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Continuous Practice of Conservation Agriculture for 3–5 Years in Intensive Rice-Based Cropping Patterns Reduces Soil Weed Seedbank

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Citation: Hossain, M.M.; Begum, M.; Hashem, A.; Rahman, M.M.; Haque, M.E.; Bell, R.W. Continuous Practice of Conservation Agriculture for 3–5 Years in Intensive Rice-Based Cropping Patterns Reduces Soil Weed Seedbank. *Agriculture* **2021**, *11*, 895. https://doi.org/10.3390/agriculture11090895

Academic Editors: Gunnar Kirchhof and Joshua O. Ogunwole

Received: 15 August 2021
Accepted: 15 September 2021
Published: 17 September 2021

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Abstract: When farmers first shift from conventional tillage (CT) to conservation agriculture (CA) practices, the control of weeds may be more difficult, due to the absence of tillage. However, continuous CA, over several years, may alter the weed seedbank. The nature of the weed seedbank changes over time, in intensively cropped rice-based rotations that are typical of the Eastern Gangetic Plain, are not well understood. Two on-farm CA experiments were sampled (in Beluapara after 3 years and Digram after 5 years) in Bangladesh for the effects of strip planting (SP) and bed planting (BP) at both the sites, plus no-tillage (NT) in Beluapara, and increased retention of the residue of previous crops (20% vs. 50%). The conventional tillage (CT) and 20% residue was the control treatment. The weed seedbank in 0–15 cm soil was quantified by assessing the emergence of weeds from soils collected from the field after irrigation, (*Boro*) rice in Digram and wheat in Beluapara, and they were allowed to emerge in trays in a shade-house experiment. The year-round count of emerged weeds at both the locations revealed the fewest number of weed species (especially broadleaf weeds), and the lowest weed density and biomass in SP, followed by CT, BP, and NT, with 50% crop residue mulch. Relative to CT, the SP, BP, and NT produced relatively more perennials weeds, as follows: *Alternanthera denticulata* ((R.) Brown.), *Cyperus rotundus* (L.), *Dentella repens* (L.), *Jussia deccurence* (Walt.), *Leersia hexandra* (L.), and *Solanum torvum* (Sw.), which was the opposite of CT that was enriched with the following annual weeds: *Cyperus iria* (L.), *Digitaria sanguinalis* (L.), *Euphorbia parviflora* (L.), *Fimbristylis miliacea* (L.), *Lindernia antipoda* (L.), *L. hyssopifolia* (L.), and *Monochoria hastata* (L.). The soil weed seed bank reduced by 13% in SP, while it increased by 19% and 76% in BP and NT, respectively, compared with CT. The species diversity reduced in SP and NT, by 24% and 11%, respectively, but increased by 2% in BP. In 50% residue, the soil weed seed bank and species diversity reduced by 16% and 14%, respectively, relative to that of 20% residue. The continuous practice of CA, for 3 or more years, in two rice-based crop rotations, decreased the size of the weed seedbank, but increased the relative proliferation of specific perennial weeds.

Keywords: annual weeds; crop residue; perennial weeds; reduced tillage; strip planting

1. Introduction

Conservation agriculture (CA) has a major influence on the relative abundance of weed species, while weed control is perceived as one of the most challenging issues with the initial adoption of CA [1]. Due to a cessation of tillage, the composition and dynamics of weeds in the soil weed seedbank will change, compared to conventional tillage that leads to shifts in the weed communities [2]. Minimum soil disturbance of the CA system generally favors the emergence of perennial weed species, relative to annual weed species in the seedbank [3]. It is reported to encourage perennial weeds, such as *Cyperus rotundus* L., *Saccharum spontaneum* L., and *Sorghum halepense* (L.) Pers, in the soil weed seedbank of minimally disturbed soil, since tubers and rhizomes present underground in soil are not buried or uprooted [4]. Also, in no-tillage systems, the annual grass populations usually increase [5], concurrent with a decrease in the populations of dicotyledonous weeds. On the other hand, the seedbank of annual and perennial grasses, perennial dicot species, wind-disseminated species, and volunteer crop species was reported to increase, and the annual dicot species was reported to decrease in a reduced tillage (RT) system [6]. For example, the seedling density of *Amaranthus* spp. was much higher in the no-till soils than the tilled soils [7]. Notwithstanding the above effects of decreased soil disturbance by CA on the weed seedbank, there have been no comparable studies in the intensive, triple-cropping systems, where there is an annual period of soil submergence for wetland rice crops.

