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Soil Weed Seed Bank Response to Crop Management Practices on Smallholder Farms Across an Agroclimatic Gradient in Zimbabwe

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ABSTRACT

Weed seed banks function as subterranean reserves that continuously replenish weed populations, driving future infestations on farms. This study examined how various crop management practices on smallholder farms influence the size and composition of weed seed banks, analyzing farmer-managed fields across an agroclimatic gradient in Zimbabwe. Tillage intensity, soil fertility management, crop rotation, intercropping, mulching, timing of first weeding, and weeding frequency were monitored across 75 smallholder principal maize fields, spanning three agroecological regions (AERs) (2, 3, and 4) during the 2022/23 and 2023/24 cropping seasons. At the end of the 2023/24 season, soil samples were collected at depths of 0–10, 10–20, and 20–30 cm using a 10 cm diameter bucket auger, pooling nine core samples per field into a composite sample. To determine weed seed bank size and composition, a glasshouse soil incubation experiment was established using the seedling emergence method. The trial followed a 3×3 factorial arrangement structured within a randomized complete block design (RCBD), evaluating AER and soil depth as the primary factors, while individual farmer fields nested within AERs served as replicates. Across the studied farms, diverse seed banks were recorded, comprising 25 distinct weed species belonging to 14 families, with community diversity and density varying significantly by both soil depth and AER. Seven species (*Richardia scabra* L., *Cyperus esculentus* L., *Galinsoga parviflora* Cav, *Leucas martinicensis* L., *Digitaria ternata* (A. Rich) Roem, *Eleusine indica* (L.) Gaertn, and *Acanthospermum hispidum* D.C.) dominated the community, contributing 90.4% of the relative density. The largest seed bank of 316 weed seedlings was recorded in the wetter AER 2 compared to AER 3 (141) and AER 4 (194). Agronomic practices significantly drove seed bank dynamics. Conservation tillage using planting basins reduced seed density by 31% compared to conventional tillage. Cattle manure application showed divergent regional effects, suppressing emergence in AER 2 and 4, but increasing it in AER 3. Finally, early weeding at 2 weeks post-crop emergence and a high weeding frequency ≥ 3 times significantly minimized seed bank density and diversity. Ultimately, weed seed bank communities proved highly responsive to management choices. Integrating planting basins with early, frequent weeding, and region-specific fertilizer management offers a robust strategy for suppressing long-term weed pressure on smallholder farms.

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1 | Introduction

Weeds are a menace in all crop production systems, where they cause a substantial reduction in agricultural production [1]. Weeds thrive in disturbed agricultural ecosystems due to key adaptive traits, including high fecundity, efficient seed dispersal, dormancy, and environmental plasticity, that enhance their persistence in these ecosystems [2]. Weeds form an important part of agroecosystems as they improve biodiversity [3]. However, weeds reduce crop yields if they are not well managed by interfering with crop growth and development [4]. When weed management is ineffective, weeds persist and deposit seeds into the soil, leading to the accumulation of weed seed banks, which are the largest reservoir of weed seeds and propagules [5]. The weed seed bank is primarily composed of seed deposited as seed rain from flowering plants [6] and vegetative perennating structures produced in the soil by perennial weeds. A smaller proportion of weed propagules enters the soil from external sources, including manure, contaminated crop seeds, wind, and the movement of animals or farm equipment [7]. While cattle manure application improves soil fertility, when not fully cured, it has the potential to disperse weed seeds into agricultural fields [8]. Examples of animal-dispersed weeds include *Acanthospermum hispidum* D.C. and *Bidens pilosa* L., which have specialized achenes that allow them to attach to animal fur and be transported over long distances [9]. Common sow thistle (*Sonchus olaraceus* L.) seeds are capable of being readily dispersed between fields because of their unique pappus morphology, which acts like a parachute capable of drifting in the wind [10].

Soil weed seed banks are a critical component of weed population dynamics because seeds deposited over successive seasons can remain in a dormant but viable state for long periods, germinating only when conditions become favorable for breaking dormancy, allowing seedling emergence and growth [11]. These seed banks act as soil-surface reserves of dormant seeds that continuously replenish weed populations [12]. Weed seed longevity determines whether seed banks are classified as either transient or persistent. In transient seed banks, seeds remain viable in the soil for 1–2 years, while in persistent seed banks, seeds survive in the soil for more than a decade [7].

Under well-managed crop production systems, soil weed seed banks can be reduced by up to 95% within 4–5 years if seed deposition is prevented [13]. Weeds adapt to cropping practices, and seed bank composition is shaped by management strategies [4, 14, 15], including continuous cultivation, crop rotation, tillage, planting density, fertilization, weed regimes, and residue retention [16–20]. Rotating crops alters the ecosystem and disrupts the ecological niches of specialized weeds, interrupting their life cycles before seeds can replenish [21]. For example, continuous wheat (*Triticum aestivum* L.) cultivation yielded higher seed bank densities than long-term rotations with chickpeas (*Cicer arietinum* L.) or sugar beet (*Beta vulgaris* L.) [21]. Conversely, short-term maize (*Zea mays* L.) rotations with allelopathic cover crops—such as velvet bean (*Mucuna pruriens* L.), pigeon pea (*Cajanus cajan* [L.] Millsp.), and jack bean (*Canavalia ensiformis* L.)—did not affect seed bank density or diversity [22]. This suggests that while long-term diverse crop sequences substantially suppress seed accumulation, short-term rotations, even those involving allelopathic cover crops, may be insufficient on their own to alter the community structure [15, 21].

Tillage also strongly influences seed bank dynamics, with reduced or no-tillage systems frequently associated with high weed density and diversity [23–25]. Conventional tillage brings buried dormant weed seeds to the soil surface, where light, temperature fluctuations, and moisture cycles trigger germination and seedling emergence. Conversely, tillage buries surface seeds to depths where darkness induces secondary dormancy [7]. Under conventional tillage, positively photoblastic broad-leaved weeds and small-seeded grasses dominate the surface, resulting in a uniform seed distribution throughout the 0–25 cm plow zone [26]. In contrast, no-till systems retain 80% of weed seeds within the top 10 cm of soil [27].

Soil fertilization alters weed seed bank dynamics, though nutrient interactions vary. For instance, in a study [28], nitrogen (N) fertilizer application reduced seed bank size, and more so when co-applied with potassium—whereas phosphorus application increased seed bank size. As an organic amendment, cattle manure can directly introduce weed seeds and expand the seed bank because robust seed coats allow certain species to survive animal digestion [8, 29]. Conversely, consistent mulching depletes seed banks by blocking light, moderating soil temperature and moisture fluctuations, and enhancing seed predation, all of which suppress weed germination and deplete the weed seed bank over time [30, 31]. This suppression alters community composition in a species-selective manner; small photoblastic seeds fail to germinate under mulch, preventing replenishment [24]. In contrast, large-seeded species or those containing active phytochrome (Pfr) may initiate germination in darkness without light triggers [32]. However, these seedlings often become etiolated and die from energy exhaustion before penetrating the mulch layer [33].

Understanding weed seed banks forms an important component in integrated weed management (IWM) because forthcoming weed problems can be anticipated as the existence of a weed seed bank always leads to weed infestations [15]. Effective management must adopt a dual strategy: controlling above-ground weed growth to prevent seed production and investing in seed bank depletion measures to halt weed continuity [7]. In Zimbabwe, previous studies have evaluated how isolated practices—such as mulching, cover cropping, tillage, and fertilization—influence germinable seed banks under controlled conditions [22, 24, 29, 34]. However, how these co-occurring management strategies collectively impact smallholder weed seed banks remains unknown. Furthermore, agroecological variation may fundamentally moderate these dynamics: favorable conditions may stimulate germination and subsequent depletion of the seed bank, whereas harsher or variable environments can promote dormancy and persistence, contributing to seed bank replenishment. To address these gaps, this study evaluated weed seed bank dynamics across an agroclimatic gradient under farmer-managed systems. We hypothesized that crop management practices, specifically tillage intensity, fertilization regimes, mulching, and weeding frequency—regulate the size and composition of soil weed seed banks, and that these effects are strongly moderated by agroecological factors.

2 | Materials and Methods

2.1 | Study Location and Site Characteristics

Field monitoring was conducted in Murehwa and Mutoko districts in north-eastern Zimbabwe, spanning three distinct agroecological regions (AERs): AER 2, AER 3, and AER 4 (Figure 1). These study sites have a well-defined altitudinal and climate gradient and have similar edaphic characteristics. AER 2 is situated at a highveld altitude of 1200–1500 m above sea level, whereas AERs 3 and 4 occupy lower altitudes below 1200 and 900 m, respectively. This altitudinal decline corresponds directly with an increase in ambient heat and a reduction in moisture. Mean annual temperatures increase from cooler conditions in AER 2 (~18–20°C) to warmer conditions in AER 3 (~22–24°C) and AER 4 (~24–28°C). Concurrently, mean annual rainfall decreases along the gradient, ranging from 700–1050 mm in AER 2, to 500–800 mm in AER 3, and 450–650 mm in AER 4 [34]. Across all AERs, precipitation follows a unimodal pattern during a single cropping season that commences in November and concludes in April.

The edaphic profile across the three regions is predominantly characterized by granite-derived sandy loam Lixisols, interspersed with minor pockets of red clay soils classified as Chromic Luvisols [33]. Soil texture characterization of the participating smallholder farms confirmed a dominance of coarse-grained sandy soils, followed by medium-grained sandy soils (Table S1). Crop production patterns across these regions are, in part, driven by suitability to the climate. While AER 2 is dominated by intensive maize production, AER 3 transitions to a mixed cropping system supporting both maize and traditional grains. In contrast, other than maize, smallholder production in the more drought-prone AER 4 increasingly focuses on climate-resilient traditional grains, such as sorghum (*Sorghum bicolor* (L.) Moench) and millets. Other crops cultivated across all the three regions include grain legumes such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L.) Walp).

