbHerb, nbInsect, qminN
Collembola diversity							
Richness	-4.47	<0.001***	4.81	<0.001***	-0.68	0.503	(+) soilP, nbHerb ; (-) nbDTill, nbSTill, nbOrg
Shannon	-3.52	0.002**	3.70	0.001**	-0.07	0.944	(+) soilP, nbHerb ; (-) nbDTill
Evenness	1.35	0.194	-2.46	0.024*	0.43	0.674	(-) nbHerb, nbFung
(b) 2021							
Acari density							(+) nbCrop ; (-) nbDTill
Actinidida	-0.52	0.607	0.76	0.455	-0.20	0.844	(-) nbInsect, nbOrg
Gamasida	-0.19	0.848	-1.05	0.308	2.22	0.039*	n.s.
Oribatida	-1.38	0.182	-0.03	0.974	0.18	0.861	(+) nbCrop ; (-) nbDTill
Collembola density							(-) nbDTill, nbSTill
Epedaphic	-4.46	<0.001***	2.22	0.039*	-0.54	0.593	(+) soilP, nbHerb, nbCrop, qminN ; (-) nbDTill, nbSTill, nbOrg
Euedaphic	0.57	0.577	-0.50	0.623	1.19	0.248	n.s.
Hemiedaphic	-1.60	0.125	0.36	0.723	0.69	0.500	(-) nbSTill
Other organisms	-1.37	0.187	1.19	0.250	1.01	0.325	(-) nbSTill
Collembola diversity							
Richness	-1.81	0.087	0.05	0.959	0.33	0.742	n.s.
Shannon	-0.65	0.524	-1.45	0.164	0.95	0.351	(-) qminN
Evenness	1.28	0.215	-1.58	0.131	0.63	0.533	n.s.

ltill: tillage intensity index, ltreat: pesticide treatment intensity index, lorg: organic input intensity index, nbDTill: nb of deep tillage, nbSTill: nb of surface tillage, soilP: type of tillage (5 y), nbHerb: nb of herbicides, nbFung: nb of fungicides, nbInsect: nb of insecticides, nbOrg: nb of organic amendments (5 y), nbRes: nb of times crop residues were retained (5 y), qminN: quantity of mineral nitrogen (kg N.ha⁻¹), nbCrop: nb of crops (5 y), n.s.: no significant effect.

Figure 1. PCA on primary cropping practice indicators in (a) 2020 and (b) 2021. Ellipses represent 95% confidence estimates for the different cropping systems. Practice indicators are colored according to their contribution. Conv: conventional agriculture; CA: conservation agriculture; OA: organic agriculture; Conv-CA, Conv-OA and CA-OA: transitioning systems (initial-recent system).

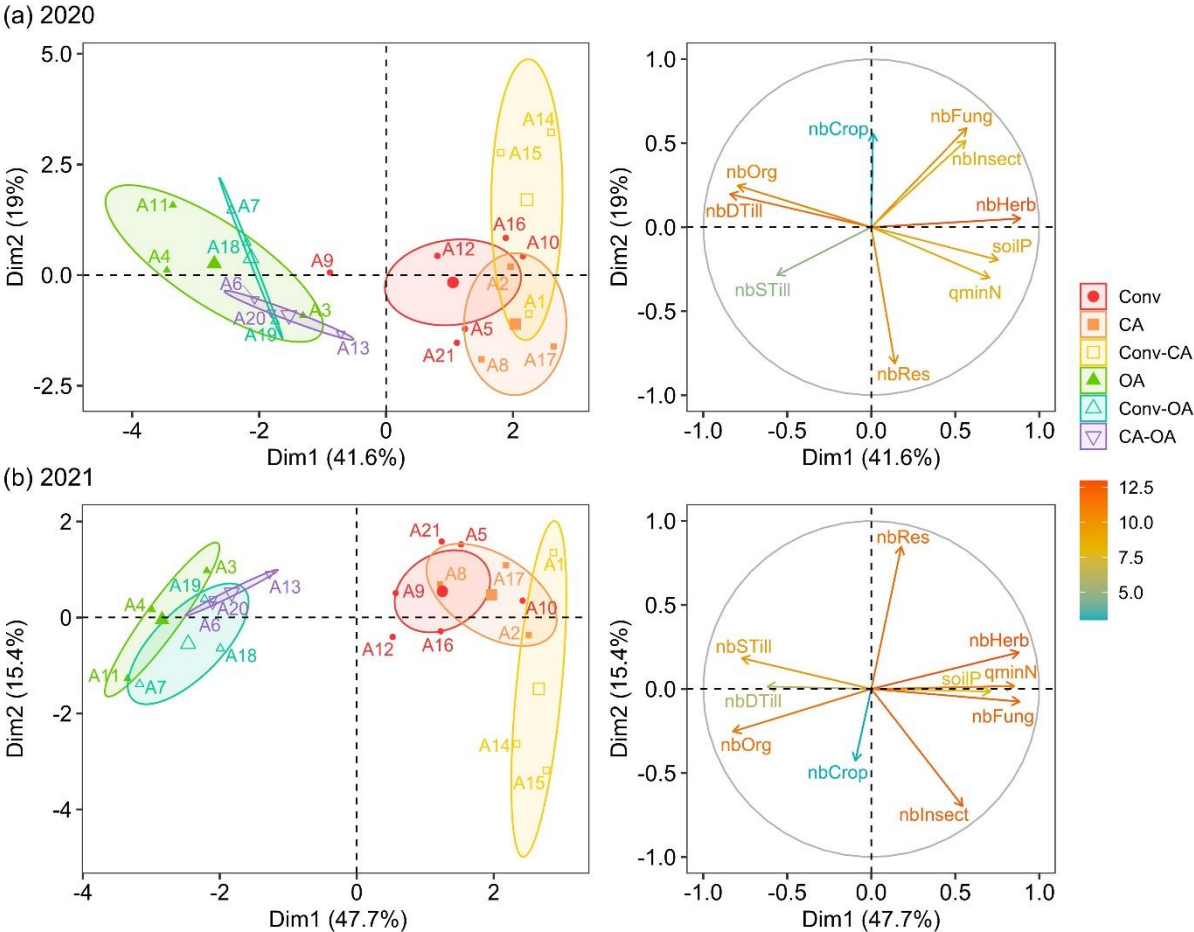


Figure 2. Effects of cropping systems and practice intensity on (a) total mesofauna, (b) Acari and (c) Collembola densities in 2020 and 2021. Significant differences between systems are represented with different lower-case letters and significant effects of intensity indexes are reported for each year ($P < 0.05^*$, $< 0.01^{**}$, $< 0.001^{***}$), all according to the results of GLM with a quasi-Poisson error distribution. Conv, CA and OA: conventional, conservation and organic agriculture, Conv-CA, Conv-OA and CA-OA: transitioning systems (initial-recent system), Itill: tillage intensity, Itreat: pesticide treatment intensity, lorg: organic input intensity.

