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Article in *Journal of Applied Ecology* · June 2023

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RESEARCH ARTICLE

Linking agricultural diversification practices, soil arthropod communities and soil health

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Funding information

National Institute of Food and Agriculture, Grant/Award Number: #2017-68002-26819

Handling Editor: S. Emilia Hannula

Abstract

1. Soil arthropods comprise a substantial portion of soil biodiversity and regulate processes in the soil ecosystem. Despite this, cropping system diversification designed to improve soil health for agriculture is rarely evaluated for its effects on soil arthropod biodiversity and community structure. As a result, soil arthropods are not usually considered in management decisions.
2. To address this gap, we evaluated the effects of agricultural diversification through rotation on soil arthropods and soil properties using replicated large-plot field studies representing two climatically distinct agroecological classes (AECs) in the dryland cereal-growing region of the inland Pacific Northwest, USA. We investigated how different 3-year annual crop rotations affected soil arthropod biodiversity and community structure. Treatments reflected 'business-as-usual' rotations in dryland systems and diversified rotations achieved by incorporating novel winter pea (WP) or forage crops (FORs). We also assessed relationships between the Soil Biological Quality index (QBS-ar), which uses soil arthropods as bioindicators of soil health, and other biological and physiochemical soil health indicators.
3. We collected 710 community samples with 82,509 arthropod specimens across 66 taxa. Novel crops in diversified rotations promoted soil arthropod abundance and biodiversity relative to crops they could replace in rotation. Crop type determined community composition. Most taxa driving differences in community structure were predators and detritivores associated with WP and FORs. In addition to effects on soil arthropods associated with specific crops, effects were also detected across rotations. Incorporating WP into rotations improved QBS-ar across entire rotations, not just in the WP phases, in both AECs. Links between QBS-ar and other soil health indicators were complex and varied by AEC.
4. *Synthesis and applications:* Soil arthropods respond to agricultural diversification and can be used as bioindicators to assess the effects of diversification on soil health. Below-ground arthropod communities are structured by crop type, suggesting that planting specific crops may promote soil arthropods and their

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services. We showed that incorporating winter pea and forage crops into dryland cereal rotations supported soil arthropod biodiversity and soil health. Results indicate that soil arthropod assessments can be included in the soil health framework to guide agricultural management decisions.

KEYWORDS

agricultural diversification, biodiversity, community ecology, QBS-ar, soil arthropods, soil health

1 | INTRODUCTION

Industrial agricultural practices result in simplified agroecosystems in which naturally occurring ecosystem processes are diminished and often are entirely or partially replaced with off-farm inputs. These effects extend into agroecosystem soils where tillage (Stinner & House, 1990), pesticide applications (Pearsons & Tooker, 2021) and the use of chemical fertilizers (Eisenhauer et al., 2012) adversely affect soil biological and physiochemical properties. Coupled with decreased plant diversity typical of modern industrial agroecosystems, these practices reduce soil biodiversity and associated ecosystem functioning (Bardgett & van der Putten, 2014; Tsiafouli et al., 2015), effectively perpetuating unsustainable agricultural practices that may negatively influence human health (Wall et al., 2015).

Earthworms are often used to evaluate agricultural practices and soil health (Lehmann et al., 2020), but here we focus on soil arthropods. Arthropods are a main component of the soil biota. Approximately 23% of all described organisms inhabit the soil and arthropods constitute 85% of those taxa (Decaëns et al., 2006). Dominant soil arthropod groups are Collembola and Acari. Other prominent taxa include Myriapoda and Insecta (Dindal, 1990). Soil arthropods contribute to soil health and plant productivity in agroecosystems through litter decomposition, nutrient cycling and pest/pathogen control (Culliney, 2013; Neher & Barbercheck, 2019). While microbial communities are the main drivers of biogeochemical cycles, soil arthropods are important in soil organic matter formation and shape microbial processes (Grandy et al., 2016). Indeed, practices that reduce soil mesofauna and macrofauna (primarily arthropods) can result in reduced soil ecosystem services with cascading effects above-ground (Bender & van der Heijden, 2015; Bradford et al., 2014; Wagg et al., 2014). These findings suggest that promoting soil biodiversity, and specifically the biodiversity of soil arthropods, may support more sustainable and resilient agroecosystems through improved delivery of soil ecosystem services.

Ecological engineering to increase biodiversity, including soil arthropods, in degraded agricultural soils is a proposed strategy to restore the associated soil processes, ecosystem service provisioning and improve the sustainability of agroecosystems (Bender et al., 2016). Despite the documented contributions of soil arthropods to soil processes, agronomic studies rarely consider their responses to management or use soil arthropods as a component of soil health assessments (Stewart et al., 2018). As a result, little is

known about how agricultural practices can preserve or enhance soil arthropod biodiversity. Agricultural diversification focuses on incorporating functional biodiversity into cropping systems across different spatial and/or temporal scales, with the objective of restoring biotic interactions that contribute to ecosystem services supporting crop yields (Kremen et al., 2012). It often promotes biodiversity and ecosystem services (Lefcheck et al., 2015) and has been advocated as a pathway to improve the sustainability of modern agriculture (Kremen et al., 2012). Agricultural diversification practices such as rotational diversification (Tiemann et al., 2015) and cover cropping (Kim et al., 2020) increase soil microbial diversity and activity. Among the few studies of agricultural diversification effects on soil arthropods, Kelly et al. (2021) demonstrated that cover crops and no-till management in irrigated crops promoted the abundance of soil arthropods. Kelly et al. (2020) also found that reducing the use of fallow (F) in dryland systems increased the abundance of these taxa. These findings argue for continued investigation to identify management practices that enhance these critical components of soil ecosystems.

Agricultural diversification is occurring on a global scale, with positive effects on crop yield and environmental sustainability (Beillouin et al., 2019). Nonetheless, in some systems, including dryland cereal-based agroecosystems across diverse regions such as the Canadian prairies, the Australian wheat belt, the Central Plains of the United States and the inland Pacific Northwest (iPNW) of the United States (Kelly et al., 2020; Maaz et al., 2018), adoption of diversified practices is lagging. 'Business-as-usual' (BAU) management practices in dryland cereal systems across the globe typically rely on restrictive rotations that frequently use F (Maaz et al., 2018), resulting in declining crop productivity and reduced soil health (Kirby et al., 2017), defined by the USDA Natural Resource Conservation Service as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans". Despite this lag, producers in several countries are adopting diversified agricultural practices in these systems (Kassam et al., 2018). For example, cereal producers in the iPNW, USA are diversifying their systems through increased incorporation of alternate winter cash crops and cover crops for soil improvement, haying or for livestock grazing (Kirby et al., 2017). How these management changes affect soil arthropod communities and soil processes is unknown. Investigating these effects will improve understanding of the impacts of agricultural diversification on below-ground biodiversity and soil health in

dryland cereal cropping systems in the iPNW, USA with implications for improving these systems worldwide.