2.2 | Field Monitoring of Agricultural Practices

To document agronomic management by smallholder farmers, maize production practices were closely monitored across two consecutive production cycles (2022/23 and 2023/24 cropping seasons). A multistage sampling framework was deployed prior to the onset of the first season—2022/23. First, three villages within a designated ward were purposively selected to represent each AER: Ward 28 in Murehwa District (AER 2) and Wards 10 and 8 in the neighboring Mutoko District (AER 3 and 4, respectively). Second, using localized household registers provided by local agricultural extension officers, 25 farms were randomly selected per AER ($n = 75$ farms in total) utilizing the sample function in R (version 4.4.3).

At the start of the monitoring segment of the study, each of the 75 participating farmers was asked to identify their primary maize field, which must also have been cropped with maize during the 2021/22 cropping season. For these fields, a baseline context was established by documenting management history, focusing specifically on historical cropping sequences, nutrient management, and weed control. Thereafter, these fields were tracked during the 2022/23 and 2023/24 cropping seasons. Field monitoring was done at four distinct maize growth stages per season: emergence, vegetative, flowering, and physiological maturity. Data collection at each growth stage combined semi-structured household interviews with direct, in-field physical observations for verification of practices up to crop harvest. The primary agricultural practices recorded included tillage type, crop rotation, residue mulching,

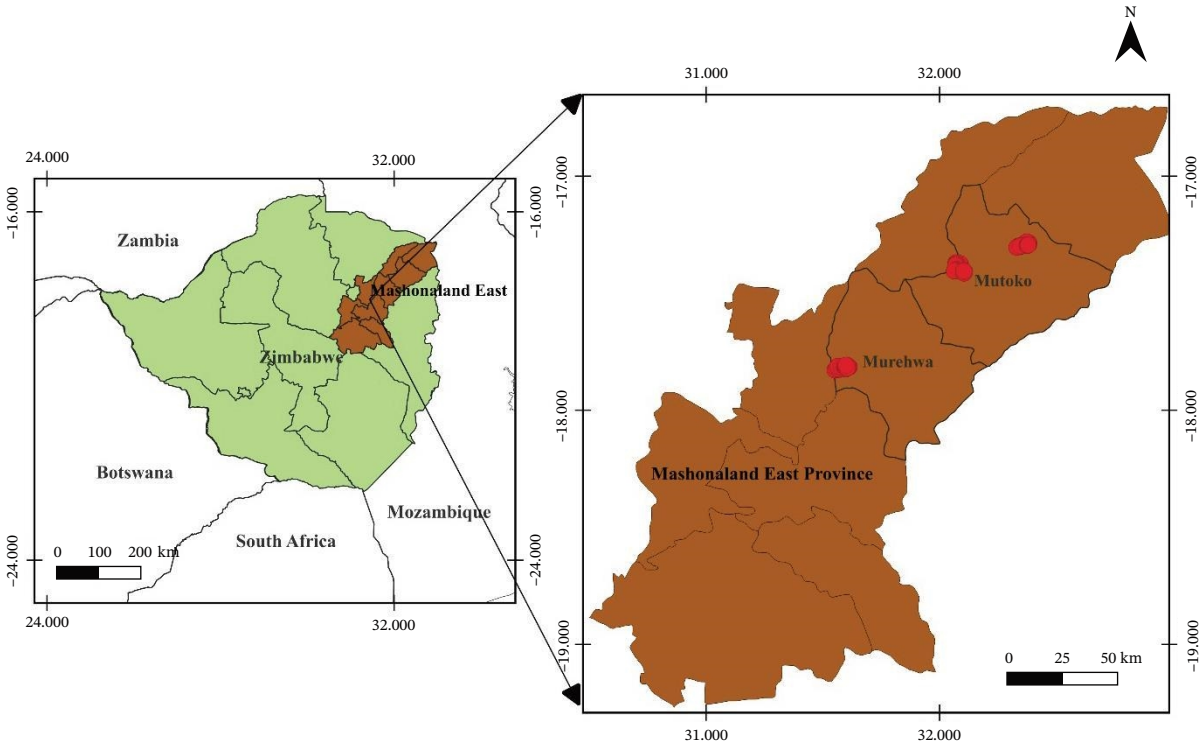

FIGURE 1 | Study map showing study locations in Murehwa and Mutoko districts in north-eastern Zimbabwe.

intercropping patterns, the timing and frequency of weeding events, cattle manure application rates, and mineral fertilizer management (Table 1).

2.3 | Soil Sampling for Weed Seed Bank Studies

At the conclusion of the second monitoring season, soil samples were collected at depths of 0–10, 10–20, and 20–30 cm from each of the 75 monitored fields using a 10 cm diameter bucket auger. Within each field, core samples were collected from nine points using a zig-zag sampling pattern and thoroughly mixed to form a single composite sample per depth, resulting in a total of 225 composite soil samples. A representative 2 kg sub-sample from each composite was transferred to the University of Zimbabwe laboratory, where it was air-dried and stored at room temperature (~25°C) prior to the setup of the glasshouse weed seed bank experiment.

2.4 | Weed Seed Bank Experiment

To determine the impact of field management practices on weed seed bank size and composition, a glasshouse soil incubation experiment was conducted using the seedling emergence method [12]. The trial followed a 3 × 3 factorial arrangement structured within a randomized complete block design (RCBD). AER and soil sampling depth were evaluated as the primary fixed factors, while the monitored individual farmer fields nested within each AER served as true replicates. The first factor, AER, consisted of three levels (AER 2, AER 3, and AER 4). The second factor, sampling depth, also comprised three levels (0–10, 10–20, and 20–30 cm). In total, 675 experimental units were established, corresponding to the 225 collected soil samples replicated across the three blocks. Spatial distance from the glasshouse entrance door was utilized as the blocking factor to account for the microclimatic gradient.

Soil samples (600 g each) were incubated in circular plastic trays (18 cm diameter) under unregulated glasshouse conditions, where diurnal temperatures fluctuated between 23 and 30°C during the day and 18 and 19°C at night. Trays were initially watered to field capacity to stimulate weed seed germination and seedling emergence [35]. Subsequently, irrigation was applied every 2 days using a watering can fitted with a fine rose, delivering 660 mL of water per tray. Weekly and for a 3 months period, emerged weed seedlings were identified, enumerated, and removed. Because a known limitation of the seedling emergence method is its exclusive quantification of nondormant seeds capable of germinating under prevailing glasshouse conditions, the soil in each tray was manually turned once per month and rewatered to field capacity to break dormancy and stimulate further emergence.

TABLE 1 | Crop management practices on maize-based smallholder farms in three study sites ($N = 75$) in north-eastern Zimbabwe.

Variable	Response	Frequency (N)	Proportion of fields (%)
Tillage practice	Planting basins	34	45
	Plowing	41	55
Mulching	Mulch applied	6	8
	No mulch applied	69	92
Crop rotation	Crop rotation	50	67
	Monoculture	25	33
Cropping system	Intercropping	12	16
	Monocropping	63	84
Organic manure	Cattle manure applied	38	51
	No manure	37	49
Mineral fertilizer	Mineral fertilizer applied	59	79
	No mineral fertilizer	16	21
First weeding	2 WACE	32	43
	3 WACE	32	43
	4 WACE	11	14
Weeding frequency	1 weeding	36	48
	2 weedings	33	44
	3 weedings	6	8

Note: Frequencies and percentages represent pooled data across the 2022/2023 and 2023/2024 cropping seasons.
Abbreviation: WACE, weeks after crop emergence.

2.5 | Data Analysis

Statistical data analyses were performed using R software version 4.4.3. Prior to analysis, the data were checked for normality by both visual inspections (quantile–quantile plots and density distributions) and using the Shapiro–Wilk test. Additionally, the homogeneity of variances was assessed using Levene's test. Weed seed bank density (WSD) data failed to satisfy the assumption of normality and were consequently square-root transformed ($\sqrt{x + 0.5}$) prior to the analysis. The weed parameters which were analyzed were WSD, species richness (S), species evenness (E), and species diversity (H). Relative WSD (RWD) was calculated as follows [36]:

$$\mathrm{RWD} = \left(\frac{\mathrm{wdi}}{\mathrm{WD}}\right) \times 100\%,$$

where wdi is the weed density of individual weed species and WD is the overall weed density.

Weed species richness (S) was the total number of weed species that emerged per experimental unit. Weed diversity Shannon–Weiner diversity index (H) was used to measure diversity within the seed banks and was calculated as follows [37]:

$$H = -\sum_{i=1}^{s} p_i \ln(p_i),$$

with $pi = ni/N$; where Pi is the relative abundance of each group of organisms, ni is the number of individuals of a species, and N is the total number of individuals of all species.

Weed species evenness (E) was used to measure how weed seeds are distributed in the soil seed banks, and values range from 0 to

1, with values close to 1 showing uniform distribution in fields [36]. Evenness was calculated as follows:

$$E = \frac{H'}{\ln S},$$

where E represents evenness, S represents weed species richness, and H represents weed diversity index

Weed species richness, Pielou's evenness, and Shannon–Weiner diversity index were calculated in R statistical package using the vegan package. The effects of crop management practices (tillage, crop rotation, mulching, intercropping, timing of first weeding, weeding frequency, cattle manure use, and mineral fertilizer application) were evaluated on WSD, richness, evenness, and diversity using analysis of variance type III for unequal samples. Linear models were fitted using the lm function from the stats package. The significance of effects was determined by calculating p-values through likelihood ratio tests. Least significance difference (LSD) was used to compare factor levels, where the F-test was significant at $p < 0.05$. Canonical correspondence analysis (CCA) was done to determine the relationship between weed seed bank composition and crop management practices.

3 | Results

3.1 | Floristic Composition and Structure of Seed Bank

In total, 25 weed species belonging to 21 genera and 14 families were observed and recorded from soil weed seed banks of three AERs in north-eastern Zimbabwe. Among the 25 weed species, 72% were annual broadleaves, 20% were annual grasses, and 8% were perennial sedges (Table 2). The dominant weed families that had more than three weed species were Poaceae (5), Asteraceae (4), and Cleomaceae (3). These families contributed 48% of the total floristic composition of the weed seed bank community in this study. The occurrence of individual weed species varied across AERs, with *Galinsoga parviflora* Cav dominating the seed bank in AER 2, *Digitaria ternata* (A. Rich) Roem in AER 3 soil seed banks, and *Richardia scabra* L. dominating in AER 4. Weed species composition varied in the AERs. AER 2 and AER 4 each supported 18 weed species, and AER 3 recorded the highest number of weed species, with 21 weed species recorded. Furthermore, all the AERs contained 13 common weed species within their soil weed seed banks. Weed species with an average relative weed seedling density of >5%, namely, *R. scabra* L., *Cyperus esculentus* L., *G. parviflora* Cav, *Leucas martinicensis* L., *D. ternata*, *Eleusine indica* (L.) Gaertn, and *Amaranthus hispidum* D.C., were dominant weed species recorded. It was noted that these seven out of 25 weed species contributed to 90.4% of the RWD, whereas 18 out of 25 weed species contributed only 9.6% of the RWD.

