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Strip Tillage and Crop Residue Retention Decrease the Size but Increase the Diversity of the Weed Seed Bank under Intensive Rice-Based Crop Rotations in Bangladesh

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Abstract: Cropping under conservation agriculture (CA) has become increasingly attractive among farmers in recent years. However, weed control may be more difficult during the transition to CA from conventional establishment methods due to the reduction in tillage intensity. Conversely, CA changes to weed dynamics can alter the weed seed bank in the longer run. In Bangladesh's intensively cropped rice-based rotations, the nature of weed seed bank shifts over time after adopting CA are poorly known. Two 2-year studies were sampled from on-farm CA experiments under wheat-mungbean-winter rice and monsoon rice-mustard-winter rice rotations. We investigated the effects of reduced soil disruption in the form of strip-tillage (ST) combined with increased deposition of standing reside from previous crops (0 vs. 50%). The weed seed bank in 0–5, 5–10, and 10–15 cm depths of soil were quantified in a shade-house experiment by measuring weed emergence over 12 months in seedling trays. After 2 years of field study, the year-round count of emerged weeds from the seed bank showed that ST plus 50% mulch had a lower weed abundance and biomass and fewer weed species than that of conventional tillage (CT) without residue. The perennial weeds *Ageratum conyzoides* L., *Alternanthera philoxeroides* L., *Cynodon dactylon* L., *Cyperus rotundus* L., *Jussia decurrence* Walt., *Leersia hexandra* L., *Scirpus mucronatus* (L.) Palla., and *Solanum torvum* Sw. were enriched in the smaller-sized ST seed banks in terms of both density and biomass. The CT, on the other hand, was dominated by annual weeds: *Cyperus difformis* L., *Cyanotis axillaris* Roem., *Echinochloa crus-galli* (L.) Beauv., *Eleusine indica* L., *Fimbristylis miliacea* (L.) Vahl., and *Rotala ramosior* L. Overall, ST plus 50% residue had a more diverse seed bank than CT without mulch. The majority of weed seeds were amassed in the 0–5 cm soil depth of the ST, while most of them were accumulated in the 10–15 cm layer of the CT. The wheat-mungbean-winter rice rotation had a more diverse floristic composition with many more weed species than the monsoon rice-mustard-winter rice rotation.

Keywords: annual weed; conventional tillage; residue mulching; perennial weeds

1. Introduction

Farmers embracing conservation agriculture (CA) in the intensive rice-based cropping patterns in the Eastern Gangetic Plain confront several challenges. The reduction or absence of plowing makes weed management one of the most difficult problems to solve when first adopting CA. Thereafter, the emergence, proliferation, and distribution of weeds and their seeds within the soil will differ in CA relative to traditional plowing systems [1].

Weeds are generally replenished over time from the soil seed pool, usually termed the weed seed bank. The weed seed bank is a storehouse from which weed infestation occurs in the field, and it consists of aboveground weed flora and viable, dormant, or dead seeds. Since it is the most important source of weeds in the crop field, it is the most challenging aspect of crop weed ecology, representing a critical focus for the control of weeds [2]. The weed seed bank also acts as the record of past weed management success or failure in cropping systems. Some previous studies reported that the composition, density, and diversity of weed seed banks are influenced by cropping [3,4]. Due to these connections, knowing the weed seed bank is much more critical for improving sustainable weed management for crop production. Weed seed germination, development, and competition against crops are all influenced by various habitat, environmental, and agrotechnical factors [5,6].

Tillage is the most significant agronomic practice affecting the weeds in conventional fields [7,8]. By contrast, CA reduces the intensity and extent of soil disturbance. The reduced tillage (RT) encourages the richness of perennial broadleaf, grass, and sedge weeds relative to the annual species [9]. Tubers, rhizomes, bulbs, and stolon are the most common sources of reproduction for perennial weeds. RT does not destroy these reproductive organs present underground in soil by not burying to depths or displacing and them [10]. According to Woźniak [11], reduced tillage increases the grassy annual weeds and the opposite of dicotyledonous weeds. Moreover, tillage simplifications favor the abundance of perennial grasses, wind disseminated species along with volunteer crops, and the elimination of annual grass and dicot species [12]. Furthermore, Naresh et al. [13] observed the no-till soils had far more *Amaranthus* weeds than plowed soils.

Reduced mechanical weed control opportunities in CA place more dependence on herbicides for control, but over time this may lead to increased resistance in monocots and dicots weeds [14,15]. In addition, herbicide persistence soils may restrict crop choice in rotations, especially when an herbicide is potentially toxic to the next crop in rotation [16]. Other agronomic practices, such as the retention of previous crops' residues in crop rotational and optimum crop density, may be combined with the herbicides for integrated weed control in the RT practice of CA.

The residues from previous crops hamper weed seeds and seedlings by introducing physical barriers and interfering with sunlight interception and changes in soil temperature. Surface residues reduce soil temperature that will slow germination [17]. Shading of emerged weed seedlings produces smaller and less vigorous plants [18]. In addition, increased residue retention may stimulate microbial populations and seed predation, which depletes the weed seed bank [19].

Crop rotations affect seed banks by changing weed control options, including herbicide rotation from different modes of action in successive crops. There are more chances for effective weed control in rotations than in monocultures due to variations in crop and weed management methods. In a rotational cropping system, different crops with different planting dates alter the timing of field operations, which tends to be important in minimizing weed emergence and seed bank size [2,20].

Understanding the effect of CA practices—applying herbicides, reduced soil disturbance, and mulching residues of previous crops in a rotational system—on the dynamics of weed seed banks is a crucial first step in strengthening CA's weed control strategies. Farmers/crop growers need to know weed control systems that would improve productivity and effectiveness, including understanding the weed seed bank's behavior to the aboveground weed population. Since it is well understood that the tillage system, weed control, and the influence of the climate all affect weed seed banks, the inadequacy of seed bank studies in Bangladesh's Eastern Gangetic Plain poses a significant knowledge gap for farmers in the region. The present study was therefore undertaken to understand the proliferation, composition, and distribution of weed seed banks due to different tillage systems and the retention of different volumes of standing stubble residues of the previous crops in the rotation under CA in Bangladesh.

2. Materials and Methods

2.1. The Glimpse of the Field, Crops, and Climate of on-Farm CA Experiments

Two crop establishment systems were implemented during the field study between 2014 and 2016: intensive conventional tillage (CT) and single-pass strip-tillage (ST). Two levels of residue mulching, no-mulch (R_0) vs. 50% standing mulch (R_{50}), were applied with each of the tillage types. The sequence of wheat, mungbean, and monsoon rice crops was followed in one rotation, while monsoon rice, mustard, and winter rice crop were in the other rotation on separate fields situated at the Durbachara zone of Bangladesh (N: 24.75° and E: 90.50°).

The Sonatala sequence of dark grey non-calcareous alluvium soils characterize the Old Brahmaputra Floodplain soil of this study. Sand, silt, and clay comprised 25, 72, and 3%, respectively, in the soil silty loam texture. Composite soil samples were collected from every plot and prepared for chemical analysis. Standard operating procedures [21] were followed to analyze the chemical properties at the Soil Science Laboratory of Bangladesh Agricultural University, Mymensingh, Bangladesh. Approximately 0.990% organic matter was found in the soil. The chemical properties of the soil of the experimental field are shown in Table 1.

Table 1. The chemical properties of soil (0–15 cm) of the experimental field.

Properties	Values
pH	6.69
Total nitrogen (%)	0.11
Available phosphorus (mg kg^{-1})	16.2
Exchangeable potassium (cmol kg^{-1})	0.31
Available sulfur (mg kg^{-1})	14.0

The site experiences a subtropical climate with elevated temperatures, high humidity, and heavy monsoon rains in April–September and low precipitation plus relatively low temperatures in October–March. The mean maximum and minimum temperatures were 29.9 and 21.4 °C, respectively, with an estimated annual gross precipitation of 2016 mm (Figure 1). During April–June, the mean temperature ranges from 32.3−33.5 °C. Between April and September, there was 90% rainfall.