An underutilized component of assessing soil health in response to agricultural diversification is using bioindicators (Lehmann et al., 2020). The Soil Biological Quality index (QBS-ar) (Menta et al., 2018; Parisi et al., 2005), a soil health index that uses soil arthropods as bioindicators, could be a useful method to assess the outcomes of diversified agricultural practices on soil health and incorporate arthropods into the soil health framework. The QBS-ar has rarely been employed to evaluate the outcomes of agricultural diversification practices (Menta et al., 2020; Sapkota et al., 2012) and has not been applied in studies of dryland cereal systems (Menta et al., 2018). Its utility as an indicator of more widely used soil health metrics such as the Haney Soil Health Score (HSHS) (Haney et al., 2018) has never been evaluated.

This study aimed to determine how soil arthropod communities respond to agricultural diversification in dryland cereal-based agroecosystems and identify rotations and crops that promote soil arthropod biodiversity and QBS-ar. We used a 3-year crop rotation experiment to investigate the effects of diversified crops on soil arthropod biodiversity, community composition and functional groups. Rotation treatments included a BAU wheat-based rotation, an incrementally diversified rotation that incorporated a novel food-grade Austrian winter pea (WP) crop (McGee et al., 2017), and an aspirational (ASP) rotation that incorporated multispecies cover crops for livestock grazing (i.e. forage crops [FORs]). Incremental approaches to rotational diversification imply minor modifications to current practices whereas ASP approaches may require major changes to management practices. Since the agronomic performance of crop diversification strategies and the resulting effects on soil communities may vary within and across agricultural regions (Beillouin et al., 2019; Kirby et al., 2017), we assessed responses to diversification at two climatically distinct sites in the iPNW, USA. We tested the hypotheses that WPs and FORs: (1) promote overall soil arthropod abundance and biodiversity, (2) increase abundance of individual taxa and (3) differentially affect functional groups relative to the crops they would replace in rotation, such as spring-planted legumes or F. We also investigated whether crop type was a factor in determining community composition of soil arthropods. Finally, we evaluated the QBS-ar as a measure of soil health against other soil health metrics. We tested the hypothesis that QBS-ar is highest in diversified compared to BAU rotations across a full 3-year crop rotation.

2 | MATERIALS AND METHODS

2.1 | General site information

This study was conducted in a wheat-based production region that spans southeastern Washington, western Idaho and northeastern Oregon, in the iPNW, USA (Figure S1). The iPNW is characterized by a Mediterranean-type climate with cold, wet winters and hot,

dry summers. An extreme climatic gradient exists with mean annual precipitation ranging from 25 cm in the western region to over 50 cm in the east (Papendick, 1996). This region has been categorized into four agroecological classes (AECs) based on soil type, precipitation and the predominant cropping rotations (Brown & Huggins, 2012). The four AECs are annual cropping (limited annual F), transition cropping (e.g. rotations with F, but not every year), crop-F and irrigated. The annual, transition and crop-F AECs respectively make up approximately 25%, 32% and 43%, of the non-irrigated region (Kirby et al., 2017). The primary soil type in our study region is Palouse silt loam (Pachic Ultic Haploxerolls) (Soil Survey Staff, 2023).

2.2 | Experimental design

This study was conducted at representative sites in the transition AEC (St. John, Washington) and annual cropping AEC (Genesee, Idaho) (Figure S1). Both sites had a history of no-till practices for 10 years or longer prior to the start of the experiment. Permission for fieldwork at both sites was obtained from landowners. Within each AEC we investigated three different rotations: BAU, 'incremental' (INC) and ASP. BAU rotations in the transition AEC include a F period that generally occurs once in 3 years, whereas BAU in the annual AEC typically employs a 3-year rotation of spring or winter cereals and a spring legume. We explored options for improving agricultural diversification in BAU systems through the incorporation of WP and FORs into rotations, practices that some progressive producers have begun to implement. In each AEC, two alternative systems were tested, one termed 'incremental' and one termed 'aspirational' depending upon how much they differed from the 'business-as-usual' rotation at each site (Table 1). INC rotations at both sites involved incorporating WP, while ASP rotations differed but employed a cover crop intended for use as forage for livestock.

TABLE 1 Diversified and 'business-as-usual' (BAU) rotations at both study sites.

Annual cropping AEC (Genesee, Idaho)	Rotation type
Chickpea (CP)–winter wheat (WW)–spring wheat (SW)	BAU
Winter pea (WP)–winter wheat (WW)–spring wheat (SW)	INC
Chickpea (CP)–winter wheat (WW)–forage crop (FOR)	ASP
Transition cropping AEC (St. John, Washington)	
Fallow (F)–winter wheat (WW)–spring wheat (SW)	BAU
Winter pea (WP)–winter wheat (WW)–spring wheat (SW)	INC
Forage crop (FOR)–winter wheat (WW)–spring wheat (SW)	ASP

Abbreviations: ASP, aspirational diversified rotation; INC, incremental diversified rotation.

At each site, replicated trials (9.7×23 m strip-plots) were established in 2017 and all rotations were maintained for 3 years (2018–2020) to accommodate a full rotation. At each site, all three crops in each rotation ($n=9$ strips) were grown in each of five blocks in a randomized complete block design for a total of 45 strip-plots per site (Figure S2). Plot management details are available in the Supporting Information.

2.3 | Soil arthropod sampling

Strip-plots at each site were sampled for soil arthropods once within each of three time periods each year (Table S1). The sampling did not require ethical approval. On each sample date, four soil cores were collected from each strip-plot using a 10 cm diameter golf-hole cutter to a depth of 12 cm. Sample locations within each plot were randomized. The four cores were homogenized in a mixing-bin in the field (e.g. Oliveira et al., 2021) and 2000 cm³ of this homogenized soil was collected into a plastic resealable zipper storage bag and placed in a cooler. Debris and crop residue on the soil surface were not removed before sampling. Within 4 h of collection, each sample was taken to the laboratory and placed in a Berlese-Tullgren funnel under a 60 W bulb for an extraction period of 72 h. Soil arthropods were extracted into 95% ethanol. Adult Hexapoda were identified to order or family using keys published in Triplehorn and Johnson (2004). Immature Coleoptera were identified to order or family using Stehr (1987). Immature dipterans, hemipteran nymphs, crustaceans, spiders and pseudoscorpions were identified to order (Triplehorn & Johnson, 2004). Myriapods were identified to class, except Polyxenidae (Class: Diplopoda) and Geophilomorpha (Class: Chilopoda), which were identified to family and order, respectively, due to their importance in calculating QBS-ar (Menta et al., 2018). Acari were identified to suborder (Order Trombidiformes: Prostigmata) and order (Oribatida and Mesostigmata) using the LUCID Key for soil microarthropods (Walter and Proctor, https://keys.lucidcentral.org/keys/v3/soil_microarthropods/soil_microarthropods.html).