3.2 | Effects of Agroecological Region, Soil Sampling Depth, and Crop Management on Weed Seed Bank Composition

The effects of AER, soil depth, and crop management on the weed seedbank density, species richness, evenness, and diversity are summarized in Table 3. It was noted that the effects of agroecology, tillage, crop rotation, cattle manure, mineral fertilizer application, timing of first weeding, and weeding frequency were significant ($p < 0.05$) on weed density (weed seed bank size) and weed species diversity. In some cases, AER interacted significantly ($p < 0.05$) with some crop management factors on WSD, species richness, evenness, and weed diversity. Generally, WSD and diversity were reduced with increasing soil depth in all the AERs. WSD, species richness, evenness, and diversity were significantly highest in the 0–10 cm soil layer, followed by 10–20 cm and were lowest at 20–30 cm soil depth. In this study, it was found that mulching and intercropping effects were not significant on weed density and diversity.

3.3 | Influence of Tillage Practice on the Weed Seed Bank Size and Composition

Tillage practice significantly ($p < 0.05$) affected the WSD, species richness, species evenness, and species diversity (Table 3). The highest weed seedling density was observed in farmers' fields where plowing is practised, while those that use planting basins recorded the lowest weed seedling density (Figure 2a). The soil weed seed bank in plowed fields recorded higher weed species richness compared with fields where planting basins were used (Figure 2b). Similarly, weed species evenness was higher in seed banks where plowing was used to prepare the land, whilst planting basins reduced weed species evenness (Figure 2c). Weed species diversity was higher in plowed fields, whereas planting basins had lower species diversity (Figure 2d).

3.4 | Influence of Crop Rotation on the Weed Seed Bank Size and Composition

WSD ($F_{2,\ 657} = 3.69$), species richness ($F_{2,\ 657} = 3.79$), and species diversity ($F_{2,\ 657} = 3.28$) were significantly ($p < 0.05$) affected by the AER × crop rotation interaction (Table 3). The highest WSD was recorded in the wetter environment of AER 2 recorded under crop rotation (Figure 3a). Additionally, moving across the climate gradient to more drier regions, a reduction in the weed seed bank size was recorded, and lowest seed bank densities were recorded in AER 3 in fields under continuous cultivation. Weed species evenness was similar under crop rotation and no rotation systems in AER 2 and AER 4, whilst in AER 3, the weed seed bank community evenness was reduced under continuous cultivation compared with crop rotation (Figure 3b). However, the weed seed bank community that had higher species evenness was recorded in AER 2 under both crop rotation and continuous cultivation compared with that in the other AERs (Figure 3b). Similarly, weed species diversity was significantly higher in AER2 than in AER3 and AER4, while it was comparable between crop rotation and no rotation in all the regions (Figure 3c).

3.5 | Influence of Cattle Manure and Mineral Fertilizer on the Weed Seed Bank Size and Composition

The AER × cattle manure interaction was significant ($p < 0.05$) on WSD ($F_{2,\ 657} = 3.71$) and weed species richness ($F_{2,\ 657} = 4.51$) (Table 3). The highest germinable WSDs were recorded in AER 2, and within this region, applying cattle manure resulted in a lower seed bank compared to no manure application. In contrast, AER 3 and AER 4 recorded no statistical differences in seed bank

TABLE 2 | Relative weed seed bank density (RWD) of weed species in different agroecological regions of Zimbabwe.

Weed species	Family	Class	Relative weed density (%)			
			AER2	AER3	AER4	RWD
Richardia scabra L.	Rubiaceae	AB	9.96	14.35	31.17	17.21
Cyperus esculentus L.	Cyperaceae	PS	22.65	12.69	11.22	17.09
Galinsoga parviflora Cav.	Asteraceae	AB	29.21	1.99	0.92	14.91
Leucas martinicensis L.	Lamiaceae	AB	13.16	17.34	12.10	13.75
Digitaria ternata (A. Rich) Roem	Poaceae	AG	4.73	24.88	11.46	11.09
Eleusine indica (L.) Gaertn	Poaceae	AG	6.23	7.70	18.98	10.35
Acanthospermum hispidum D.C.	Asteraceae	AB	3.65	9.81	7.16	6.02
Bidens pilosa L.	Asteraceae	AB	3.01	2.22	1.41	2.36
Setaria verticillata (L.) P. Beauv	Poaceae	AG	2.00	3.16	1.69	2.16
Cleome hirta (Klotzsch) Oliv.	Cleomaceae	AB	1.95	0.83	1.53	1.58
Commelina benghalensis L.	Commelinaceae	ABG	1.60	1.77	0.60	1.34
Ceratotheca sesamoides Endl.	Pedaliaceae	AB	-	0.61	0.80	0.37
Sida alba L.	Malvaceae	AB	0.44	0.11	0.24	0.31
Amaranthus hybridus L.	Amaranthaceae	AB	0.20	0.17	0.40	0.25
Spergula arvensis L.	Caryophyllaceae	AB	0.52	-	-	0.25
Argemone mexicana L.	Papaveraceae	AB	0.42	-	0.08	0.23
Melinis repens (Willd,) Zizika	Poaceae	AG	-	0.55	-	0.12
Spermacoce senesis (Klotzsch) Hiern	Rubiaceae	AB	-	0.33	0.16	0.12
Portulaca oleracea L.	Portulacaceae	AB	0.20	0.06	-	0.11
Fimbristylis exilis Kunth.	Cyperaceae	PS	-	0.44	-	0.10
Phyllantus pentandrus Schumach & Thonn	Phyllanthaceae	AB	-	0.44	-	0.10
Cleome monophyla L.	Cleomaceae	AB	-	0.33	-	0.07
Panicum novermnerve Stapf.	Poaceae	AG	-	0.22	-	0.05
Cleome gynandra L.	Cleomaceae	AB	0.05	-	0.04	0.04
Tagetes minuta L.	Asteraceae	AB	0.02	-	0.04	0.02
Total	—	—	100	100	100	100

densities in fields with and without cattle manure applied as an organic amendment (Figure 4a). Weed species richness varied significantly in the different aAERs, and the highest number of weed species was observed in AER 2 compared with AER 3 and AER 4 (Figure 4b). Similar to seed bank density, in AER 2, weed species richness was significantly lower in fields where cattle manure was used compared to those without manure. In AER 3 and AER 4, the number of weed species observed was comparable in fields with and without cattle manure. There was a significant ($p < 0.05$) soil depth × cattle manure interaction on weed species richness ($F_{2,\ 657} = 3.27$), weed species evenness ($F_{2,\ 657} = 3.37$), and weed species diversity ($F_{2,\ 657} = 3.62$) (Table 3). Generally, increasing the soil depth from 0–10 cm to 20–30 cm significantly reduced weed seed bank species richness, evenness, and diversity. However, weed seed bank richness, evenness, and diversity were comparable with and without cattle manure at the varying soil depths (Figures 4c–e).

The interaction of soil depth × mineral fertilizer on WSD ($F_{2,\ 657} = 5.82$), weed species richness ($F_{2,\ 657} = 6.68$), evenness ($F_{2,\ 657} = 3.76$), and diversity ($F_{2,\ 657} = 6.39$) was significant ($p < 0.05$) (Table 3). In this study, the highest densities, richness, evenness, and diversity of the soil seed bank were generally observed in the first 10 cm of the soil profile and decreased significantly with an increase in soil sampling depth to 30 cm. In the uppermost soil sampling layer, mineral fertilizer application recorded the lowest WSD compared to that when no fertilizers were used (Figure 5a). Comparable weed species richness, evenness, and diversity in the 0–10 and 20–30 cm soil depths were recorded with and without mineral fertilizer application (Figures 5b–d). Conversely, at the 10–20 cm soil depth, weed species richness, evenness, and diversity were significantly higher in fields with mineral fertilizer applied compared to no fertilizer. Weed species richness ($F_{2,\ 657} = 4.62$) and species diversity ($F_{2,\ 657} = 3.26$) were significantly ($p < 0.05$) affected by the AER × mineral fertilizer interaction (Table 3). Weed species richness and diversity

TABLE 3 | *F*-value and statistical significance summary for weed seed bank density m^{-2} (WSD), weed species richness (*S*), Pielou's evenness index (*E*), and Shannon–Weiner diversity index (*H*) after the analysis of variance type III for unequal samples.