Every year, the same sequence of crops were grown in the same plot with the same treatments. The size of each plot was 9 × 5 m.

2.2. Methods of Land Preparation

A two-wheel tractor (2 WT) was used to perform the CT, which included four rotary tillage passes and cross plowing, followed by two days of sun drying (in wheat, mungbean, and mustard), and finally inundation and leveling (in rice). The ST was done by a versatile multi-crop planter (VMP) in a single pass operation. Strips were prepared for four rows, each of 6 cm wide and 5 cm deep made at a time. Before the VMP operation, glyphosate herbicide was sprayed at 3.7 L per hectare to kill the existing weeds. The land was inundated for 24 h to make the land soft enough, and rice seedlings were transplanted on the raised furrows. Wheat, mustard, and mungbean were sown simultaneously at the time of VMP operation [22].

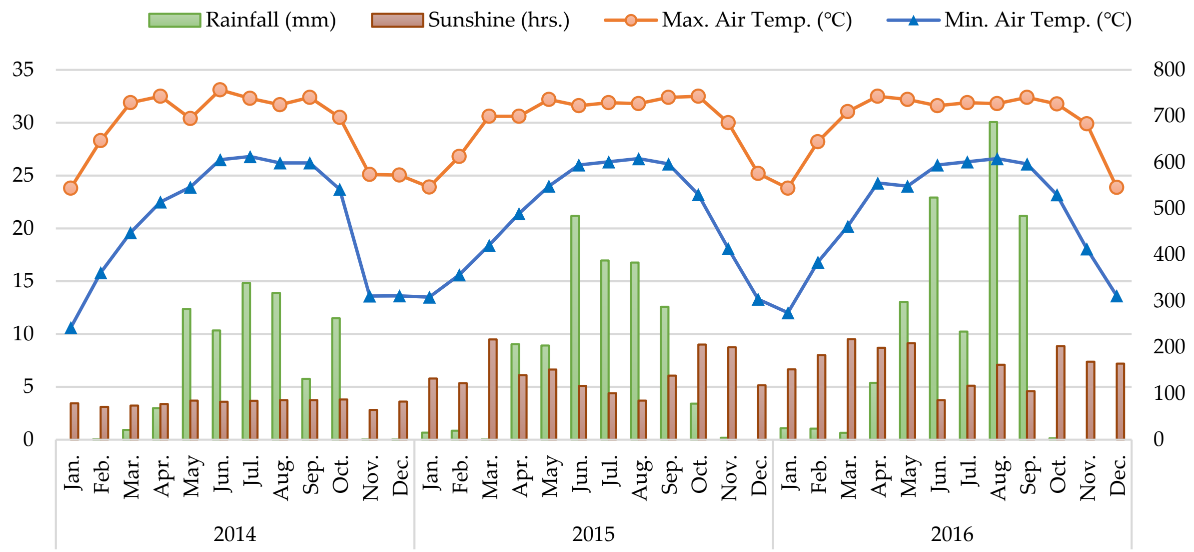

Figure 1. Monthly average temperatures, precipitation, and daylight hours in 2014–2016 of the Durbachara zone of Bangladesh.

2.3. Mulching of Crop Residues

We used two levels of residue mulching: no-residue and 50% standing residue. The previous crop was cut at the ground level, and all plant parts were removed for no-residue treatment. On the other hand, crops were harvested at 50% height from the ground level of the crop plant for 50% residue treatment.

2.4. Weeding Methods

Weeds that emerged during the growth of each crop in CT were managed by hand weeding (HW). HW was performed in rice and wheat at 25, 45, and 65 DAT/DAS and in mungbean and mustard at 25 and 45 DAS. In the field of ST, weed was controlled using specific herbicides for rice, wheat, mustard, and mungbean, as listed in Table 2. Except for ethoxysulfuron-ethyl, the rest of all herbicides were applied when the soil was close to field capacity moisture content.

Table 2. List of herbicides used to control weeds in different crops under ST.

Herbicides	Crop	Application Rate of Product (ha^{-1})	Time of Application [1]
Glyphosate	All crops	3.7 L	3 DBS/T
Pendimethalin	All crops	2.7 L	3 DAT/S in rice and wheat IAS in mustard and mungbean
Ethoxysulfuron-ethyl	Rice	100 g	3 WAT
Carfentrazone-ethyl + isoproturon	Wheat	1.25 kg	3 WAS
Isoproturon	Mustard	650 mL	3 WAS
Fenoxaprop-p-ethyl	Mungbean	650 mL	3 WAS

[1] DBS/T: Days before seeding/transplanting, DAT/S: Days after seeding/transplanting, IAS: Immediately after seeding, WAT/S: Weeks after transplanting/seeding.

2.5. Analysis of Soil Weed Seed Bank

The status of the weed seed bank of the experimental soil was determined using the "seedling emergence" approach at the shade house of Bangladesh Agricultural University, Mymensingh, Bangladesh. Samplings of soil were done two times: i. Initial sample: before starting the field CA trials in 2014, and ii. Final sample: after 2 years of CA trials in 2016.

In each plot, 5 cores of soil using an 8-cm-diameter stainless steel cylinder were recovered from 0–5 cm, 5–10 cm, and 10–15 cm soil depths following the "W" shape sampling pattern [23]. Subsamples from each plot were then mixed, and roughly 1 kg of soil was deposited in 33 cm diameter pots. The pots were put in the shade house using an entirely random pattern that was repeated four times. The pots were watered daily using a sprinkler irrigation system. All sprouting weeds were uprooted at 45 days after emergence (DAE) and counted by species and by group (grass, broadleaf, and sedge). After counting, weeds oven dried for 72 h at 70 °C temperature for a biomass measurement. Following the uprooting of each cohort of seedlings, soils were air dried, thoroughly mixed, and rewetted to allow for additional emergence. The additional emergence weed count and biomass were again measured at 45 DAE as described above until the emergence continued. The total number of emerged weeds were reported in m^{-2} basis.

2.6. Indicators of Diversity, Dominance, and Similarity

The composition of the weed seed bank was examined by calculating the values of the following indicators:

Shannon's Diversity Index, $H' = -\sum Pi \ ln \ Pi$ [24].

Simpson's Dominance Index, $SI = \sum Pi^2$ [25], here, Pi denotes the chance of species occurrence in the sample.

The dominant weed species was determined by calculating the importance value (IV) of species using the following formula [26].

$$IV\ (\%) = \frac{Number\ of\ each\ species}{Total\ number\ of\ all\ species} \times 100$$

To compare the similarity of the seed bank in different treatments, we used the Sørensen's similarity index (%) [27]

$$\text{Sørensen's similarity index } (\%) = [2C/(A+B)] \times 100$$

where A and B are the number of species in the 1st and 2nd community, and C is the number of common species in the two communities.

2.7. Data Analysis

We used *STAR* software to analyze data following two-way ANOVA and Duncan's multiple range test [28].

3. Results

3.1. Analysis of Weed Species Composition in the Seed Bank

3.1.1. Weed Species Composition at 0–5 cm Soil Depth

The initial seed bank produced 33 weed species. Twenty-one were broadleaf species, six grasses and six sedges comprising 19 annual and 14 perennial weeds (Table 3). *Echinochloa crus-galli* (L.) Beauv. was the most dominant species, followed by *Cyperus difformis* L., *Cyanotis axillaris* Roem., *Jussia decurrence* Walt., and *Fimbristylis miliacea* (L.) Vahl. (Figure 2).

Table 3. Composition of initial and final soil seed bank at 0–5 cm depth under different treatments (average for wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice rotation).