2.4 | Soil biological quality

An assessment of soil health was made using the QBS-ar index. QBS-ar is based on the concept that soil arthropods morphologically well-adapted to soil are more abundant in high-quality soils. To calculate the QBS-ar, taxa classified at the order/class level from the soil arthropod community are assigned an Ecological-Morphological Index (EMI) score based on their degree of adaptation to living in the soil. The EMI scores range from 1 (minimal adaptation to soil, e.g. Dermaptera) to 20 (maximum adaptation to soil, e.g. Protura). Using the EMI key in Menta et al. (2018) and following the QBS-ar protocol, an EMI score was assigned to each taxon in every community sample. The QBS-ar score for a sample was calculated by summing the EMI values.

2.5 | Soil measurements

At the same time as soil arthropod sampling, we measured soil temperature (°C) (temp) (Dial Thermometer, VeeGee Scientific) and soil volumetric water content (%) (VWC) (HydroSense II Handheld Soil Moisture Sensor, Campbell Scientific) in each strip-plot in the field at a depth of 10 cm. After soil arthropod extraction, we collected soil from each sample to measure pH (1:1 soil:water) using a benchtop pH metre (Accumet Model10 pH metre, Fisher Scientific). Soil organic matter measured as loss-on-ignition (%) (SOM-LOI), Solvita microbial respiration (ppm CO₂-C), water extractable organic carbon (ppm-C) (WEOC), water extractable organic nitrogen (ppm-N) (WEON), number of earthworm individuals m⁻² and the HSHS (Haney et al., 2018) were measured or calculated in each strip-plot to assess the relationship between QBS-ar and other soil health metrics. Solvita microbial respiration, WEOC and WEON are the individual variables used to calculate the HSHS and should be highly correlated. Methodological details for these analyses and calculations are available in the supporting methods.

2.6 | Data analysis

We calculated abundance (number of individuals), taxa richness and Shannon's diversity (H') for the overall soil arthropod community, and for predator, detritivore and herbivore functional groups (see Supporting Methods for details). These metrics, along with soil abiotic variables (pH, temp and VWC), were analysed for effects of crop treatment using a linear mixed-effects model (LMM) with crop and sampling year as fixed effects, and replicate (blocking factor) and strip-plot number nested in sampling period (to account for autocorrelation by repeated sampling in the same strip-plots over time) as random effects. Our primary focus was on the crop effect and our final model included year only as an additive effect. We assessed significant differences ($\alpha=0.05$) in response variables among crop treatments using pairwise comparisons and adjusted p values using Sidak's method. Changes in the abundance of individual taxa were evaluated as described above. Response variables were $\log(x+1)$ transformed to meet the assumptions of the LMM when necessary. Normality and homoscedasticity for all models were verified graphically. We used Pearson correlations to assess the relationship between QBS-ar and the previously described soil health metrics. Since we only collected the soil health metrics other than QBS-ar in the early sampling period (spring) in 2019 and 2020 (Table S1), we only tested for correlation between those metrics and QBS-ar from that sampling period in 2019–2020.

For multivariate analyses, taxa abundance across the three sampling years was pooled for each crop in each rotation across the five replications ($n=45$ communities). We removed taxa with fewer than five individuals collected (22 taxa/site). Soil arthropod communities were visualized using nonmetric multidimensional scaling (NMDS) of Bray–Curtis distances using the VEGAN package in R (Oksanen et al., 2020) to assess the effects of crop treatment on

soil arthropod community composition. The dissimilarity of community structure in response to crop type was statistically analysed on Bray–Curtis distances using a permutation-based (999 permutations) multivariate analysis of variance (PERMANOVA) using the VEGAN package (Oksanen et al., 2020). To assess between-crop differences, we compared group centroids visually with NMDS and performed pairwise comparisons using the *pairwise.adonis* function (Martinez Arbizu, 2019) with a Benjamini–Hochberg *p* value correction. Taxa abundances were correlated with community structure using the VEGAN package (Oksanen et al., 2020). Only correlations of $p \leq 0.04$ (annual AEC) and $p \leq 0.007$ (transition AEC) were displayed to avoid cluttering the ordination. Soil abiotic variables were correlated with community structure using the same procedure ($p \leq 0.05$). We determined the associations between soil arthropod taxa and crop types using the point biserial correlation coefficient (r_{pb}) association index. The significance of the associations was assessed using 999 permutations in the INDICESPECIES package (DeCaceres & Legendre, 2009). Correlation indices are useful for understanding the ecological preferences of taxa among a set of different groups (DeCaceres & Legendre, 2009), such as the crop types in our study.

QBS-ar was analysed for crop and rotation treatment effects using a LMM and multiple comparison procedures as previously described. Planned contrasts were used to assess significant differences in QBS-ar between BAU and each of the diversified rotations using Hommel *p* value adjustments.

Due to differences in climate, farming history and plot management, response variables were analysed and are presented separately for each site. We conducted all statistical analyses using R ver. 1.4.1717 (R Core Team, 2020).

3 | RESULTS

A total of 82,509 individuals from 66 different taxa were collected and identified from 710 community samples over the duration of this study. Acari and Collembola were the most abundant groups collected, with 44,188 and 26,316 total individuals respectively. Thirteen Coleoptera families were collected, dominated by Staphylinidae, Melyridae, Elateridae and Curculionidae. Other abundant insect taxa included Thysanoptera and Psocoptera, with total counts of 2600 and 2989 individuals respectively. Additionally, 1593 myriapods were collected, dominated by Symphyla and Chilopoda. Additional class, order and family level data for taxa collected at each site are provided in Tables S2 and S3.

3.1 | Annual agroecological class (Genesee, ID)

Crop affected overall soil arthropod Shannon's diversity and richness, but not abundance. Shannon's diversity was greater in WP than in CP. Richness was greater in WP and FOR as compared with

CP (Table 2). Crop did not affect predator Shannon's diversity or richness, but predator abundance was greater in FOR compared to CP (Table 2). In contrast, detritivore abundance and Shannon's diversity did not differ among crops, but detritivore richness was greater in WP than in CP (Table 2). Crop affected herbivore abundance, Shannon's diversity and richness. Herbivore abundance was greater in WP, winter wheat (WW) and FOR than in CP. Shannon's diversity and taxa richness of soil arthropod herbivores was less in CP than in WP and FOR (Table 2). Soil VWC (%) was highest under FOR compared to WW and spring wheat (SW) (Table 2). Year was significant for all metrics in Table 2 at the annual AEC ($p < 0.001$).