Crop management practices	WSD	*S*	*E*	*H*
Tillage practice				
AER	0.37	0.69	1.02	1.63
Soil depth	16.57***	13.87***	5.88**	6.47**
Tillage	4.16*	5.88*	6.57*	9.00**
AER × soil depth	1.25	3.54**	3.07*	3.36**
AER × tillage	1.92	2.32	1.43	2.71
Soil depth × tillage	0.25	0.13	0.69	0.89
AER × soil depth × tillage	0.63	0.36	0.56	0.75
Mulching				
AER	0.68	0.13	0.03	0.00
Soil depth	4.49*	0.85	0.75	1.28
Mulch current	0.01	0.40	0.10	0.02
AER × soil depth	0.40	1.44	0.69	0.47
AER × mulch current	0.76	0.17	0.01	0.00
Soil depth × mulch current	0.90	0.48	0.33	0.25
AER × soil depth × mulch current	1.03	0.61	0.46	0.29
Crop rotation				
AER	0.30	0.13	2.38	1.55
Soil depth	24.64***	18.84***	8.83***	11.66***
Crop rotation	0.01	0.13	0.15	0.10
AER × soil depth	3.13*	4.77***	3.46**	3.65**
AER × crop rotation	3.69*	2.87	3.79*	3.28*
Soil depth × crop rotation	0.04	0.21	0.35	0.10
AER × soil depth × crop rotation	1.06	0.77	0.91	0.85
Intercropping				
AER	0.47	3.85*	1.50	2.39
Soil depth	7.70***	5.99**	2.38	3.88*
Intercropping	2.24	1.20	0.00	0.42
AER × soil depth	1.19	3.19*	1.80	2.42*
AER × intercropping	0.48	2.20	1.94	2.82
Soil depth × intercropping	2.42	1.98	0.56	1.12
AER × soil depth × intercropping	0.34	2.12	1.46	1.52
Cattle manure				
AER	0.28	1.90	0.61	1.16
Soil depth	21.78***	17.23***	10.73***	11.58***
Manure current	9.99**	9.93**	3.74	6.41*
AER × soil depth	3.30*	7.14***	4.62**	5.38**

(Continues)

TABLE 3 | (Continued)

Crop management practices	WSD	*S*	*E*	*H*
AER × manure current	3.71*	4.51*	1.93	2.86
Soil depth × manure current	2.67	3.27*	3.37*	3.62*
AER × soil depth × manure current	1.18	1.24	0.98	1.30
Mineral fertilizer				
AER	3.52*	1.85	0.06	0.58
Soil depth	31.31***	22.13***	11.44***	15.47***
Fertilizer	10.66**	8.30**	0.59	4.28*
AER × soil depth	5.01***	8.48***	4.31**	6.30***
AER × fertilizer	2.10	4.62*	2.90	3.26*
Soil depth × fertilizer	5.82**	6.68**	3.76*	6.39**
AER × soil depth × fertilizer	1.03	2.17	1.60	1.84
First weeding				
AER	3.89**	6.06**	4.30*	4.71**
Soil depth	0.55	1.56	1.39	0.98
First weeding	6.15**	8.45***	6.30**	7.12***
AER × soil depth	1.30	3.11*	2.71*	2.57*
AER × first weeding	4.03**	3.45*	3.09*	3.47*
Soil depth × first weeding	1.58	1.07	2.65*	3.97*
AER × soil depth × first weeding	1.62	0.92	0.95	0.91
Weeding frequency				
AER	14.98***	8.85***	3.39*	5.63**
Soil depth	43.42***	21.43***	11.49***	16.56***
Weeding frequency	8.40***	6.71**	2.73	5.66**
AER × soil depth	0.58**	2.57*	0.91	1.22
AER × weeding frequency	5.88***	6.72***	5.11***	6.62***
Soil depth × weeding frequency	0.82	1.10	1.42	1.09
AER × soil depth × weeding frequency	1.03	1.42	1.26	1.49

Note: * * *, * *, and * indicate $p < 0.001$, $p < 0.01$, and $p < 0.05$, respectively.

in all three AERs were comparable regardless of whether mineral fertilizers were applied or not. However, significantly higher species richness was recorded in AER 2 compared with AER 3 and AER 4 (Figure 5e). Overall, weed seed bank diversity was highest in AER 2 in fertilizer-applied fields, although comparable in unfertilized fields (Figure 5f). Species diversity was significantly lowest in the driest environment of AER 4 in unfertilized fields, although it was comparable to farmers' fields in AER 3 with and without fertilizers.

3.6 | Influence of Weed Management on the Weed Seed Bank Size and Composition

There was a significant ($p < 0.05$) AER × first weeding interaction on WSD ($F_{2,\ 657} = 4.03$), weed species richness ($F_{2,\ 657} = 3.45$), evenness ($F_{2,\ 657} = 3.09$), and diversity ($F_{2,\ 657} = 3.47$) (Table 3). Delaying first weeding in all the AERs beyond 2 weeks after crop emergence (WACE) significantly increased the weed seed bank size (Figure 6a). In AER 3 and AER 4, WSD was lowest when weeding commenced at 2 WACE, followed by 3 WACE, and lastly 4 WACE. Early weeding at 2 WACE across all AERs significantly reduced weed seed bank richness, with a smaller number of weed species observed; however, delaying weeding resulted in a more species-rich soil weed seed bank (Figure 6b). Additionally, timely weeding at 2 WACE in AER 2 had a greater influence on reducing weed species richness compared with that in other AERs. Similarly, this was also observed with weed species evenness and diversity in AER 2, while in AER 3, the effect of the first weeding time was comparable at all the weeding initiation timings (Figure 6c,d). The soil depth × first weed interaction was significant ($p < 0.05$) on weed species evenness ($F_{2,\ 657} = 2.65$)

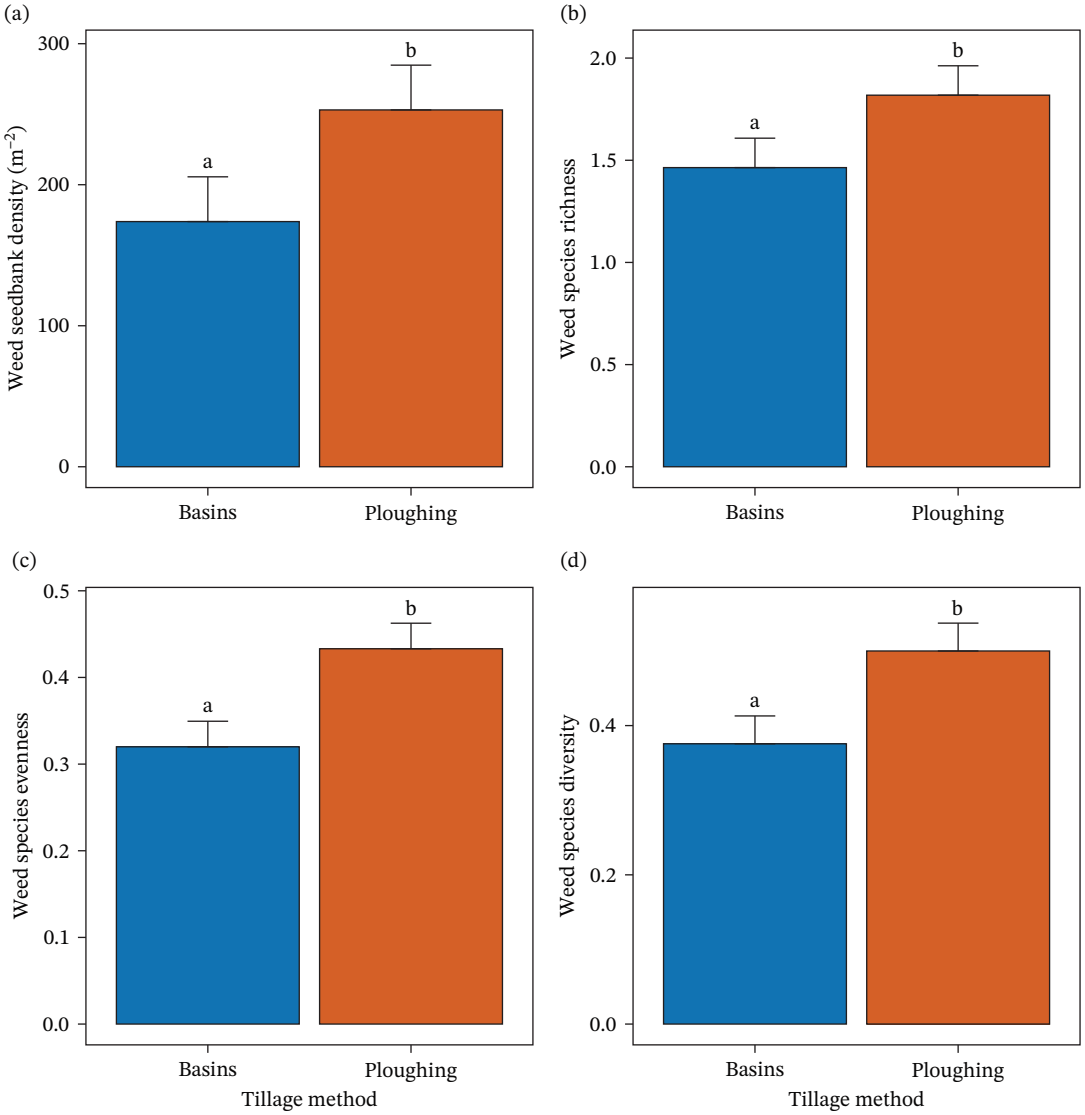

FIGURE 2 | Bar plots of (a) number of weed seeds germinated, (b) weed species richness, (c) weed species evenness, and (d) weed species diversity as influenced by tillage practice. Error bars represent least significant difference (LSD) at $p<0.05$. Different lowercase letters above bars show significant differences among treatments. Each treatment group is based on $n=25$ farmer field soil sample replicates per region × depth, with replication across three blocks in the randomized complete block design (total $n=75$ per treatment group).

and diversity ($F_{2,\ 657}=3.97$) (Table 3). The 0–10 cm soil layer recorded comparable weed species evenness, although in the 10–20 cm layer, evenness increased significantly as first weeding was delayed to 3 and 4 WACE (Figure 6e). Furthermore, the highest species evenness was recorded within the top 0–10 cm layer regardless of timing of weeding, while the lowest was observed at 20–30 cm depth at the earliest time of first weeding. Similar to species evenness, the highest seed bank diversity was recorded in the 0–10 cm soil layer, and the highest diversity was observed at 4 WACE and the lowest in the 20–30 cm layer at 2 WACE (Figure 6f). Overall, seed bank diversity decreased gradually with increasing soil depth.

WSD ($F_{2,\ 657}=5.88$), weed species richness ($F_{2,\ 657}=6.72$), evenness ($F_{2,\ 657}=5.11$), and diversity ($F_{2,\ 657}=6.62$) were significantly ($p<0.05$) affected by the AER × weeding frequency interaction (Table 3). Generally, the largest germinable WSDs were observed when weeding was done only once across the agroclimatic gradient. However, AER 2 recorded the significantly highest density of 360 weed seeds m^{-2}. Increasing weeding frequency to two weedings significantly reduced the WSD, and the lowest seed bank density (95 seeds m^{-2}) was achieved with three weedings (Figure 7a). Additionally, AER 3 recorded comparable seed bank densities, regardless of weeding frequency, and, in AER 4, weeding once recorded the highest density, and increasing weeding frequency resulted in reduced comparable densities. Weeding once throughout the cropping season resulted in the highest weed species richness in AER 2, while in AER 3 and AER 4, weed species richness was comparable irrespective of the number of times weeding was carried out (Figure 7b). Generally, weeding once in AER 2 recorded the highest weed species evenness and diversity, while increasing weeding frequency to two and three weeding resulted in lower, however comparable evenness and diversity (Figure 7c,d). Furthermore, in the arid regions of AER 3 and AER 4, evenness and diversity were similar, regardless of the weeding regime.