Weed Species	Type	Ontogeny	Initial Seed Bank (Seeds m^{-2})	Final Seed Bank (Seeds m^{-2})			
				CT R_0	CT R_{50}	ST R_0	ST R_{50}
Ageratum conyzoides L.	B	P	170	194	169	239	Absent
Alternanthera sessilis L.	B	P	173	203	184	181	168
A. philoxeroides L.	B	P	160	190	165	157	146
A. spinosus L.	B	A	136	141	122	114	Absent
Amaranthus viridis L.	B	A	118	157	136	Absent	Absent

Table 3. *Cont.*

Weed Species	**Type**	**Ontogeny**	**Initial Seed Bank (Seeds m^{-2})**	**Final Seed Bank (Seeds m^{-2})**			
				CT R_0	**CT R_{50}**	**ST R_0**	**ST R_{50}**
Brassica kaber L.	B	A	89	136	147	Absent	Absent
Centipeda minima Lour.	B	P	Absent	103	89	125	116
Cyanotis axillaris Roem.	B	A	288	94	167	186	Absent
Cynodon dactylon L.	G	P	129	Absent	201	234 ^{v}	315
Cyperus difformis L.	S	A	348	381 ^{iii}	337	148	137
C. iria L.	S	A	209	123	Absent	Absent	110
C. rotundus L.	S	P	161	259	112	303 ^{ii}	381
Dentella repens L.	B	P	142	142	123	Absent	Absent
Desmodium triflorum L.	B	P	116	124	108	Absent	Absent
Digitaria sanguinalis L.	G	A	137	154	134	Absent	231
Echinochloa crus-galli (L.) Beauv.	G	A	351	512 ^{i}	445	169	157
E. colonum L.	G	A	Absent	131	114	Absent	184
Eclipta alba L.	B	A	98	166	145	Absent	Absent
Eichhornia crassipes Mart.	B	P	102	188	163	135	146
Eleocharis atropurpurea Ret.	S	A	83	47	Absent	Absent	Absent
Eleusine indica L.	G	A	165	208	179	Absent	127
Euphorbia parviflora L.	B	A	104	150	129	Absent	Absent
Fimbristylis miliacea (L.) Vahl.	S	A	275	302 ^{iv}	258	253 ^{iv}	214
Gnaphalium luteo-album L.	B	A	99	Absent	Absent	Absent	Absent
Hedyotis corymbosa L.	B	A	144	202	175	Absent	Absent
Jussia decurrence Walt.	B	P	261	490 ^{ii}	426	356 ^{i}	330
Leersia hexandra L.	G	P	196	236	209	271 ^{iii}	252
Lindernia antipoda L.	B	A	139	134	Absent	Absent	212
L. hyssopifolia L.	B	A	103	113	Absent	Absent	209
Marsilea quadrifolia L.	B	A	122	152	Absent	110	102
Monochoria hastate L.	B	P	115	163	187	157	146
Nicotina plumbaginifolia L.	B	A	174	217	198	141	Absent
Panicum distichum L.	G	P	73	Absent	Absent	158	133
Physalis heterophylla Nees.	B	A	Absent	Absent	167	Absent	Absent
Pistia stratiotes L.	B	P	163	132	114	123	Absent
Polygonum coccineum L.	B	A	Absent	173	150	Absent	Absent
Rotala ramosior L.	B	A	Absent	213	185	Absent	Absent
Scirpus mucronatus (L.) Palla.	S	P	199	Absent	121	198	Absent
S. juncoides L.	S	P	Absent	99	86	137	Absent
S. supinus L.	S	P	Absent	274 ^{v}	238	119	Absent
Solanum torvum Sw.	B	P	Absent	Absent	Absent	171	Absent
Spilanthes acmella L.	B	A	Absent	227	198	Absent	Absent
Total number of species			33	36	34	24	19
Shannon's diversity index (*H'*)			3.41	3.47	3.44	3.07	2.92
Simpson's dominance index (*SI*)			0.36	0.34	0.35	0.49	0.58

B: Broadleaf, G: Grass, S: Sedge, A: Annual, P: Perennial, CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue, i–v in final seed bank coloums: five most dominant species.

After 2 years of trial, the CT without residue produced 36 species: 24 broadleaves, 5 grass, and 7 sedge types, consisting of 23 annuals and 13 perennials (Table 3). Three species, *Gnaphalium luteo-album* L., *Cynodon dactylon* L., *Panicum distichum* L., and *Scirpus mucronatus* (L.) Palla., disappeared, but eight species, *Centipeda minima* Lour., *Physalis heterophylla* Nees., *Polygonum coccineum* L., *Rotala ramosior* L. *Spilanthes acmella* L., *Echinochloa colonum* L., *Scirpus juncoides* L., and *S. supinus* L., were new in the seed bank after 2 years. *Echinochloa crus-galli* (L.) Beauv., *Jussia decurrence* Walt., *Cyperus difformis* L., *Fimbristylis miliacea* (L.) Vahl., and *Scirpus supinus* L. were the most dominant weeds here.

On the other hand, the ST + 50% residue generated only 19 weed species in the seed bank comprising nine broadleaves, six grass, and four sedge types. Among them, 10 were annuals and 9 perennials (Table 3). Compared to initial seed bank, 14 species, *Ageratum conyzoides* L., *Amaranthus spinosus* L., *A. viridis* L., *Brassica kaber* L., *Cyanotis axillaris* Roem., *Dentella repens* L., *Desmodium triflorum* L., *Eclipta alba* L., *Eleocharis atropurpurea* Ret., *Euphorbia parviflora* L., *Gnaphalium luteo-album* L., *Nicotina plumbaginifolia* L., *Pistia stratiotes* L., and *Scirpus mucronatus* (L.) Palla., were not found after 2 years, but two species, *Centipeda minima* Lour. and *Echinochloa colonum* L., were introduced after 2 years. We found *Jussia decurrence* Walt., *Cyperus rotundus* L., *Leersia hexandra* L., *Fimbristylis miliacea* (L.) Vahl., and *Cynodon dactylon* L. were the most dominant perennial species.

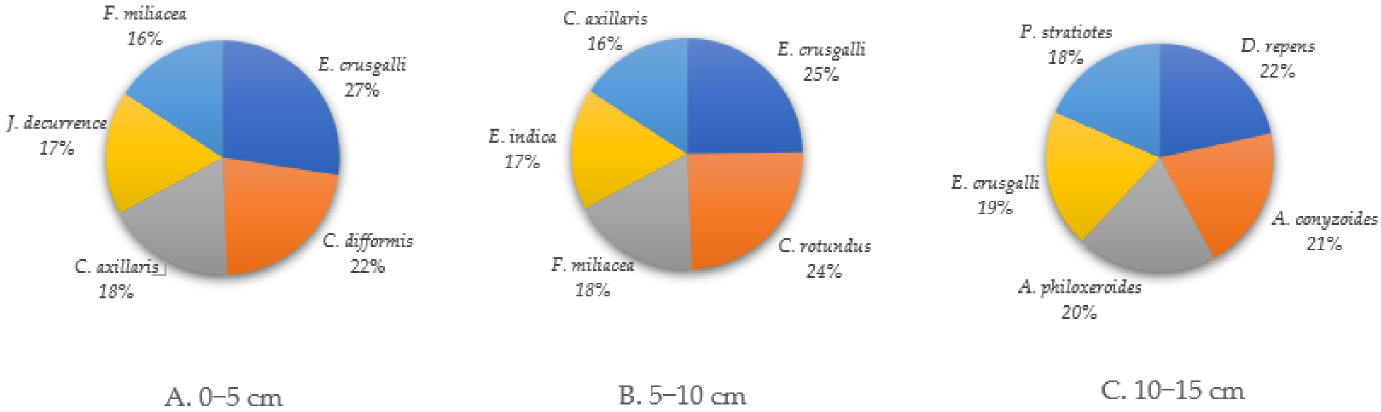

Figure 2. Five most dominant weed species based on the importance value at (**A**) 0−5 cm, (**B**) 5−10 cm, and (**C**) 10−15 cm soil depth of initial soil seed bank in 2014.

Retention of 50% residue both with the CT and ST reduced the species number by two fewer species in CT + 50% residue (34 species) and by five fewer species in ST + 50% residue (19 species) relative to no-residue after 2 years (Table 3).