Crop determined soil arthropod community composition (PERMANOVA, $F_{4,40} = 3.04$, $R^2 = 0.23$, $p = 0.001$) (Figure 1). WP and FOR communities differed from those sampled under spring-planted crops (CP and SW) (Table S4). Analysis of taxa ecological associations using r_{pb} detected several taxa that were significantly associated with WP and FOR, whereas only two taxa were associated with SW, one with WW and none with CP (Table 3).

QBS-ar was negatively correlated with SOM-LOI ($R^2 = -0.28$, $p = 0.006$) and microbial respiration ($R^2 = -0.27$, $p = 0.01$). QBS-ar was positively correlated with WEON ($R^2 = 0.3$, $p = 0.007$) and soil temp ($R^2 = 0.25$, $p = 0.02$) (Figure 2). QBS-ar was affected by crop and rotation. QBS-ar was greater in FOR and WP than in CP (Table 2). Both INC (mean: 59.20 ± 2.86 SEM) and ASP (mean: 59.98 ± 2.56 SEM) rotations had greater QBS-ar relative to the BAU rotation (mean: 52.07 ± 2.56 SEM) (Figure 3).

3.2 | Transition agroecological class (St. John, WA)

Crop affected overall soil arthropod abundance and richness, but not Shannon's diversity. Soil arthropod abundance was greater in WP than in F. Richness was greater in WP and FOR than in F, SW and WW (Table 2). Predator abundance was greater in all crops compared to that measured under F. Predator Shannon's diversity was greater in WP and FOR than in F. Predator richness was greater in WP and FOR as compared to F, SW and WW (Table 2). Crop did not affect soil arthropod detritivore abundance, Shannon's diversity or richness. Crop affected herbivore abundance, Shannon's diversity and richness. Herbivore abundance was greater in WP compared to that measured in the other crops. Herbivore Shannon's diversity and richness were greater in WP than in F, SW and WW (Table 2). Soil VWC (%) was highest under F compared to all other crop types. Soil pH was lower in F than in FOR (Table 2). Year was significant for all metrics in Table 2 at the transition AEC ($p < 0.001$).

Crop type determined soil arthropod community composition (PERMANOVA, $F_{4,40} = 2.61$, $R^2 = 0.21$, $p = 0.001$) (Figure 1). WP communities differed from all other crop types besides FOR (Table S4). Analysis of taxa ecological associations using r_{pb} detected several taxa that were significantly associated with WP and FOR, whereas only two taxa were associated with other BAU crops (Table 3).

QBS-ar was negatively correlated with SOM-LOI ($R^2 = -0.21$, $p = 0.05$) and microbial respiration ($R^2 = -0.33$, $p = 0.002$). QBS-ar

TABLE 2 Mean soil abiotic variables and soil arthropod abundance, H', and taxa richness 2000 cm⁻³ soil for crops across rotations at each AEC. Mean ± standard error. *p* values from the LMMs for crop type and year are presented below with values ≤0.05 for crop type in bold. Means within rows assigned different letters are significantly different.

Annual AEC (Genesee, ID)	Crop					<i>p</i>
	Chickpea	Winter pea	Spring wheat	Winter wheat	Forage crop	
Total						
Abundance	84.58 ± 9.53	129.73 ± 17.93	141.54 ± 30.61	114.01 ± 14.97	122.8 ± 21.21	0.12
H'	1.39 ± 0.05a	1.60 ± 0.07b	1.44 ± 0.04ab	1.54 ± 0.03ab	1.57 ± 0.08ab	0.005
Richness	7.80 ± 0.41a	10.6 ± 0.77c	8.57 ± 0.40ab	8.87 ± 0.39ab	10.03 ± 0.40bc	<0.001
QBS-ar	50.58 ± 2.88a	66.70 ± 5.35b	54.10 ± 3.21ab	57.41 ± 2.80ab	66.57 ± 5.88b	0.002
Soil pH	5.35 ± 0.04	5.36 ± 0.05	5.39 ± 0.04	5.47 ± 0.03	5.47 ± 0.07	0.06
Soil VWC (%)	15.17 ± 1.34bc	14.44 ± 1.95bc	12.65 ± 1.41ab	11.19 ± 0.96a	17.09 ± 1.98c	<0.001
Soil temp. (°C)	17.17 ± 0.45	16.72 ± 0.60	16.64 ± 0.43	16.50 ± 0.34	17.19 ± 0.64	0.39
Predators						
Abundance	16.57 ± 1.95a	25.7 ± 4.12ab	23.44 ± 3.75ab	25.88 ± 3.29ab	38.20 ± 8.13b	0.003
H'	0.64 ± 0.04	0.68 ± 0.06	0.65 ± 0.04	0.65 ± 0.03	0.68 ± 0.06	0.97
Richness	2.74 ± 0.16	3.33 ± 0.28	2.75 ± 0.15	2.92 ± 0.14	3.31 ± 0.35	0.12
Detritivores						
Abundance	65.14 ± 7.82	89.85 ± 13.48	114.18 ± 26.97	76.57 ± 10.65	77.09 ± 14.01	0.24
H'	0.82 ± 0.05	1.00 ± 0.06	0.86 ± 0.04	0.91 ± 0.04	0.93 ± 0.08	0.16
Richness	3.87 ± 0.21a	5.08 ± 0.38b	4.32 ± 0.21ab	4.29 ± 0.19ab	4.49 ± 0.39ab	0.01
Herbivores						
Abundance	2.23 ± 0.47a	12.63 ± 3.22c	3.17 ± 0.56ab	10.24 ± 4.58bc	6.60 ± 1.46bc	<0.001
H'	0.19 ± 0.04a	0.38 ± 0.07b	0.27 ± 0.04ab	0.25 ± 0.03ab	0.38 ± 0.08b	0.006
Richness	0.96 ± 0.12a	1.73 ± 0.24b	1.21 ± 0.12ab	1.30 ± 0.12ab	1.66 ± 0.13b	<0.001
Transition AEC (St. John, WA)						
	Crop					<i>p</i>
	Fallow	Winter pea	Winter wheat	Spring wheat	Forage crop	
Total						
Abundance	67.23 ± 8.99a	177.85 ± 31.52b	117.77 ± 10.81ab	111.10 ± 10.21ab	137.94 ± 25.73ab	0.001
H'	1.39 ± 0.09	1.56 ± 0.07	1.46 ± 0.04	1.45 ± 0.04	1.52 ± 0.07	0.45
Richness	8.12 ± 0.52a	11.33 ± 0.79b	9.22 ± 0.35a	9.07 ± 0.33a	10.94 ± .90b	<0.001
QBS-ar	50.95 ± 2.97a	66.18 ± 4.25b	55.50 ± 2.11a	52.98 ± 5.15a	60.91 ± 5.15ab	0.002
Soil pH	6.02 ± 0.10a	6.25 ± 0.16ab	6.27 ± 0.06ab	6.14 ± 0.06ab	6.17 ± 0.09b	0.009
Soil VWC (%)	17.17 ± 1.46a	10.71 ± 1.53b	9.15 ± 0.79b	10.59 ± 0.99b	11.77 ± 1.71b	<0.001
Soil temp. (°C)	16.88 ± 0.59	17.11 ± 0.55	17.23 ± 0.34	17.37 ± 0.34	17.59 ± 0.62	0.35
Predators						
Abundance	11.6 ± 1.78a	31.48 ± 5.63b	30.13 ± 3.06b	26.82 ± 2.66b	31.66 ± 6.91b	<0.001
H'	0.62 ± 0.06a	0.89 ± 0.07b	0.77 ± 0.03ab	0.72 ± 0.04ab	0.85 ± 0.07b	0.003
Richness	2.5 ± 0.19a	4.03 ± 0.33c	3.36 ± 0.14b	3.33 ± 0.14b	4.03 ± 0.41c	<0.001
Detritivores						
Abundance	51.03 ± 7.64	122.43 ± 22.08	83.0 ± 8.2	79.4 ± 8.21	97.97 ± 19.19	0.14
H'	0.85 ± 0.07	0.83 ± 0.07	0.81 ± 0.03	0.80 ± 0.04	0.84 ± 0.06	0.94
Richness	4.00 ± 0.29	4.38 ± 0.33	4.18 ± 0.17	4.04 ± 0.16	4.66 ± 0.37	0.41
Herbivores						
Abundance	4.30 ± 1.00a	21.5 ± 7.58b	4.18 ± 0.54a	4.52 ± 0.60a	7.6 ± 2.14a	<0.001
H'	0.31 ± 0.06a	0.60 ± 0.07b	0.34 ± 0.04a	0.32 ± 0.04a	0.50 ± 0.08ab	<0.001
Richness	1.5 ± 0.20a	2.65 ± 0.26b	1.53 ± 0.12a	1.53 ± 0.12a	2.00 ± 0.26ab	<0.001