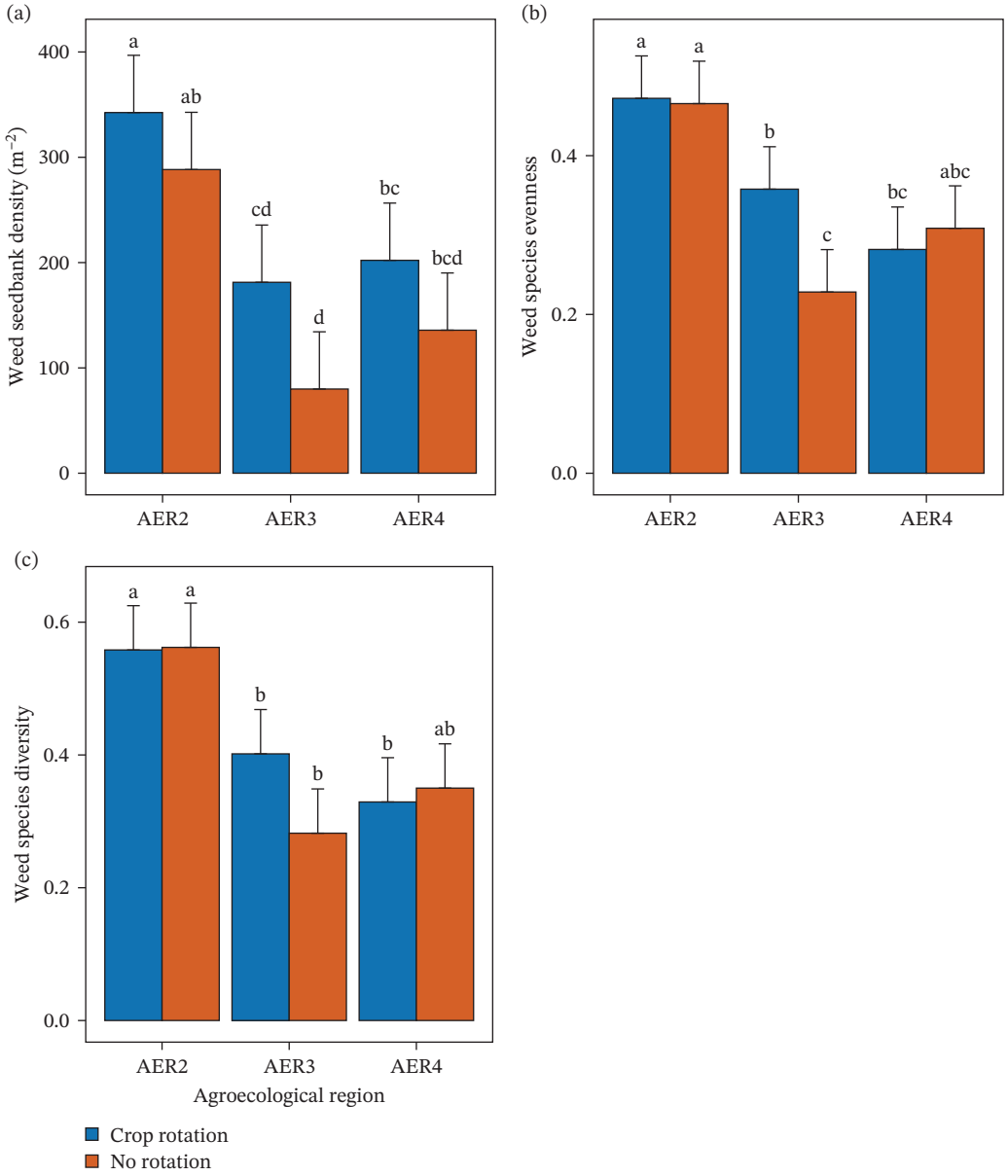

FIGURE 3 | Bar plots of (a) weed seed bank density, (b) weed species evenness, and (c) weed species diversity as influenced by crop rotation. Error bars represent interaction LSD at $p < 0.05$. Different lowercase letters above bars show significant differences among treatments. Each treatment group is based on $n = 25$ farmer field soil sample replicates per region × depth, with replication across three blocks in the randomized complete block design (total $n = 75$ per treatment group).

3.7 | Relationship Between Crop Management Practices and the Floristic Composition of the Weed Seed Bank

The CCA model comprised of 11 explanatory variables which explained 9.3% variation. The first canonical axis (CCA1) accounted for 40.9% of the total constrained variation in the weed species composition, while the second canonical axis explained an additional 16.3%. Together, these two axes explained 57.3% of the total variation attributable to measured explanatory variables (Table 4). The explanatory variables included in the CCA model were the AER, soil sampling depth, and the crop management practices observed on monitored smallholder farms. However, there were significant ($p < 0.05$) relationships between weed species and the AER, soil sampling depth, crop rotation, land preparation, and organic amendments. The CCA axis 1 was positively related to the AER and crop rotation, indicating a strong influence of weed species composition. Weed species such as *Phyllantus pentandrus*, *Ceratotheca sesamoides*, and *Spermacoce senesis* were positively associated with this axis, while *Galinsoga parviflora*, *Portulaca oleracea*, and *Tagetes minuta* were negatively associated (Figure 8). On CCA axis 2, weed species composition was mainly associated with the soil sampling depth, land preparation method, and organic amendments. *Eleusine indica* was positively associated with CCA axis 2, while *Cyperus esculentus*, *Setaria verticillata*, *Cleome gynandra*, and *Spergula arvensis* were negatively related to the axis (Figure 8). *Leucas martinicensis*, *Cleome hirta*, *Commelina bengalensis* and *Amaranthus hybridus*, *Acanthospermum hispidum*, and *Richardia scabra* are located close to the origin, indicating no association with the explanatory variables.

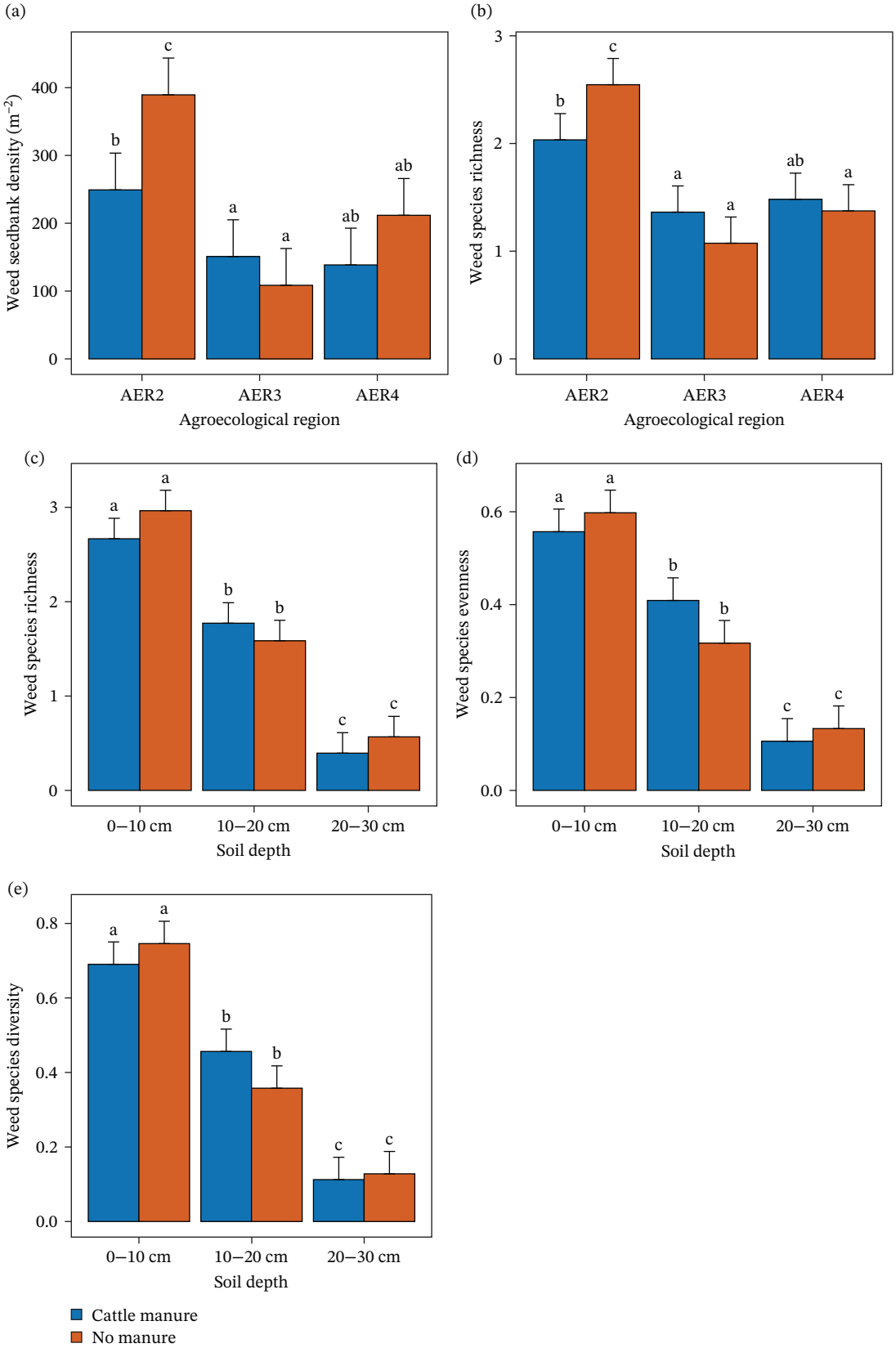

FIGURE 4 | Influence of cattle manure application on weed seed bank composition. (a) Weed seedbank density and (b) weed species richness across agroecological regions. Species richness (c), evenness (d), and diversity (e) at three soil depths. Error bars represent interaction LSD at $p < 0.05$. Different lowercase letters above bars show significant differences among treatments. Each treatment group is based on $n = 25$ farmer field soil sample replicates per region × depth, with replication across three blocks in the randomized complete block design (total $n = 75$ per treatment group).