3.1.2. Weed Species Composition at 5–10 cm Soil Depth

We found 30 species from the initial seed bank, of which 20 were broadleaf species, six grasses and four sedges comprising 15 annuals and 12 perennials (Table 4). The five most dominant species were *Echinochloa crus-galli* (L.) Beauv, *C. rotundus* L., *Fimbristylis miliacea* (L.) Vahl., *Eleusine indica* L., and *Cyanotis axillaris* Roem. (Figure 2).

Table 4. Composition of initial and final soil seed bank at 5–10 cm depth under different treatments (on average for wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice rotation).

Weed Species	Type	Ontogeny	Initial Seed Bank (Plants m^{-2})	Final Seed Bank (Plants m^{-2})			
				CT R_0	CT R_{50}	ST R_0	ST R_{50}
Ageratum conyzoides L.	B	P	89	128	110	137	127
Alternanthera sessilis L.	B	P	71	120	133	149	138
A. philoxeroides L.	B	P	64	115	115	115	92
A. spinosus L.	B	A	78	99	125	103	91
Amaranthus viridis L.	B	A	67	112	129	136	Absent
Brassica kaber L.	B	A	125	81	178	Absent	Absent
Centipeda minima Lour.	B	P	Absent	139	123	157	146
Cyanotis axillaris Roem.	B	A	117	234 [iv]	195	116	Absent
Cynodon dactylon L.	G	P	105	Absent	Absent	Absent	Absent
Cyperus difformis L.	S	A	125	91	188	172	160
C. iria L.	S	A	185	108	80	Absent	Absent
C. rotundus L.	S	P	307	292 [ii]	180	324 [ii]	301
Dentella repens L.	B	P	136	84	103	Absent	Absent
Desmodium triflorum L.	B	P	116	97	115	Absent	Absent
Digitaria sanguinalis L	G	A	131	127	160	Absent	Absent
Echinochloa crus-galli (L.) Beauv.	G	A	352	363 [i]	334	249 [iii]	232
E. colonum L.	G	A	Absent	197	107	Absent	Absent
Eclipta alba L.	B	A	117	73	101	88	107

Table 4. *Cont.*

Weed Species	Type	Ontogeny	Initial Seed Bank (Plants m^{-2})	Final Seed Bank (Plants m^{-2})			
				CT R_0	CT R_{50}	ST R_0	ST R_{50}
Eichhornia crassipes Mart.	B	P	124	111	189	99	111
Eleusine indica L.	G	A	225	263 [iii]	152	235	218
Euphorbia parviflora L.	B	A	95	140	193	Absent	Absent
Fimbristylis miliacea (L.) Vahl.	S	A	253	224 [v]	115	115	82
Jussia decurrence Walt.	B	P	227	120	93	179	166
J. repens L.	B	P	94	119	70	107	99
Leersia hexandra L.	G	P	110	135	107	371 [i]	345
Lindernia antipoda (L.) Aston.	B	A	81	226	Absent	121	Absent
L. hyssopifolia L.	B	A	125	79	Absent	71	Absent
Panicum distichum L.	S	P	87	Absent	Absent	Absent	Absent
Pistia stratiotes L.	B	P	112	67	197	Absent	Absent
Polygonum coccineum L.	B	A	99	102	164	Absent	Absent
Rotala ramosior (L.) Koch.	B	A	219	97	134	Absent	Absent
Scirpus mucronatus (L.) Palla.	S	P	Absent	Absent	Absent	225 [iv]	209
S. juncoides L.	S	P	Absent	119	147	Absent	Absent
Solanum torvum Sw.	B	P	77	63	122	215 [v]	199
Total number of species			27	31	29	21	17
Shannon's diversity index (*H'*)			3.18	3.32	3.31	2.94	2.77
Simpson's dominance index (*SI*)			0.47	0.41	0.38	0.58	0.71

B: Broadleaf, G: Grass, S: Sedge, A: Annual, P: Perennial, CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue, i–v in final seed bank coloums: five most dominant species.

After 2 years of field study, the ST + 50% residue produced 17 species comprising 10 broadleaves, 3 grasses, and 4 sedges. Among them, 11 were perennials and 6 annuals (Table 4). A total of 17 species, *Amaranthus viridis* L., *Brassica kaber* L., *Cyanotis axillaris* Roem., *Cynodon dactylon* L., *Cyperus iria* L., *Dentella repens* L., *Desmodium triflorum* L., *Digitaria sanguinalis* L., *Echinochloa colonum* L., *Euphorbia parviflora* L., *Lindernia antipoda* (L.) Aston., *L. hyssopifolia* L., *Panicum distichum* L., *Pistia stratiotes* L., *Polygonum coccineum* L., *Rotala ramosior* (L.) Koch., and *Scirpus juncoides* L., of the initial seed bank disappeared, but *Centipeda minima* Lour. and *Scirpus mucronatus* (L.) Palla. were newly recorded after 2 years. *Leersia hexandra* L., *Cyperous rotundus* L., *Echinochloa crus-galli* (L.) Beauv., *Scirpus mucronatus* (L.) Palla., and *Solanum torvum* Sw. were the most dominant species in the seed bank.

By contrast with the CA system, under the CT + no-residue, the seed bank was comprised of 31 species consisting of 21 broadleaves, 5 grasses, and 5 sedges, of which 19 were annuals and 12 perennials (Table 4). *Cynodon dactylon* L. and *Panicum distichum* L. were not found in the seed bank after 2 years, but three species, *Centipeda minima* Lour., *Echinochloa colonum* L., and *Scirpur juncoides* L., were introduced after 2 years. Five species, *Echinochloa crus-galli* (L.) Beauv., *C. rotundus* L., *Eleusine indica* L., *Cyanotis axillaris* Roem., and *Fimbristylis miliacea* (L.) Vahl., were the most dominant.

The retention 50% residues produced two fewer species in CT (29 species) but four less in ST (17 species) than the no-residue (Table 4).

3.1.3. Weed Species Composition at 10–15 cm Soil Depth

The deepest soil samples at 10–15 cm depth generated 19 weed species, including 13 broadleaves, 3 grasses, and 3 sedges. Here, 11 were annual and 8 perennial species (Table 5) with the 5 most dominant weeds, *Dentella repens* L., *Alternanthera philoxeroides* L., *Ageratum conyzoides* L., *Pistia stratiotes* L., and *Echinochloa crus-galli* (L.) Beauv., recorded (Figure 2).

Table 5. Composition of initial and final soil seed bank at 10–15 cm depth under different treatments (average for wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice rotation).

Weed Species	Type	Ontogeny	Initial Seed Bank (Seeds m^{-2})	Final Seed Bank (Seeds m^{-2})			
				CT R_0	CT R_{50}	ST R_0	ST R_{50}
Ageratum conyzoides L.	B	P	117	95 ii	100	97 v	74
A. philoxeroides L.	B	P	92	19	64	114 iv	73
Alternanthera sessilis L.	B	P	84	78	57	75	66
Amaranthus viridis L.	B	A	51	74	85	Absent	Absent
C. rotundus L.	S	P	82	74	58	109 i	167
Cynodon dactylon L.	G	P	63	67	70	173 ii	59
Cyperus difformis L.	S	A	99	88	69	Absent	Absent
Dentella repens L.	B	P	103	28	73	96	51
Desmodium triflorum L.	B	P	97	81	73	Absent	69
E. colonum L.	G	A	74	87	54	97	Absent
Echinochloa crus-galli (L.) Beauv.	G	A	68	81 i	129	69	48
Eichhornia crassipes Mart.	B	P	62	55	34	85	31
Euphorbia parviflora L.	B	A	86	79	85	Absent	Absent
Fimbristylis miliacea (L.) Vahl.	S	A	69	93	44	67	43
Jussia decurrence Walt.	B	P	53	84v	77	118 iii	96
Lindernia antipoda (L.) Aston.	B	A	111	73	82	Absent	Absent
Physalis heterophylla Nees.	B	A	120	30	Absent	Absent	Absent
Pistia stratiotes L.	B	P	112	89	54	62	Absent
Rotala ramosior (L.) Koch.	B	A	75	79iv	83	Absent	Absent
Scirpus mucronatus (L.) Palla.	S	P	Absent	62 iii	119	72	62
Total number of species			19	20	19	14	12
Shannon's diversity index (*H′*)			2.91	2.93	2.89	2.49	2.44
Simpson's dominance index (*SI*)			0.55	0.54	0.57	0.91	0.90

B: Broadleaf, G: Grass, S: Sedge, A: Annual, P: Perennial, CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue, i–v in final seed bank coloums: five most dominant species.