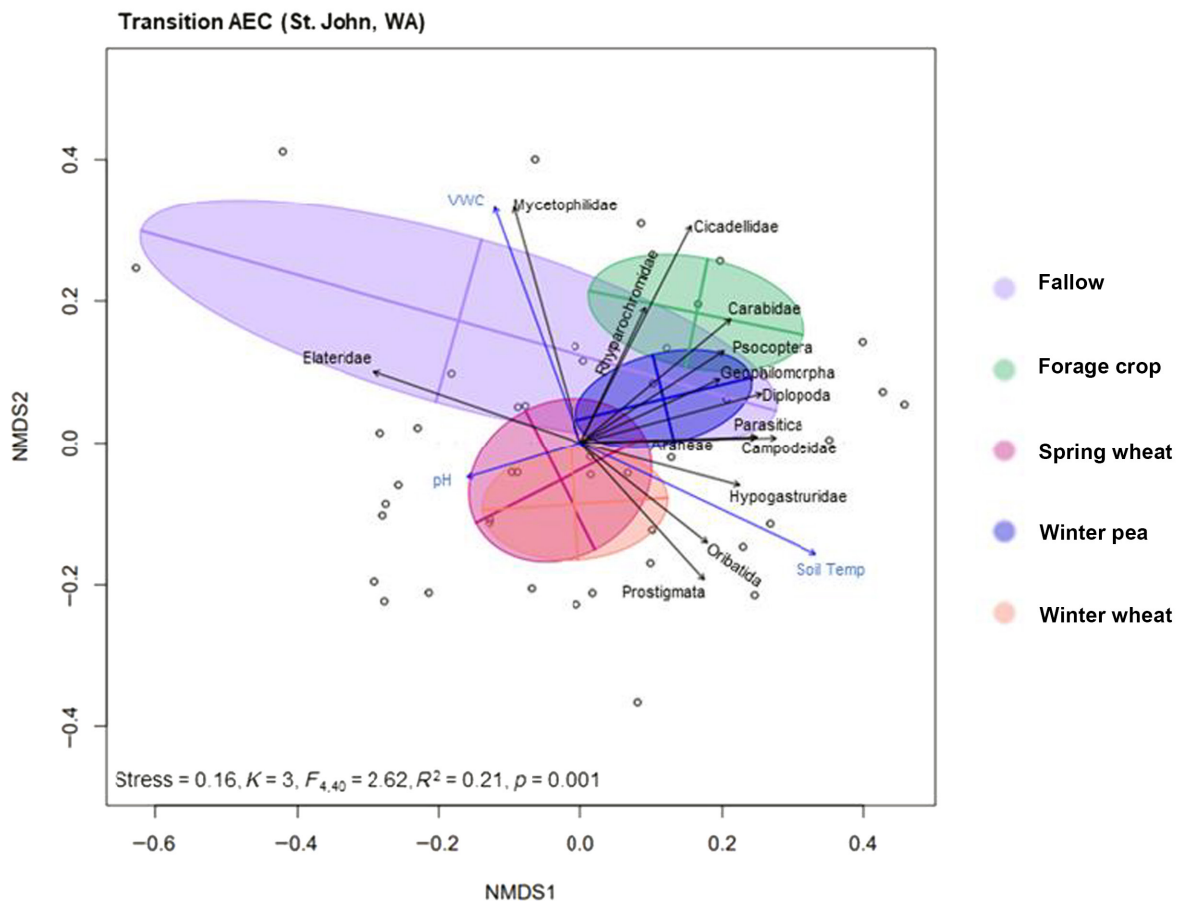
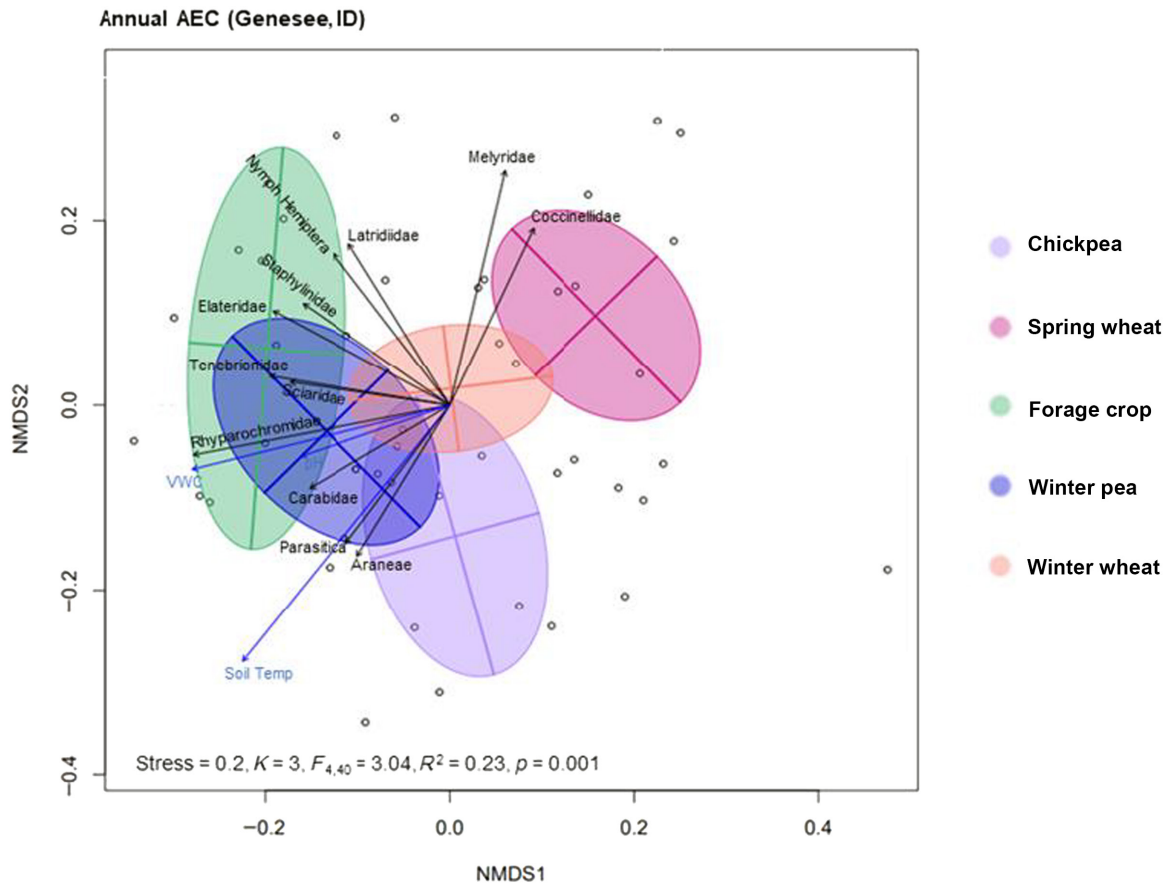