Despite its widespread global adoption, in Bangladesh, experimentation on CA began in around 2005 [8], to adapt its practices for smallholder farms. However, studies on weed species composition in the soil seedbank, and their changes after several years of CA practice, have rarely been examined. Tillage practices, crop rotation, and weed control practices may change the weed seed density in the soil, which affects the soil weed seedbank and the efficacy of weed control practices. Changes in the weed seedbank, due to crop production practices, are an important predictor of subsequent weed problems. Information on the effect of strip tillage and crop residue retention in the intensive cropping pattern on the soil weed seedbank might be a useful background for sustainable weed management in CA. Hence, in this first-ever study of the soil weed seedbank in long-term CA experiments, at two locations in Bangladesh, we assessed the weed response to tillage practice and residue retention under CA in rice-based cropping systems. The aim was to determine how weed seedbanks changed over time, and to predict changes in weed management practices that are needed to prepare for more widespread adoption of CA on smallholder, rice-based cropping systems.

2. Materials and Method

2.1. Experimental Site, Edaphic and Climatic Environments

A shade-house experiment was conducted during 2 January–29 December 2016, at the Department of Agronomy, Bangladesh Agricultural University, 24.75° N and 90.50° E. The research site was characterized by heavy monsoon rainfall with occasional gusty wind during April–September and low precipitation with moderately low temperature during October–March. The average maximum temperature varied from 32.3–33.5 °C during April–June while January was the coldest month. About 95% rainfall was received during April–September.

2.2. Cropping History at the Sites of On-Farm CA Experiments

2.2.1. Treatments

The two CA experiments were conducted in Beluapara and Digram, Bangladesh. In Digram (24°22′ N and 88°36′ E), cropping sequences were monsoon (T. *aman*) rice–mustard-irrigated (*Boro*) rice, T. *aman* rice–mungbean–lentil, and T. *aman* rice–lentil–jute during 2010–2015. The crops were grown under conventional tillage (CT), strip planting (SP) and bed planting (BP) practices. In Beluapara (23°39′45′′ N and 89°29′39′′ E), the T. *aman* rice–wheat–jute cropping pattern was followed during 2012–2015. Here, in addition to the three tillage practices (CT, SP, BP), no-tillage (NT) was included. Two levels of crop residue (height basis) were retained across the experimental sites. At all locations 20% residue (M_{20}) was comparable to the standard residue level retained on farmers' fields (1–1.6 t ha^{-1}), while 50% residue (M_{50}) represented the increased residue retention (3–4 t ha^{-1}). In M_{50}, previous crops were harvested keeping 50% by height of the standing straw/stubbles of cereal/non-cereal crops on the respective plots.

2.2.2. Tillage Operations

The CT was conducted by a two-wheel tractor (2WT) comprising four rotary tillage passes and cross plowing followed by sun-drying for two days (in non-rice crops), finally by inundation and levelling (in rice). The SP was conducted by a versatile multi-crop planter (VMP) in a single-pass operation [9]. Strips were prepared for four rows. In each line, about 6 cm wide and 5 cm deep tilled strips were made (that preserved about 80% untilled soil) in the untilled flat land by the rotary blades operated by the VMP, and seed and fertilizers were placed by a tine/furrow opener of the VMP in a single pass. In case of NT, the land was not tilled, but seed and fertilizer were dropped in furrows made by a furrow opener. In BP, raised beds (15 cm high and 60 cm wide on the top with 30 cm wide furrows) were made with the bed planting configuration of the VMP.