After 2 years under CT + no-residue, the final seed bank generated 20 species consisting of 13 broadleaves, 3 grasses, and 4 sedges of which there were 12 annuals and 8 perennials (Table 5). In addition to all the initial seed pool species, *Scirpus mucronatus* (L.) Palla. was introduced. We found that *Echinochloa crus-galli* (L.) Beauv., *Ageratum conyzoides* L., *Scirpus mucronatus* (L) Palla., *Rotala ramosior* (L.) Koch., and *Jussia decurrence* Walt. were the most dominant species.

On the other hand, in ST + 50% residue, 12 species were six broadleaves, three grasses, and three sedges with only three annuals and nine perennials (Table 5). Relative to the initial seed bank, eight species, *Amaranthus viridis* L., *Cyperus difformis* L., *Echinochloa colonum* L., *Euphorbia parviflora* L., *Lindernia antipoda* (L.) Aston, *Physalis heterophylla* Nees., *Pistia stratiotes* L., and *Rotala ramosior* (L.) Koch., were not found after 2 years, but *Scirpus mucronatus* (L.) Palla. Was newly emerged. *Cyperus rotundus* L. was the most dominant species, followed by *Cynodon dactylon* L., *Jussia decurrence* Walt., *Alternanthera philoxeroides* L., and *Ageratum conyzoides* L.

Mulching of 50% residues produced two fewer species in ST (12 species) but one less in CT (19 species) than no-residue: 14 and 20 species, respectively (Table 5).

3.2. Effect of Tillage Practices and Residue Levels on Shannon's Diversity Index (H′), Simpson's Dominance Index (SI), and SØrensen's Similarity Index of the Seed Bank

The greatest diversified weed seed bank composition was found at the 0–5 cm soil depth (Table 3) followed by 5–10 cm depth (Table 4) and 10–15 cm depth (Table 5), both in the initial and final seed bank. Two years' continuous CT practice increased Shannon's diversity index and reduced the value of Simpson's domination index, which was opposite in ST. Hence, CT's final seed bank was more diversified, and ST was less diversified than the initial seed bank. The more diversified seed bank of CT was enriched with mostly annual weeds species, *Echinochloa crus-galli* (L.) Beauv., *Cyperus difformis* L., *Fimbristylis miliacea* (L.) Vahl., *Eleusine indica* L., *Cyanotis axillaris* Roem., and *Rotala ramosior* L., while the less diversified ST seed bank was dominated by specific perennial species, *Jussia decurrence* Walt., *Cyperus rotundus* L., *Leersia hexandra* L., and *Cynodon dactylon* L., *Scirpus mucronatus* (L.) Palla., *Solanum torvum* Sw., *Alternanthera philoxeroides* L., and *Ageratum conyzoides* L.

The 50% residue had a lower value of Shannon's diversity index and higher value of Simpson's domination index than no-residue, indicating a less diversified weed seed bank.

Overall, data revealed a higher value of Shannon diversity index (3.51) and lower value of Simpson dominance index (0.32) in the wheat-mungbean-monsoon rice rotation than that of the monsoon rice-mustard-winter rice rotation (3.47 and 0.32, respectively) (Table 6). The wheat-mungbean-monsoon rice rotation also had a higher number of weeds plants m^{-2} (6506) than the monsoon rice-mustard-winter rice rotation (5498 m^{-2}).

Table 6. Composition of final soil seed bank under wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice (on average for tillage, residue, and soil depths).

Weed Species	Type	Ontogeny	Wheat-Mungbean-Monsoon Rice Rotation	Monsoon Rice-Mustard-Winter Rice Rotation
Ageratum conyzoides L.	B	Perennial	182	150
Alternanthera sessilis L.	B	Perennial	194	166
A. philoxeroides L.	B	Perennial	178	150
A. spinosus L.	B	Annual	132	120
Amaranthus viridis L.	B	Annual	147	Absent
Brassica kaber L.	B	Annual	142	Absent
Centipeda minima Lour.	B	Perennial	96	129
Cyanotis axillaris Roem.	B	Annual	131	328
Cynodon dactylon L.	G	Perennial	101	165
Cyperus difformis L.	S	Annual	359	31
C. iria L.	S	Annual	62	67
C. rotundus L.	S	Perennial	186	108
Dentella repens L.	B	Perennial	133	Absent
Desmodium triflorum L.	B	Perennial	116	120
Digitaria sanguinalis L.	G	Annual	144	120
Echinochloa crus-galli (L.) Beauv.	G	Annual	479	238
E. colonum L.	G	Annual	123	65
Eclipta alba L.	B	Annual	156	136
Eichhornia crassipes Mart.	B	Perennial	176	166
Eleocharis atropurpurea Ret.	S	Annual	24	236
Eleusine indica L.	G	Annual	194	164
Euphorbia parviflora L.	B	Annual	140	152
Fimbristylis miliacea (L.) Vahl.	S	Annual	280	310
Gnaphalium luteo-album L.	B	Annual	Absent	160
Hedyotis corymbosa L.	B	Annual	189	150
Jussia decurrence Walt.	B	Perennial	458	163
Leersia hexandra L.	G	Perennial	223	310
Lindernia antipoda L.	B	Annual	67	161
L. hyssopifolia L.	B	Annual	57	191
Marsilea quadrifolia L.	B	Annual	76	151
Monochoria hastate L.	B	Perennial	175	139
Nicotina plumbaginifolia L.	B	Annual	208	153
Panicum distichum L.	G	Perennial	Absent	121
Physalis heterophylla Nees.	B	Annual	84	190
Pistia stratiotes L.	B	Perennial	123	55
Polygonum coccineum L.	B	Annual	162	161
Rotala ramosior L.	B	Annual	199	108
Scirpus mucronatus L.	S	Perennial	61	120
S. juncoides L.	S	Perennial	93	Absent
S. supinus L.	S	Perennial	256	Absent

Table 6. *Cont.*

Weed Species	Type	Ontogeny	Wheat-Mungbean-Monsoon Rice Rotation	Monsoon Rice-Mustard-Winter Rice Rotation
Solanum torvum Sw.	B	Perennial	Absent	55
Spilanthes acmella L.	B	Annual	213	Absent
Total number of species			39	33
Total number of plants m^{-2}			6506	5498
Shannon's diversity index (H')			3.51	3.47
Simpson's dominance index (SI)			0.32	0.35

B: Broadleaf, G: Grass, S: Sedge, A: Annual, P: Perennial, CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue.

In the topmost soil layer of the final seed bank, the similarity of the initial seed bank to final seed bank of CT reached 82% and to the final seed pool of ST reached 67% (Table 7). The ST had 60% of the same weeds as CT, and 50% of the residue generated 83% of the same weeds of no-residue in CT but just 31% in ST. Moreover, at 5–10 cm depth, the CT and ST generated 96 and 74% of the same species to the initial seed bank, respectively, while after 2 years there was 80% similarity in weed species between CT and ST. The similarity between weed species in the seed bank of 50% residue and the seed bank of no-residue in CT was 96% and in ST was 89%. Furthermore, at the deepest layer, CT and ST produced 98% and 71% of the same weeds. We found 75% similarity in weed species between CT and ST after 2 years. Mulching with 50% residue with CT and ST produced 97 and 86% similarity in weed species to no-residue, respectively.

Table 7. Effect of tillage practices and residue levels on the Sørensen's similarity index (%) of the initial and final seed bank.