FIGURE 1 Nonmetric multidimensional scaling (NMDS) ordination plot of Bray–Curtis distances of soil arthropod communities by crop type at each agroecological class (AEC). Soil arthropod taxa (black) and soil abiotic (blue) variables correlated with the ordination axes are represented as vectors. The length of each arrow is proportional to the strength of the correlation. Ellipses represent standard error around the ellipse centroid.

TABLE 3 Associations of taxa with crop types using the point biserial correlation coefficient (r_{pb}) association index. Only taxa with a r_{pb} association value significant at $p \leq 0.1$ are included in the table ($p \leq 0.05$, bolded) ($p \leq 0.1$, italicized).

Annual AEC (Genesee, ID)					Transition AEC (St. John, WA)					
Crop	Taxa	Functional group	r_{pb}	p value	Crop	Taxa	Functional group	r_{pb}	p value	
SW	Oribatida	Detritivore	0.15	0.05	SW	Melyridae	Predator	0.18	0.03	
	Coccinellidae	Predator	0.19	0.02		F	Protura	Detritivore	0.17	0.04
FOR	Hemiptera Nymph	Herbivore	0.20	0.009	FOR	Cicadellidae	Herbivore	0.21	0.006	
	Formicidae	Predator	0.18	0.01		Chilopoda	Predator	0.20	0.01	
	Tenebrionidae	Detritivore	0.18	0.03		Onychiuridae	Detritivore	0.18	0.03	
	Geophilomorpha	Predator	0.18	0.02		Dermaptera	Predator	0.21	0.007	
	Dermestidae	Detritivore	0.17	0.02		Chrysomelidae	Herbivore	0.18	0.02	
	Rhyparochromidae	Herbivore	0.17	0.03		Aphodiinae	Detritivore	0.16	0.04	
	Japygidae	Predator	0.16	0.04		Isopoda	Detritivore	0.12	0.08	
	Prostigmata	Predator	0.27	0.02						
	Mesostigmata	Predator	0.14	0.06						
WP	Curculionidae	Herbivore	0.42	0.001	WP	Thysanoptera	Herbivore	0.25	0.002	
	Psocoptera	Detritivore	0.23	0.005		Entomobryidae	Detritivore	0.2	0.009	
	Immature Diptera	Detritivore	0.15	0.08		Curculionidae	Herbivore	0.29	0.001	
	Staphylinidae	Predator	0.16	0.04		Staphylinidae	Predator	0.17	0.03	
	Parasitica	Predator	0.14	0.06		Symphyla	Herbivore	0.15	0.07	
	Sminthuridae	Herbivore	0.15	0.05		Psocoptera	Detritivore	0.17	0.04	
	Cecidiomyiidae	Detritivore	0.16	0.04		Latridiidae	Detritivore	0.21	0.01	
	Isopoda	Detritivore	0.19	0.02		Parasitica	Predator	0.27	0.07	
WW	Symphyla	Herbivore	0.14	0.09	WW	Coccinellidae	Predators	0.15	0.07	

Abbreviations: F, fallow; FOR, forage crop; SW, spring wheat; WP, winter pea; WW, winter wheat.