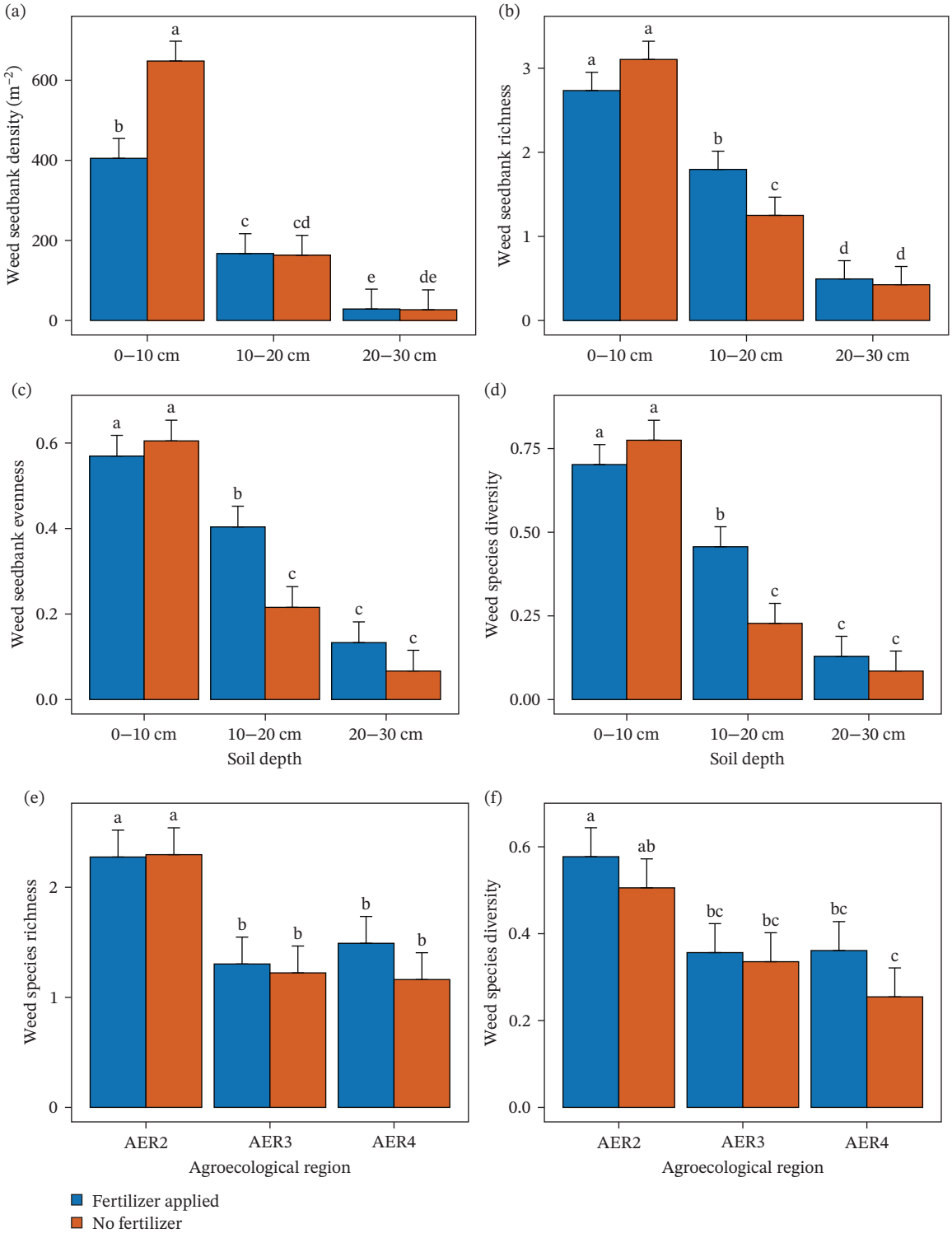

FIGURE 5 | Effects of mineral fertilizer application on weed seedbank metrics. (a) Weed seedbank density, (b) species richness, (c) evenness, and (d) diversity (*D*) at three soil depths. (e) Species richness and (f) diversity across agroecological regions. Error bars represent interaction LSD at $p < 0.05$. Different lowercase letters above bars show significant differences among treatments. Each treatment group is based on $n = 25$ farmer field soil sample replicates per region × depth, with replication across three blocks in the randomized complete block design (total $n = 75$ per treatment group).

4 | Discussion

4.1 | Floristic Composition and Structure of Seed Bank

The results from this study showed diverse weed seed banks composed of several weed species in the three AERs of north-eastern Zimbabwe. Irrespective of the diversity in the weed seed bank, the weed seed banks are largely composed of a few dominant weed species with very high proportions ranging between 70%–90% [12]. In our study, we observed that 90% of the total weeds observed are made up of seven weed species, indicating their dominance within smallholder farms in north-eastern Zimbabwe. Our results support

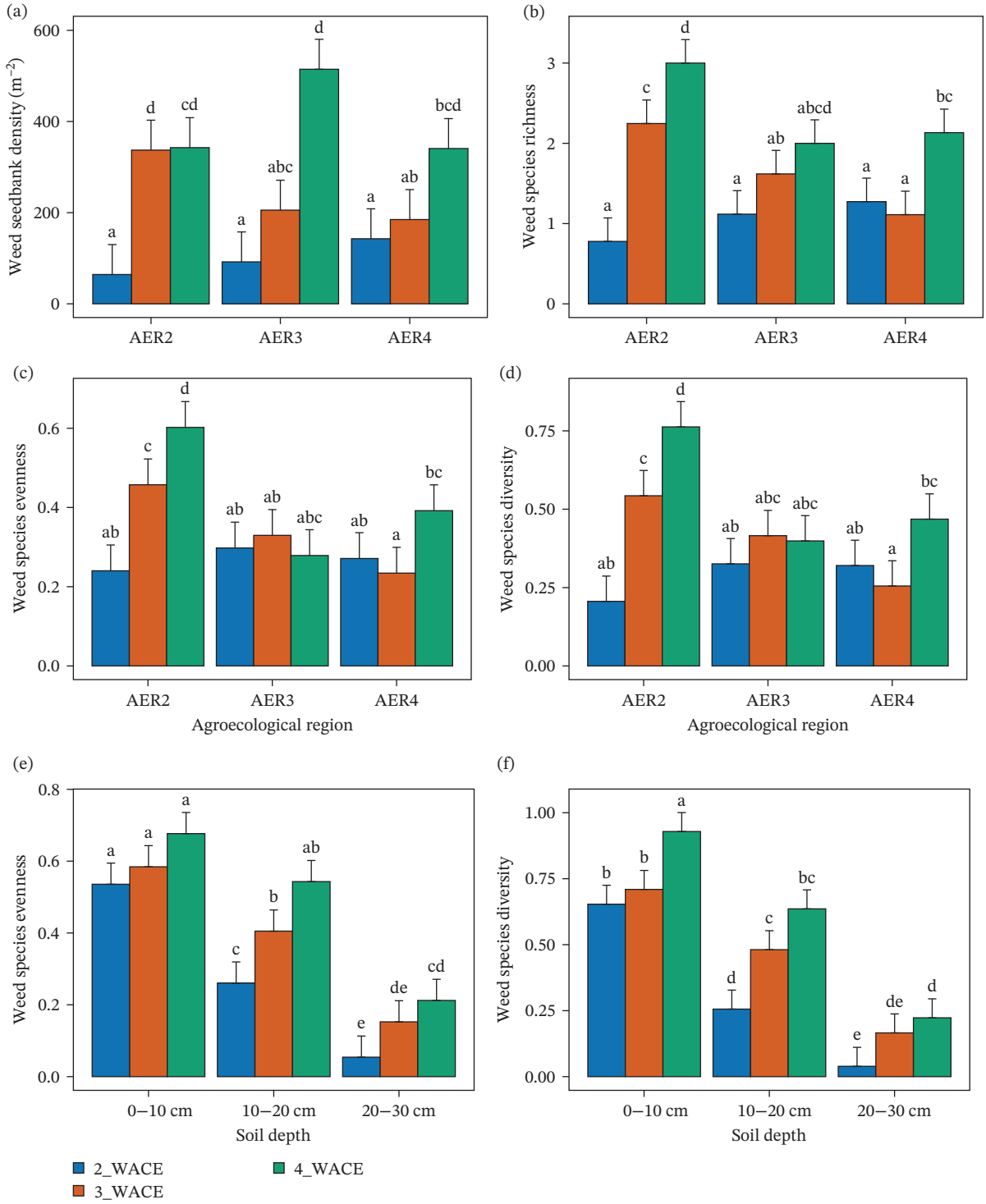

FIGURE 6 | Impact of first weeding timing on weed seedbank and community metrics. (a) Weed seedbank density, (b) species richness, (c) weed species evenness, and (d), weed species diversity across agroecological regions. (e) Weed species evenness and (f) diversity across soil depths. Error bars represent interaction LSD at $p < 0.05$. Different lowercase letters above bars show significant differences among treatments. Each treatment group is based on $n = 25$ farmer field soil sample replicates per region × depth, with replication across three blocks in the randomized complete block design (total $n = 75$ per treatment group).

the findings by He et al. [15], who reported that out of the 175 weed species observed in their study, only 28 weed species were dominant with high weed seed densities, while the majority of the weed species had low seed densities. These dominant weed species were observed in all the AERs, indicating that these weed species have adapted to the different climatic conditions in these regions. This implies that these weed species can grow and produce seeds in a broad range of growing conditions [24]. The weed seed banks in our study were dominated by annual weeds and very few perennials. This result concurs with the findings of Rugare et al. [22],