Tillage at the Different Soil Depth		Initial Seed Bank	Final Seed Bank of CT	Final Seed Bank of ST
0–5 cm	Initial seed pool	-	82	67
	Final seed pool of CT	-	-	60
5–10 cm	Initial seed pool	-	96	74
	Final seed pool of CT	-	-	80
10–15 cm	Initial seed pool	-	98	71
	Final seed pool of CT	-	-	75
Crop residue at the different soil depth		Final seed bank of CT R_0	Final seed bank of ST R_0	
0–5 cm	Final seed bank of R_{50}	83	31	
5–10 cm	Final seed bank of R_{50}	96	89	
10–15 cm	Final seed bank of R_{50}	97	86	

CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue.

3.3. *Effect of Tillage and Residue Levels on the Weed Density (Plant m^{-2}) and Biomass (g m^{-2})*

In the final seed bank, the highest plant density of weeds was recorded in nonmulched CT at 10–15 cm depth, and the lowest was in 50% mulched ST at 10–15 cm depth. In the initial seed bank, the highest plant density of all types of weeds was recorded at 0–5 cm soil followed by 5–10 cm and 10–15 cm soil (Table 8). At all the depths, broadleaf plant density dominated over grass and sedge. Compared to the initial seed bank density, CT increased the density of broadleaf, grass, and sedges by about 16, 9, and 13%, respectively. On the other hand, the ST reduced the plant density of weeds by 25, 11, and 6%, respectively. Moreover, mulching of 50% residue both with CT and ST lowered plant density by about 4 and 18% relative to non-mulched, respectively. The suppression of broadleaf was more prominent in the topmost soil layer, followed by sedge and grass at 5–10 and 10–15 cm depths.

Table 8. Effect of tillage and residue levels on the weed density (plant m^{-2}) as a group at different soil depths (on average for wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice rotation) at 45 DAE.

Weed Type	Soil Depth (cm)	Initial Seed Bank (Seeds m^{-2})	Final Seed Bank (Seeds m^{-2})			
			CT R_0	CT R_{50}	ST R_0	ST R_{50}
Broadleaf	0–5	3016 a	850 g,h	896 g,h	2195 a	1708 b
	5–10	2233 b	2406 c,d	2589 c	1793 b	1276 c
	10–15	1163 c,d	4204 a	3647 b	585 g	517 g
Grass	0–5	1051 d	249 j	224 j,k	832 e	1266 c
	5–10	1010 d	1014 g	706 h	855 e	795 e,f
	10–15	205 f	1241 e,f	1282 e,f	339 h	107 j
Sedge	0–5	1275 c	317 i	290 i	1158 c,d	842 e
	5–10	870 e	905 g	864 g,h	836 e	752 f
	10–15	250 f	1485 e	1152 f	248 i	272 i
Standard Deviation		896.1	1229.8	1122.2	645.15	512.21
Standard Error		298.6	409.9	374.08	215.05	170.73
Coefficient of Variance (%)		72.83	87.35	86.69	65.67	61.18

CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue. The means with similar letters do not differ significantly at $p \leq 0.05$.

In the initial seed bank, the species number and plant density of annual weeds led over the perennials. After 2 years of the field trial, CT increased the number of species and density of annual weeds relative to the perennial weeds in the final seed bank. However, ST has increased the proportion of perennial weed density in the seed bank (Figure 3).

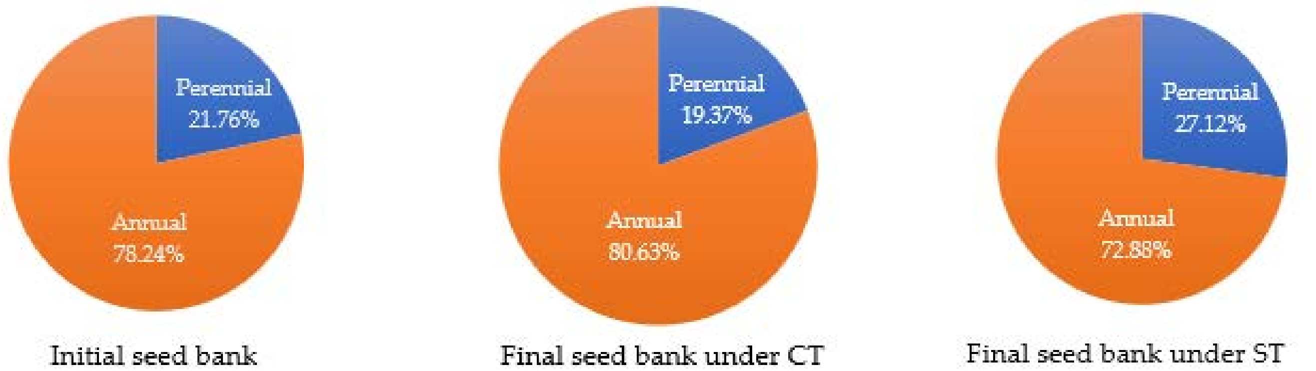

Figure 3. Percentage of annual and perennial weed species in the weed communities under different tillage systems (average for the depths and rotations).

We found the highest weed biomass at CT without residue and the lowest at ST plus 50% residue for soil at 10–15 cm depth (Table 9). Overall, data revealed that 2 years later, non-mulched CT had increased the weed biomass by 17%, but 50% mulch plus ST decreased biomass by 21% relative to the initial status. Mulching of 50% residue decreased biomass by 7% in CT and by 10% in ST. Broadleaf weeds produced the highest biomass, followed by the sedges and grasses at 0–5 cm depth, followed by 5–10 cm and 10–15 cm soil depth, in both the initial and final seed bank.

3.4. Effect of Tillage and Residue Levels on the Vertical Distribution of Weed Seeds

In the final seed bank, the CT had increased weed seed stock, while the ST decreased that relative to the initial status (Figure 4). In the ST field, most seeds were found at the topmost layer up to 5 cm, and their number decreased in line with the depth. On the other hand, the distribution of seeds in the CT's soil profile was reversed, where many seeds were recovered in the deeper layers of 5–15 cm. We found more evenly distributed seeds in CT throughout the 0–15 cm soil layer. Mulching 50% residue enriched the distribution of seeds at all the soil depths relative to no mulch, but the values were lower than that of the initial status (Figure 5).

Table 9. Effect of tillage and residue levels on the weed dry matter (g m^{-2}) as a group at different soil depths (average for wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice rotation) at 45 DAE.

Weed Type	Soil Depth (cm)	Initial Seed Bank (g m^{-2})	Final Seed Bank (g m^{-2})			
			CT R_0	CT R_{50}	ST R_0	ST R_{50}
Broadleaf	0–5	1719 a	484 e	510 d,e	1251 a	973 a
	5–10	1272 b	1371 c	1475 c	1022 b	727 b
	10–15	663 c	2396 a	2078 b	333 d,e	294 d,e
Grass	0–5	462 d	109 g,f	98 f	366 d	557 c
	5–10	444 d	446 e,f	310 f	376 d	349 d
	10–15	90 f	546 d,e	564 d	149 e,f	47 f
Sedge	0–5	599 c,d	148 g	136 g	544 c	395 d
	5–10	408 d	425 e	406 e,f	392 d	353 d
	10–15	117 e	697 d	541 d,e	127 e,f	116 e,f
Standard Deviation		532.16	722.71	661.08	384.21	289.28
Standard Error		177.38	240.90	220.36	128.07	96.42
Coefficient of Variance (%)		82.89	98.16	97.18	75.96	68.04

CT: Conventional tillage, ST: Strip tillage, R_0: No-residue, R_{50}: 50% residue. The means with similar letters do not differ significantly at $p \leq 0.05$.