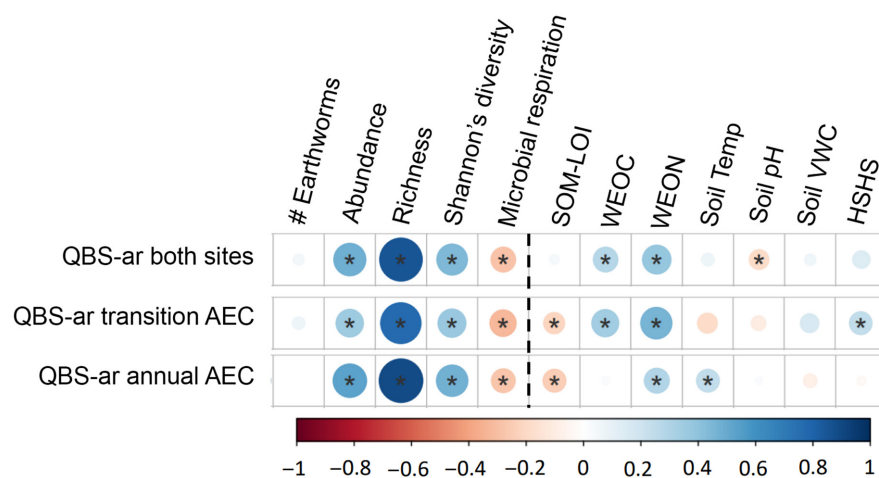
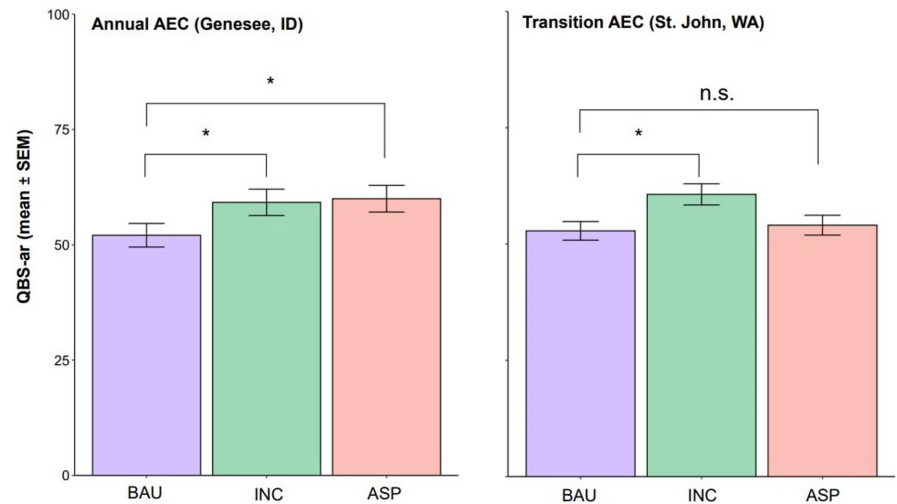


FIGURE 2 Pearson correlation analyses between Soil Biological Quality index (QBS-ar), soil biodiversity metrics, soil health indicators and soil abiotic variables. Asterisks represent a significant correlation at $p \leq 0.05$. Heatmap denotes the strength of positive/negative correlation coefficients. Dashed line separates biotic and abiotic soil health metrics.

FIGURE 3 Soil Biological Quality index (QBS-ar) values comparing 'business-as-usual' and diversified rotations at the annual and transition agroecological classes (AECs). Asterisks indicate significant differences ($p \leq 0.05$) in QBS-ar between rotations. ASP, aspirational rotation; BAU, 'Business-as-usual' rotation; INC, incremental rotation.



was positively correlated with WEOC ($R^2=0.34$, $p=0.001$), WEON ($R^2=0.46$, $p<0.001$) and the HSHS ($R^2=0.25$, $p=0.01$) (Figure 2). QBS-ar was affected by crop and rotation. QBS-ar was greater in WP than in F, SW and WW. Only the INC rotation (mean: 60.66 ± 2.28 SEM) had greater QBS-ar than the BAU rotation (mean: 52.82 ± 2.01 SEM) (Figure 3).

4 | DISCUSSION

A thorough understanding of the effects of management practices on soil biodiversity is required to support the development of sustainable agriculture. Key gaps include the contributions and roles of soil arthropods in agricultural soils (Culliney, 2013; Neher & Barbercheck, 2019), management strategies to promote soil arthropod communities in such soils (Bender et al., 2016; Menta et al., 2020), and information pertinent to dryland cereal-based agroecosystems (Kelly et al., 2020), which are critical for food production worldwide. Here we document changes in soil arthropod communities in response to agricultural diversification achieved by introducing novel rotational crops into BAU wheat rotations in the iPNW, USA. In 3-year, replicated studies at two sites representative of precipitation regimes in this region, we show that introducing a cover crop for livestock grazing FOR or a WP crop into BAU rotations alters the community structure, abundance and diversity of soil arthropods and influences an arthropod-based soil health index (QBS-ar) (Menta et al., 2018) in dryland agroecosystems. Furthermore, we determined how the QBS-ar is related to standard measures of soil health (Liptzin et al., 2022). Thus, by adopting specific rotational diversification practices, agricultural practitioners in the iPNW can alter the biodiversity and composition of soil arthropod communities that in turn regulate soil processes crucial for agroecosystem productivity. Our findings suggest that dryland cereal systems in other regions can be managed to influence soil arthropod communities as part of efforts to improve their productivity and sustainability.

Specifically in this study, introducing WP and FOR increased soil arthropod taxa richness relative to the crops they replaced in BAU rotations: CP, SW and F. This result was consistent across the lower-precipitation and higher-precipitation AECs, indicating potential for WP and FOR to augment soil biodiversity in different climatic conditions in the iPNW. Improving soil arthropod biodiversity contributes to making soil productivity less reliant on external farm inputs (Bender et al., 2016; Geisen et al., 2019) and can provide resiliency of soil processes to disturbances arising from management or climate change (Nielsen et al., 2015). Relative to the BAU crops, WP and FOR also increased the abundance or diversity within soil arthropod functional groups, potentially influencing the ecosystem services they provide (Tsiafouli et al., 2015). For example, greenhouse microcosm experiments have shown that arthropod decomposers increase nitrogen mineralization in the soil resulting in increased wheat biomass (Ke & Scheu, 2008). Ongoing experiments in the iPNW have found similar effects of field-derived soil arthropod communities on soil nutrients and wheat growth and performance (Elmquist et al., unpublished). Agricultural diversification strategies that increase the abundance and biodiversity of soil arthropods in agroecosystem soils may have an outsized impact on improving the delivery of soil ecosystem services because the positive relationship between soil arthropod biodiversity and ecosystem functioning is most pronounced in ecosystems with fundamentally low soil biodiversity, such as agroecosystems (Nielsen et al., 2011).

In addition to differences in biodiversity and abundance, changes in soil arthropod community composition also influence ecosystem functioning (Nielsen et al., 2011; Wagg et al., 2014). In our study, crop type impacted soil arthropod community composition at each AEC. We identified taxa that were 'ecologically associated' (DeCaceres & Legendre, 2009) with specific crops and were important drivers of the differences in community composition between crops in each AEC. Most taxa associated with the novel crops employed to diversify BAU rotations in our study were predators and detritivores (23 taxa), with implications for soil ecosystem functioning (Nielsen et al., 2011; Wagg et al., 2014). Thus, crops used in

diversified rotations potentially influence ecosystem functioning at least in part through their effects on the structure of soil arthropod communities.

The QBS-ar index links arthropod biodiversity with functionality and adaptability in the soil ecosystem (Menta et al., 2018). The relationships between QBS-ar and other soil health measures investigated were complex. QBS-ar was negatively correlated with microbial respiration, a measure of microbial activity, across both sites. This could reflect the fact that several soil arthropod groups, especially those with high EMI scores, are microbivores that can alter microbial activity and biomass (Grandy et al., 2016). Soils with a high QBS-ar could limit microbial respiration of CO₂ and increase the potential for long-term carbon storage in soils.