2.2.3. Weeding Regimes

In CT, weeds emerging during crop growth were controlled by hand weeding in all crops. Hand weeding (HW) was conducted at 25, 45, and 65 days after transplanting or sowing (DAT/S) in rice and wheat, while HW was conducted at 25 and 45 DAS in mustard, jute, mungbean, lentil and chickpea. On the other hand, in SP, BP, and NT, weeds were controlled using appropriate herbicides for each crop. Here, glyphosate (41%) @ 3.7 L was applied at 3 days before tillage/planting. Pendimethalin (33 EC) @ 2.5 L was applied at 3 DAT/S in rice and wheat, but immediately after seeding of mustard, jute, lentil, mungbean and chickpea. Isoproturon (75 WP) was applied in mustard at 15 DAS @ 0.75 L. Ethoxysulfuron ethyl and carfentrazone-ethyl (50%) + isoproturon (0.75%) was applied at 25 DAT/S @ 100 g and 1.5 kg in rice and wheat, respectively. Fenoxaprop-p-ethyl at 25 DAS @ 0.75 L was applied in jute, mungbean, lentil, chickpea. The doses of all herbicides were according to their product label on a per ha basis.

2.3. Soil Sampling Procedure and Experimental Set-Up

The soil was collected from the field of all locations from 0 to 15 cm soil depth. Five samples from each plot; hence 280 samples, were collected using a stainless steel pipe of 5 cm diameter following the "*W*" shape sampling pattern in each plot as described by Chancellor [10]. After collection, samples were tagged and appropriately bagged for transportation to the shade-house. After that, sub-samples from each plot were combined, and approximately one kilogram of soil was placed immediately in an individual circular plastic tray of 33 cm diameter filled to 3 cm depth. Trays were set in the shade-house following a completely randomized design, replicated four times. Each tray represented a plot and there was a total of 224 trays in the shade-house.

2.4. Weed Seed Emergence and Data Collection in Shade-House

Emerged seedlings were identified, counted, and removed at 30-day intervals using the seedling keys of Chancellor [10]. Unnamed seedlings were transferred to another pot and grown to maturity to facilitate identification. After the removal of each batch of seedlings, soils were air-dried, thoroughly mixed, and re-wetted to permit further emergence. The number of seedlings emerged was converted to the number m^{-2} using the following formula: area = πr^2, where π = 3.1416, r = radius of the tray = 16.5 cm.

The weed biomass was assessed by recording the dry matter for each species in g m^{-2} after oven drying the weed samples at 70 °C for 72 h.

2.5. Similarity Index

We used both the qualitative and the quantitative similarity index of SØrensen [11] to compare the resemblance of weed communities of seedbank in the different treatments used in the field as follows:

The qualitative index (%) = $[2C/(A + B)] \times 100$

(C denotes the number of common species in the two populations, A + B denotes total number of species in each of two populations)

The quantitative index (%) = $[2Nc/(Na + Nb)] \times 100$

(Nc denotes sum of the smallest numbers of common species in two populations, Na + Nb denote the number of all weeds in each of two populations)

2.6. Diversity Indices

The degree of diversity of weed composition in the seedbank was analyzed using the following:

(A) Shannon's diversity index, H′ = $-\sum(Pi) \times \ln(Pi)$ [12]

(B) Simpson's dominance index, SI = $\sum(Pi)^2$ [13]

(Pi is the probability of species occurrence in the sample)

2.7. Data Analysis Methods

We used *STAR* software to analyze all data following the standard procedure of two-way analysis of variance and Duncans' multiple range test at $p \leq 0.05$.