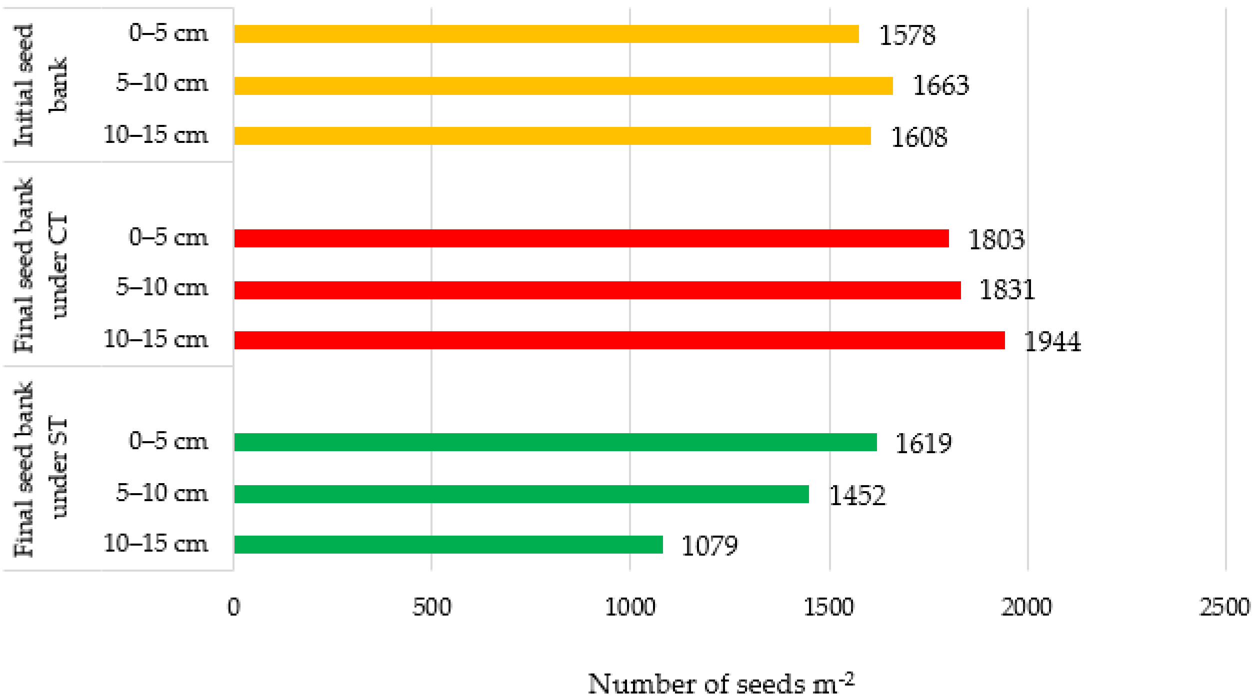

Figure 4. Vertical distribution of seeds at 0–5, 5–10, and 10–15 cm soil depth under different tillage (mean from two crop rotations).

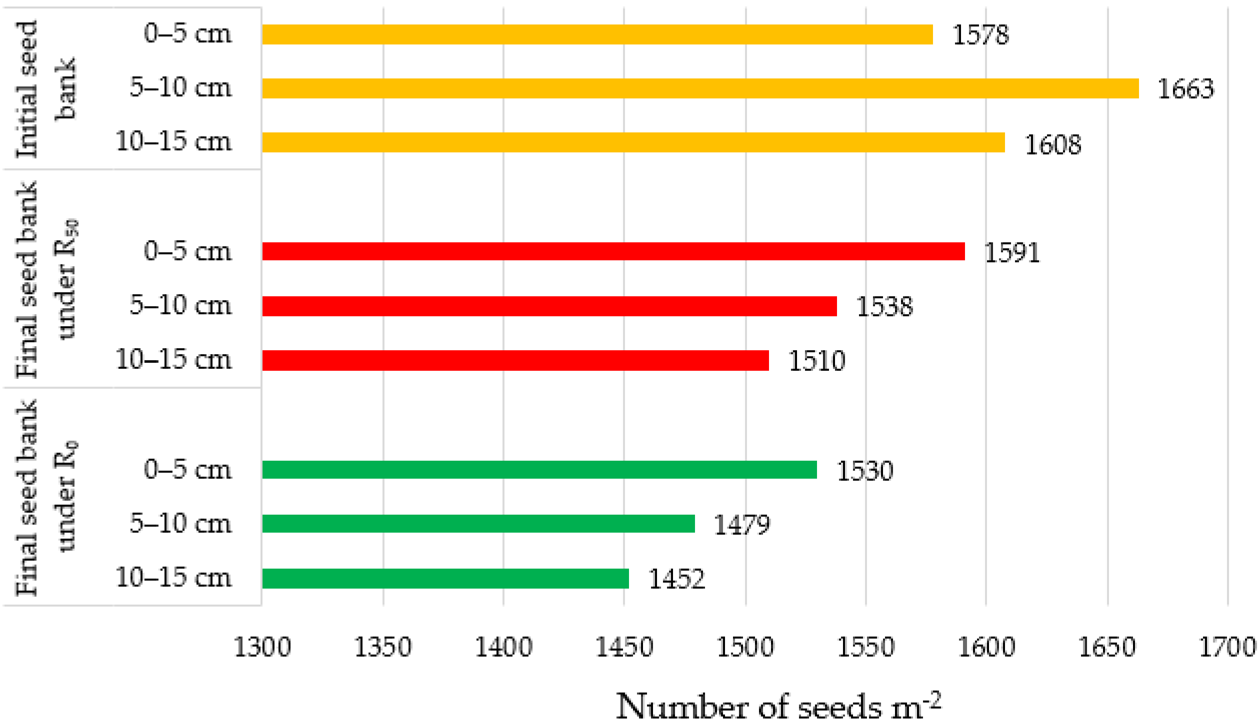

Figure 5. Vertical distribution of seeds at 0–5, 5–10, and 10–15 cm soil depth under mulched and non-mulched conditions (mean from two crop rotations).

4. Discussion

In our study, the seed bank exposed to CT + no-residue for six crops over 2 years had a higher number of broadleaves, grass, and sedge weeds than the seed bank exposed to ST + 50% for 2 years. This was attributed to weed species suppression after continuous ST involved minimum soil disruption for each of the three crops sown each year under wheat-mungbean-monsoon rice and monsoon rice-mustard-winter rice rotations. Previous research has shown that approximately 80% of disturbed soil in CT [29] brings dormant weed seeds to the soil surface from the deeper layers, where weed seed germination and emergence are stimulated. Comparatively, more aerated and warmer soils of CT boosts weed seed germination [12] and allows weeds to develop from deeper within the soil than ST, theoretically increasing the variety of weed species in CT. However, in current research, soils were sampled in 5 cm increments to a depth of 15 cm in both CT and ST. Soil samples were mixed extensively and placed in the tray at a 3 cm thick layer for germination. As a result, the current research may have overestimated the possible abundance of germinable weed seeds by producing favorable germination conditions for seeds that are normally buried too deeply in CT. Scarification, ambient CO_2 concentrations, and higher nitrate concentrations in CT make dormant seeds viable for development, resulting in a higher emergence of new weed species in CT [30]. A higher rate of weed seed survival could also contribute to a change in weed composition in CT versus ST.

In contrast, a comparatively higher level of germination stimulus close to the topsoil triggers a higher percentage of weeds in ST soil than in CT [31]. In our research, however, a reduced weed infestation in ST could be due to the presence of a larger portion of seeds on the soil surface. Only 20% of soil disruption might be attributed to an increase in the proportion of nonviable or dormant weed seeds at the soil surface in ST [32]. Desiccation and a rough environment will cause seeds to perish [12]. In a deeper, undisturbed soil layer, high seed dormancy can also contribute to seed viability loss in ST. Due to lower oxygen demand and darkness, seeds remain dormant at a deeper layer, preventing the necessary oxygen and light for maximum germination from reaching deeply buried seeds [33].

Surface accumulation of weed seed in ST will increase weed seed access for predators (ants, insects, rodents, and birds) and increase weed seed removal rates. Weed seed emergence can be reduced by 5 to 15% by predatory insects like ground beetles, field crickets, or mole crickets [34]. Overall, ST adoption may promote seed loss by predation by making seeds more available to predators. It may be a useful method for reducing the size of the weed seed bank in ST by reducing predator mortality.