Mechanisms governing the relationships between QBS-ar and some soil health indicators were site dependent (e.g. WEOC, soil temp, HSHS). We observed a positive correlation between QBS-ar and the HSHS but only at the low-precipitation AEC. This finding provides empirical support for using soil arthropods as biological indicators of soil health, but also illustrates the important influence of climatic conditions on relationships between soil health indicators within the time frame of our measurements. Refining our understanding of how QBS-ar is related to the HSHS, a soil health metric frequently used by producers, should be a goal of future research.

QBS-ar exhibits a rapid response to changing management practices, whereas other metrics like soil organic matter (SOM-LOI) can take multiple years to respond (Sapkota et al., 2012). The difference in response time between these two variables could explain their inverse relationship. Mantoni et al. (2021) also reported a negative relationship between soil carbon and QBS-ar. QBS-ar may be useful for detecting changes in soil quality early in transitional periods, such as implementation of diversified agricultural practices. Indeed, QBS-ar was better correlated with measures of labile organic matter quality (e.g. WEOC and WEON) (Haney et al., 2012) than the total soil organic matter pool (SOM-LOI) that includes a mix of recalcitrant and labile components. QBS-ar may indicate changes in soil health over short time periods, like we observed in this study, whereas changes to the total soil organic matter pool is expected to occur over longer time periods.

QBS-ar as a soil health measurement that is sensitive in the short-term aligns with soil arthropods' function as decomposers. Soil arthropods fuel initial stages of decomposition by comminuting organic matter which increases microbial access and degradation into plant available nutrients. The positive correlation between QBS-ar and WEOC/WEON, which are important indicators in relation to crop health and nutrient cycling, suggests soil arthropods are fulfilling their role as nutrient cyclers. In agroecosystems, the goal of decomposition should not be to maximize long-term soil organic matter, but to achieve a sustainable rate of decomposition to fuel nutrient uptake and crop yield. A soil health indicator that responds quickly to changes in management practices, like QBS-ar, may be useful for producers in that it can potentially indicate how their practices are altering soil nutrient cycling. Furthermore, QBS-ar

could be measuring aspects of soil health that are not detected by standard metrics. Thus, QBS-ar may provide a complement to other soil health metrics enabling a more nuanced and comprehensive understanding of soil health that is useful to guide management.

In addition to effects on soil arthropods associated with specific crops, effects were also detected across 3-year BAU and diversified rotations. In both AECs, incorporating WP into rotations improved soil health across these entire rotations, not just in the WP phases, as measured by QBS-ar. Thus, the increased adoption of WP in iPNW cereal systems (McGee et al., 2017; Schillinger, 2020) not only has agronomic advantages for the entire production system but increases the abundance and diversity of soil arthropod communities, with implications for soil health. A rotation incorporating FOR also improved QBS-ar over the BAU rotation but only in the annual AEC, suggesting that the effect of FOR on soil arthropods depends upon annual precipitation (Kelly et al., 2021). Cover crops for livestock grazing can be difficult to implement in drier regions (Kelly et al., 2020) and that may be related to the lack of response by arthropods to the use of FOR in the transition AEC.

Climate projections for the iPNW coupled with historic climate and cropping records suggest that the extent of the annual AEC will diminish relative to the transition AEC in the region if alternative agricultural diversification options are not available (Kaur et al., 2017). Our results suggest that including WP in transition AEC cropping systems may benefit soil arthropods in addition to other agronomic advantages it may provide. Additional study of other agricultural diversification options and their effects on soil arthropods and soil health are merited to anticipate this challenge.

5 | CONCLUSIONS

Our results show that specific crops used in agricultural diversification practices focused on improving soil health and agroecosystem sustainability promote distinct arthropod communities that differ in biodiversity and their functional capacities. Since loss of soil biodiversity is linked to declining soil functions that are the foundation of agricultural production (Bender et al., 2016), we propose that rotational diversification in dryland agroecosystems be considered as a strategy to promote soil arthropod biodiversity. QBS-ar was positively correlated with some soil health metrics and negatively correlated with others. Improving our understanding of these complex relationships should be a goal of future research. However, based on our experience with this index, we agree with Menta et al. (2018) and advocate for the use of soil arthropods to evaluate management decisions and improvements in soil health related to diversified agricultural practices using the QBS-ar as a stand-alone index or to complement other soil health metrics. Soil arthropods should be included in the soil health framework, acknowledged in policy developments (e.g. European Union Soil Health Law), and considered in agricultural management decisions as agroecosystems across the globe continue to diversify.

AUTHOR CONTRIBUTIONS

Dane C. Elmquist, Jodi L. Johnson-Maynard and Sanford D. Eigenbrode conceived the ideas and designed the methodology; Dane C. Elmquist and Kendall B. Kahl collected the data; Dane C. Elmquist and Sanford D. Eigenbrode analysed the data; Dane C. Elmquist led the writing of the manuscript. All authors contributed critically to drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

We thank Kurt Schroeder and Saugat Baskota for plot management and Carter Westerhold, Taylor Murphy, Kaya Labanon, and Jessica Kohntopp for assistance with data collection. We thank all producer-cooperators who offered their farmland and advice for this experiment. USDA-NIFA CAP #2017-68002-26819 supported this work. USDA is an equal opportunity employer and service provider. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the USDA.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available from the University of Idaho at <https://doi.org/10.7923/rcbw-kx90> (Elmquist et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. (a) The cereal growing region of the inland Pacific Northwest categorized by agroecological class (AEC) and location of experimental sites; (b) Google Earth aerial view of strip trial at St. John, WA.

Figure S2. Strip-plot crop phases for each year in the (a) annual agroecological class (AEC) (Genesee, ID) and (b) transition AEC (St. John, WA). Plots are colored by rotation type.

Table S1. Sampling dates and corresponding sampling period designation for each site.

Table S2. Taxa abundance 2000 cm⁻³ soil by crop type at the annual agroecological class (Genesee, ID) site.

Table S3. Taxa abundance 2000 cm⁻³ soil by crop type at the transition agroecological class (St. John, WA) site.

Table S4. Results of pairwise comparisons of soil arthropod communities by crop.

Table S5. Total fertilizer nitrogen (from all fertilizer sources) applied to strip-plots (kg/ha).

Table S6. Harvest dates for strip plots in Genesee and St. John.

Table S7. Functional group classifications.

How to cite this article: Elmquist, D. C., Kahl, K. B., Johnson-Maynard, J. L., & Eigenbrode, S. D. (2023). Linking agricultural diversification practices, soil arthropod communities and soil health. *Journal of Applied Ecology*, 00, 1–12. <https://doi.org/10.1111/1365-2664.14453>