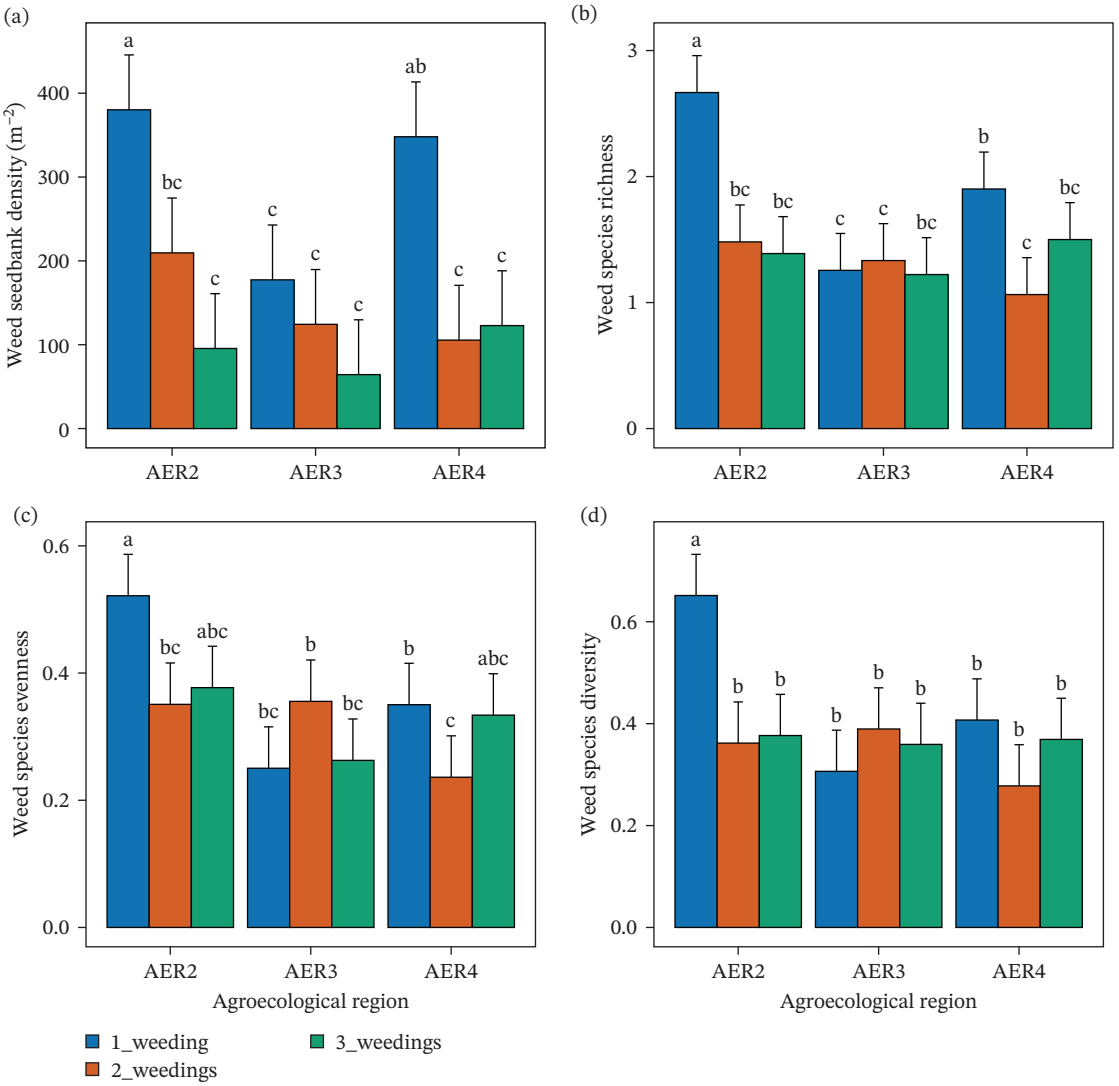

FIGURE 7 | Bar plots of (a) number of weed seeds germinated, (b) weed species richness, (c) weed species evenness, and (d) weed species diversity as influenced by weeding frequency across agroecological regions. Error bars represent interaction LSD at $p < 0.05$. Different lowercase letters above bars show significant differences among treatments. Each treatment group is based on $n = 25$ farmer field soil sample replicates per region × depth, with replication across three blocks in the randomized complete block design (total $n = 75$ per treatment group).

who reported that *Cyperus* spp was the only perennial weed observed in their study, and low numbers of perennial weeds may arise from soil sampling, which can miss perennating structures, including rhizomes and stolons. The dominance of annual weeds is also attributed to the type of tillage that is dominant in the study area. Generally, perennial weeds are dominant in reduced tillage systems. Comparison of weed floristic composition among the AERs shows that there were 13 similar weed species across the agroclimatic gradient, and the remaining species were found in either one or two regions. The presence of region-specific weeds in this study indicates that there are some weeds that thrive only in local edaphoclimatic conditions. Region-specific weeds reflect ecological adaptation, where species evolve or persist in response to the unique rainfall patterns, temperature regimes, and concomitant crop management practices of each AER. Such weeds thrive under local edaphoclimatic conditions that favor their germination, survival, and competitive ability, making them characteristic indicators of particular agroecological environments [11].

4.2 | Effects of Agroecological Region, Soil Sampling Depth, and Crop Management on Weed Seed Bank Composition

The largest weed seed bank size was observed in the wetter environment of AER 2 compared to the drier environments of AER 3 and AER 4. High moisture levels favor weed proliferation, and incessant rains may compromise weed control, thus leading to greater seed deposit into the seed bank [38]. Across all AERs, the uppermost sampled soil layer (0–10 cm) recorded the highest seed bank density, richness, evenness, and diversity. These parameters reduced with increasing soil depth, suggesting that the top soil is where most of the weed seed rain accumulates when weed seeds are dispersed. This result concurs with the findings by [27, 39–41], who reported that the uppermost soil layer serves as the active seed bank, with seed bank density and species diversity decreasing with increasing soil depth. High numbers of weed seeds and diversity in the active seed bank can be attributed to the accumulation of weed seed rain on the soil surface and in the first

TABLE 4 | Summary of canonical correspondence analysis.

Explanatory variable	CCA axis 1	CCA axis 2
Agroecological region	0.50734	0.08325
Soil sampling depth	−0.10663	0.21201
Crop rotation	0.24863	0.01752
Land preparation method	−0.02496	0.11716
Mulching	0.00094	0.02889
Intercropping	0.06330	0.07407
Organic amendment	−0.05661	−0.07903
Mineral fertilizer	0.13937	−0.06543
Weeding frequency	0.18354	−0.02940
First weeding	−0.28166	−0.05331
Eigenvalues	0.26	0.10
Percentage of variance	40.96	16.38
Cumulative percentage variance	40.96	57.34
Species-environment correlations	0.20	0.12
F-ratio	15.04	6.01
p-Value	0.001	0.015

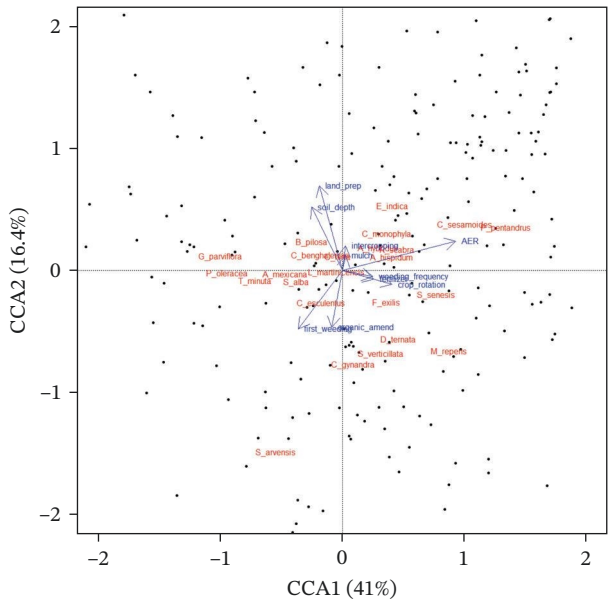

FIGURE 8 | Canonical correspondence analysis ordination diagram indicating the relationships between weed species and crop management practices.

5 cm of the soil [42]. Vertical weed seed bank distribution is mostly influenced by soil disturbance, highlighting a pivotal role of tillage practices in shaping the weed seed bank [21].

4.3 | Influence of Tillage Practice on the Weed Seed Bank Size and Composition

Tillage practice at land preparation influenced WSD, species richness, evenness, and diversity. The findings of this study show that farmers using planting basins recorded lower seed bank size and diversity compared to those employing conventional tillage practices (plowing). This result corroborates the results of Forte et al. [25], who reported lower WSD in no tillage systems compared with conventional tillage. Weed seed banks in conventional tillage are typically large because of continuous inversion of the soil that spreads weed seeds vertically in the soil profile [40]. This practice delays turnover of seeds from the seed bank by causing weed seed dormancy when seeds are buried, ultimately creating persistent seed banks where weed seeds remain in the seed banks for extended periods [7]. When seed seeds are buried deep in the soil, they fail to germinate and emerge, enabling them to remain viable in the soil [27]. However, no tillage systems are often associated with high weed infestations due to weed seed accumulation on the soil surface, where conditions for breaking weed seed dormancy and germination prevail. Plowing, on the other hand, evenly distributes weed seeds in the soil profile because of frequent inversion of the soil [24]. Our results contradict the findings of Zamljen et al. [5], who reported that low disturbance tillage practices increased weed seed bank richness, evenness, and diversity as compared with conventional tillage [43]. It was also reported that reduced tillage regimes supported a larger seed bank than conventional tillage. This difference is because planting basins, previously associated with high weed infestations, are now managed with more effective weed control measures such as early weeding and higher weeding frequency, which deplete the shallow (0–10 cm) seed bank. In contrast, conventional tillage redistributed seeds into deeper layers (10–30 cm), where they remained dormant and viable for longer, protected from germination. Effective weed management during initial years of conservation agriculture (CA) adoption has been shown to reduce weed infestations, potentially contributing to smaller weed seed banks than in conventional tillage [44]. In the context of our study, the majority of farmers have practiced reduced tillage through basin planting for over two decades after the promotion of CA by the Food and Agriculture Organization [45]. This has likely facilitated a progressive depletion of the soil weed seed banks by exposing weed seeds to conditions that favor germination and predation [7]. Despite the initial challenges of high weed infestations during the early stages of CA adoption, low-disturbance tillage practices progressively reduce the weed seed bank by depleting seeds concentrated near the soil surface.