Weed seed dispersal will also increase the seed bank in CT versus ST. The dispersed seeds and other propagules were found to be 2–3 m in the direction of plowing, but just a meter in reduced tillage soils [35]. Reduced tillage in ST of this study reduced weed seed spread both within and through fields by restricting movement.

Herbicide use can result in less weed seed establishment in ST. The herbicides glyphosate and pendimethalin were used on both crops in ST plots. Furthermore, isoproturon was used in mustard, carfentrazone-ethyl + isoproturon in wheat, and fenoxaprop-p-ethyl in mungbean. These herbicides have previously been shown to decrease weed seed viability and induce seed dormancy, potentially reducing weed pressure in ST more than CT [36–38]. Several herbicides have been shown to decrease seed yield and germination by several orders of magnitude based on the biotype. Glyphosate has been shown to almost inhibit pollen and seed generation entirely in *Ambrosia artemisiifolia* L. [36], while pendimethalin herbicide inhibited 31% seed germination in *Chenopodium album* L. [37], and 98–100% seeds of *Echinochloa glabrescens* L. were destroyed by ethoxysulfuron-ethyl [38]. Furthermore, carfentrazone-ethyl + isoproteuron caused 100% mortality of *Emex spinosa* L. seeds [39]. In another study, about 97% of *Phalaris minor* L. seeds were destroyed when applied with arfentrazone-ethyl + isoproteuron [40]. However, higher seed dormancy of *Lolium rigidum* Gaud., *Bromus diandrus* Roth., and *Hordeum murinum* L. in ST, enriched the seed bank in ST relative to CT [30,41]. Few previous studies found higher weed density at CT than ST, which coincides with the current study's results [40–43]. In a study by Fracchiolla et al. [8], herbicides depleted the seed bank sharply, both in terms of richness and variety. Herbicides' weed-killing effects may have influenced a smaller seed bank in ST than in CT in our study.

Retaining 50% of crop residues in both tillage methods reduced weed biomass. In this study, the emergence of smaller, etiolated, and less branched weeds with less seed set capacity can result in less vigorous weeds with less biomass in ST than in CT. The current study found about 20% and 33% less density and biomass, respectively, with 50% residue deposition than in no-residue. When a pre- and postemergence herbicide was used to suppress weeds in ST [42], CT had around 30% more weed density and 40% more weed biomass than ST in a CA study. Zahan et al. [43] also reported reduced weed density and biomass in ST when combined with more than one herbicide and increased residue of previous crops. Zhang and Wu [44] concur with us, stating that crop residue retention reduces species richness in soil seed banks by lowering the similarity percentage of weed communities.

On the contrary, reduced tillage raised the density and biomass of weeds considerably more than plowed tillage, according to Woźniak [11]. While reduced tillage intensity increased weed infestation and biomass, herbicides and crop residue mulching decreased biomass in reduced tillage [45]. Chauhan and Abugho [46] concluded that the combination of increasing residues plus herbicides lessens weed emergence and weed biomass relative to that of conventional practice.

We observed a less diverse weed community in ST than in CT, as reflected in a higher value of Simpson's Dominance Index (SI-value) and a lower value of Shannon's Diversity Index (H'-value). Conn's [47] findings support the lower prevalence of weed species in ST as shown by higher and lower values of diversity and dominance indices, respectively. Similarly, another study supports us by pointing out that reduced tillage systems have lower H'-value and higher SI-value [7]. By contrast, Cardina et al. [48] and Borin et al. [49] found that increasing the intensity of plowing in CT resulted in a decline in the species diversity. Feldman et al. [50] discovered an enormous variation of weed species diversity in the minimal soil disruption accompanied by decreased tillage. The values of Sørensen's similarity index showed differences in the similarity of weed species composition between ST and CT. Feledyn-Szewczyk et al. [51] and Zanin et al. [52] support our research findings as they reported the more similar species composition in CT relative to ST.

In the current research, the annual species *Cyperus difformis* L., *Cyanotis axillaris* Roem., *Echinochloa crus-galli* (L.) Beauv, *Eleusine indica* L., *Fimbristylis miliacea* (L.) Vahl., and *Rotala ramosior* L. outnumbered perennial weeds in CT, but the perennials *Ageratum conyzoides* L., *Alternanthera philoxeroides* L., *Cynodon dactylon* L., *Cyperus rotundus* L., *Jussia decurrence* Walt., *Leersia hexandra* L., *Scirpus mucronatus* (L.) Palla., and *Solanum torvum* Sw. dominated annual weeds in ST based on the importance value. Many experiments support our findings that the CT system prefers annual weeds and reduced tillage systems favor perennial weeds [51,52]. Perennial species, such as *Alternanthera sessilis* L., *Cyperus rotundus* L., *Jussia deccurence* Walt., *Leersia hexandra* L., and *Solanum torvum* Sw., were correlated with decreased tillage structures in a study conducted by Hossain et al. [53]. Buhler et al. [54] discovered an uptick in perennial weeds as tillage severity was decreased over a 14-year period in the Midwestern United States. Annual weeds, on the other hand, were associated with CT [55]. The dominance of perennial weeds in less disturbed systems is also suggested by ecological succession theory [10]. Since CT destroys most below-ground vegetative propagules (runners, stolon, bulbs, rhizomes, tubers), perennial weeds are suppressed, while annual weeds propagate mainly seeds [56]. Reduced tillage in ST, on the other hand, saves these reproductive parts that preferred weeds of a perennial nature in the seed pool of our study.

Most weed seeds in ST were found at 5 cm soil depth, and the number declined gradually as depth increased. The distribution of seeds in the CT profile was inverted, with a significant number of seeds to the subsoil layer (5–15 cm). Piskier and Sekutowski [57] discovered the presence of the largest number of weed seeds at 0–5 cm soil in reduced tilled corn cultivation. They also found that weed seeds were more uniformly spread across the 0–20 cm deep soil in CT. This is consistent with the findings of Clements et al. [58], who discovered that in reduced tillage, more than 60% of the seed pool was condensed in the top 5 cm, and CT accumulates them in the deeper layer rather than the top layer. Reduced tillage, on the other hand, causes seeds to invade the soil through surface fractures, and soil fauna (beetles, crickets) accumulates 60–90% weed seeds to 5 cm of the soil [59,60]. Chauhan et al. [32] found more than 75% of seeds deposited in the top 1 cm of low disturbed soil, while high disturbed soil retained just 11% weed seed. According to Bàrberi and Lo Cascio [61], decreased soil inversion in ST is generally correlated with increased seed percentage because freshly dropped seeds remain close to the soil surface, where weed seedlings have a greater chance of emerging, which may have resulted in the richness of weed seed bank at 0–5 cm depth than that of the 5–10 cm and 10–15 cm depths in the current research.

5. Conclusions

Strip tillage-based CA with 50% crop residue retention decreased the size of weed seed banks in the soil and the species diversity. Continuous traditional tillage in the field without residual mulching, on the other hand, increased the admixture of numerous weed species in the seed bank over time. Crop rotation with wheat-mungbean-winter rice increased the species diversity compared to the less diverse monsoon rice-mustard-winter rice rotation. The richness of the perennial weeds *Ageratum conyzoides* L., *Alternanthera philoxeroides* L., *Cynodon dactylon* L., *Cyperus rotundus* L., *Jussia decurrence* Walt., *Leersia hexandra* L., *Scirpus mucronatus* (L.) Palla., and *Solanum torvum* Sw. was higher in ST, which was opposite to CT, which had a greater abundance of the annual weeds *Cyperus difformis* L., *Cyanotis axillaris* (Roem.), *Echinochloa crus-galli* (L.) Beauv., *Eleusine indica* L., *Fimbristylis miliacea* (L.) Vahl., and *Rotala ramosior* L. Under the ST, the majority of weed seeds were stored in the topsoil at 0–5 cm but at the 10–15 cm layer in the conventional practice. We conclude that practicing CA principles together with varied, effective herbicides minimizes the soil weed seed bank status yet increases the risk of perennial weeds. Weed management programs for perennial weeds must be developed for CA practice in these intensive rice-based crop rotations of the Eastern Gangetic Plain.

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