4.4 | Influence of Crop Rotation on the Weed Seed Bank Size and Composition

A previous report by Hosseini et al. [21] stated that crop rotation was more influential in reducing weed seed banks than other cropping practices, and changes in weed populations can be seen after 2 years of doing rotations. However, in this study, we observed that crop rotations favored larger weed seed banks than continuous cultivation, suggesting that rotation does not guarantee weed seed bank suppression. In Murehwa and Mutoko, the predominant crop rotation sequence on intensively managed fields that receive substantial inputs and labor involves maize, followed by groundnuts, and then back to maize. While crop rotation is traditionally expected to suppress weeds, this study observed an increased seed bank density, a result likely driven by the disproportionate land allocation within the systems studied. Although

maize and groundnuts form the primary rotation sequence, legumes typically occupy only 10%–30% of the arable area. This leaves the vast majority (70%–90%) under continuous maize, which maintains a stable environment for dominant weed species and failure to disrupt their life cycles. Consequently, farmers have been unable to realize the benefits of diverse crop rotations. This outcome may also be attributed to poorly chosen rotations that fail to introduce sufficient variation in cropping practices, allowing dominant weed species to persist and leading to the development of well-adapted weed spectra [3, 46]. Crop diversification is yet to be fully embraced on smallholder farms in Zimbabwe, where rotations remain narrow and underutilized. Restricted access to improved seed varieties has reinforced reliance on maize as the primary crop, supplemented by underperforming landraces. Consequently, farmers have been unable to realize the weed-suppressive benefits of diverse crop rotations. Our results contradict the findings of Rugare et al. [22], who demonstrated that maize-cover crop rotations significantly reduced WSDs. This reduction is attributed to the allelopathic properties of the cover crops, which release bioherbicidal compounds capable of suppressing weed germination and seedling development [47]. Larger seed bank size and diversity in our study concur with Hosseini et al. [21], who stated that weed species adapt to specific crop sequences and any changes in the crop production system are likely to change the weed seed bank. Findings from this study indicate that weeds have adapted to the preferred rotation sequence, and some weed species are thriving, reproducing, and depositing into the soil seed bank. Therefore, there is a need to improve the rotation sequence and introduce leguminous green manure cover crops that have been reported to reduce the weed seed bank [48, 49].

4.5 | Influence of Cattle Manure and Mineral Fertilizer on the Weed Seed Bank Size and Composition

The results from this study showed that the weed seed bank responds to organic and mineral fertilizers. The application of cattle manure influenced the WSD, species richness, evenness, and diversity. In wet and arid environments of AER 2 and AER 4, respectively, manure application reduced the weed seed bank size and number of weed species observed in the seed bank. The regional variation in seed bank response to cattle manure suggests a dual role for organic amendments; while manure can suppress weed seed return by enhancing crop competitiveness in AER 2 and 4, it may also serve as a primary source for weed propagules in AER 3, particularly if incomplete composting allows for the survival of seeds ingested during rangeland grazing [8]. Kuht et al. [50] reports that during the initial transition to organic production, manure application resulted in a 28% increase in weed seed density; however, by the end of the six-season conversion period, weed seed density had declined to levels comparable to those observed under conventional mineral fertilization. The depth-specific impacts of cattle manure reflect contrasting ecological mechanisms. In the surface layer (0–10 cm), the decline in richness, evenness, and diversity suggests a selective filter, where manure-derived nutrients or specific weed seeds allow a few dominant, competitive taxa to proliferate. Conversely, the increased diversity at depth (10–20 cm) indicates that deeper manure burial unevenly alters soil conditions, with leached nutrients creating localized nutrient patches that support a wider variety of species [51]. Cattle manure application improves crop-weed competition by enhancing soil fertility and promoting crop vigor, which enables the crop to develop a dense canopy that outcompetes weeds for essential resources [52]. While the release of nutrients from manure is slower than that in mineral fertilizers, the improved growth allows the crop to secure more resources and reduce the impact of nutrient mining by weeds. Furthermore, this increase in nutrient availability may stimulate a synchronized flush of weed germination, which potentially depletes the soil weed seed bank if the emerged seedlings are removed by early weeding or subsequently suppressed by the crop. However, our results contradict the findings of Forte et al. and Maqsood et al. [25, 40], who reported that the application of farm yard manure increased the weed seed bank size by 11% compared with the control where no fertilization was done. Findings by Materechera and Modiakgotla and Chipomho et al. [8, 29] also reported the increased WSD and diversity in manured fields and went on to further recommended manure curing to mitigate this issue. The use of mineral fertilizers on smallholder farms in this study was observed to reduce the WSD, species richness, evenness, and diversity in the top 0–10 cm of the soil, which is the active seed bank. This concurs with the findings of Lal et al. [28] who reported that the efficacy of nitrogen (N), phosphorus (P), and potassium (K) fertilizers in reducing the weed seed bank size and weed species diversity in a long-term experiment on fertilizer effects in rice production. However, only weeds with strong adaptability to compete in highly fertile conditions will survive and be strongly represented in the weed seed bank as a result of loss of diversity caused by mineral fertilizers. The application of mineral fertilizers also improves crop-weed competition by promoting crop vigor, thereby enabling crops to outcompete weeds for essential resources and reducing nutrient mining by weeds [53]. Due to the high costs of fertilizers, application of fertilizers is often associated with effective weed control, as farmers aim to maximize returns through improved crop performance. Basal fertilizer application is usually done at planting in weed-free fields to ensure nutrient availability for crop establishment, whereas top dressing is conducted after effective weed control to maximize nutrient uptake by the crops. Therefore, the results from this study suggest that nutrient management plays an important role in shaping the soil weed seed bank community; however, this may depend on other associated crop management practices such as weeding.

4.6 | Influence of Weed Management on the Weed Seed Bank Size and Composition

The timing of first weeding played a pivotal role in minimizing the weed seed bank size and reducing species richness, evenness, and diversity. Early weeding effectively reduced the weed seed bank size and diversity, while delayed weeding increased the weed seed bank size. Early weeding at 2 WACE was associated with lower WSDs and reduced floristic diversity, suggesting that controlling weeds that germinate together with the crop may effectively reduce weed seed deposits in the seed bank. Similar recommendations were given by Page et al. [54], who reported the importance of early season weed control. Maqsood et al. [55] demonstrated that early weeding at 20 days after sowing (DAS), coupled with another weeding at 40 DAS, was effective in depleting the seed bank. Therefore, early season weed control is important in interrupting weed reproduction and seed set, thus limiting

weed seed bank expansion. This implies that controlling weeds early before they reproduce will help reduce the amount of weed seed rain that is deposited into the soil weed seed bank. Weeding frequency impacted the weed seed bank size and its composition, with more frequent weeding effectively suppressing the weed seed bank build-up. Our results align with the findings of Dereje et al. [56], who observed that hand weeding four times per season reduced the weed density in maize production systems. Frequent weeding reduces weed seed deposits into the soil weed seed bank, limiting future weed infestations. Mashavakure et al. [24] demonstrated that weeding four times and maintaining clean weeded plots was effective for reducing seed bank densities of *A. hybridus* and *G. parviflora*. This approach managed to suppress weed seed accumulation in the seedbank over time. These findings highlight the role of timely and sustained weed management in limiting weed seed rain and accumulation in the soil seed bank. Farmers can benefit from effective weed management when complemented with other crop management practices that reduce reliance on frequent hand weeding, especially on farms where labor shortages exist.

4.7 | Relationship Between Crop Management Practices and the Floristic Composition of the Weed Seed Bank

In this study, the AER was an important driver in the floristic composition of weed seed banks on smallholder farms. This result concurs with the findings of Romaneckas et al. [26], who reported that environmental conditions had stronger impacts on weed seed bank distribution than tillage practices in *Vicia faba* L. cultivation. The results from the study indicate that climatic variation shapes the weed community composition by selecting weeds with traits that adapt them to specific environments [3]. Certain weeds such as *Ceratotheca sesamoides* and *Phyllantus pentandrus* are adapted to specific environmental conditions, such as high temperatures and low precipitation, and they dominated seed banks in drier environments of AER 4. Temperature and moisture availability are important requirements for breaking dormancy and germination of weed seeds [57]. Understanding climatic factors that favor weed proliferation is essential in predicting weed community shifts and allows for the development of ecologically informed weed management strategies. These strategies can be precisely tailored to control problematic species within the agroecosystem, minimizing soil seed bank replenishment and improving overall crop production.

5 | Conclusion

The objective of this study was to investigate the influence of crop management practices on the weed seed bank size and composition in farmer-managed fields across an agroclimatic gradient in Zimbabwe. The AER was an important driver in the floristic composition of weed seed banks. The weed seed bank size and composition are influenced by crop management practices that are currently in use on smallholder farms in north-eastern Zimbabwe. Minimum tillage, both organic and inorganic fertilization, early weeding, and frequent weeding reduced the seed bank size, species richness, evenness, and diversity. Other crop management practices including crop rotations, mulching, and intercropping were not effective in reducing the WSD and diversity. The findings of this study highlight that soil weed seed banks can be managed through the implementation of crop management practices already accessible on smallholder farms. By optimizing these established techniques, farmers can improve weed control and minimize weed seed bank accumulation. Smallholder farmers are encouraged to prioritize early and repeated weeding throughout the season to prevent weed seed replenishment. Soil fertilization using fertilizers and manure and the adoption of minimum tillage methods such as planting basins should be recognized for their gradual benefits through long-term depletion of shallow seed reserves. Strengthening farmer training on timely weeding and low-intensity tillage and ensuring access to inputs such as diverse crop seed and fertilizers would enhance adoption and support integrated weed seed bank management strategies.

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Disclosure

The contents of this document are the sole responsibility of the authors and can under no circumstances be regarded as reflecting the position of the European Union.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information.** Table S1 shows the soil texture characterization results of all the soil samples used in the study.