3. Results

3.1. Weed Seedbank Composition under Different Tillage and Residue Mulch

In Beluapara, the CT + 20% residue produced 14 weed species (3,708 plants m^{-2}), but at 50% residue, 12 weed species (2,956 plants m^{-2}) emerged (Table 1). The SP + 20% residue produced 10 weed species (2,966 plants m^{-2}), while the SP + 50% residue mulch produced nine species (2,365 plants m^{-2}), but one perennial species, *Leersia hexandra* L., was absent. In BP with 20% residue (4,153 plants m^{-2}), 17 species were found, but with 50% residue, 15 weed species (3,427 plants m^{-2}) were found. In the case of NT with 20% residue, there were 19 weed species (6,881 plants m^{-2}), but in NT with 50% residue, only 16 weed species (6,064 plants m^{-2}) emerged.

The least diversified weed seedbank composition (based on the lowest diversity index and highest dominance index) was found in the SP + 50% residue (2.28 and 0.63), followed by CT (2.39 and 0.51), BP (2.76 and 0.51), and NT (2.93 and 0.49), all with 50% residue, while the NT + 20% residue was the most diversified (2.95 and 0.53). The CT + 20% residue (2.61 and 0.53) was more diversified than the SP + 50% residue (Table 1). The highest number of weed seed species producing the highest number of plants was in NT. The higher and lower values of diversity and dominance indices, respectively indicates the most diversified and the species-enriched weed seedbank composition. In NT, we found the dominance of the following perennial species: *Alternanthera denticulata*, *Dentella repens*, *Solanum torvum*, *Cyperus rotundus*, and *Eleusine indica* over the annual species (Table 1).

Compared to NT with 20 or 50% residue, the weed seedbank of BP was less diversified, with diversity indices of 2.78 and 2.76, respectively. The BP also favored the occurrence of the following perennial weeds over annuals: *Dentella repens*, *Jussia deccurence*, *Cyanotis axillaris*, *Cyperus rotundus*, *Eleusine indica*, *Digitaria sanguinalis*, *Commelina benghalensis*, *Echinochloa colonum*, and *Lindenia antipoda* (Table 1).

The weed pool in SP was described by the lowest and highest values of diversity and domination indices, respectively, suggesting the least diversified species composition, with the dominance of the following specific perennial species: *Alternanthera denticulata*, *Leersia hexandra*, *Dentella repens*, *Jussia deccurence*, *Solanum torvum*, *Hedyotis orymbose*, and *Echinochloa colonum* over the annual species in SP (Table 1).

Table 1. Seedbank composition and weed density (plants m^{-2}) as affected by tillage and residue mulch treatments in Beluapara after 3 years.

Weed Type, Species, and Life Cycle *		CT		SP		BP		NT	
		M_{20}	M_{50}	M_{20}	M_{50}	M_{20}	M_{50}	M_{20}	M_{50}
1. *Alternanthera denticulata* R. Brown.	Perennial	-	-	413 [i]	372 [i]	-	-	570 [i]	687 [i]
2. *Amaranthus spinosus* L.	Annual	245	224	-	-	156	-	199	-
3. *Commelina benghalensis* L.	Annual	-	210	-	-	171	284 [iii]	-	-
4. *Cyanotis axillaris* Roem.	Annual	-	-	-	-	322 [iii]	112	328	-
5. *Dentella repens* L.	Perennial	-	-	361 [iii]	343 [ii]	479 [i]	247	473 [ii]	502 [iv]
6. *Eclipta alba* L.	Annual	210	231	-	-	230	-	126	179
7. *Euphorbia parviflora* L.	Annual	219	346 [i]	-	-	140	195	-	125
8. *Hedyotis corymbosa* (L.) Lamk.	Annual	-	-	151	287 [iii]	128	251	322	302
9. *Jussia deccurence* Walt.	Perennial	299 [iii]	272 [v]	349 [iv]	280 [iv]	469[ii]	-	449 [iv]	611 [ii]
10. *Lindernia antipoda* Alston.	Annual	323	280 [iv]	219	171	84	269 [v]	349	364
11. *L. hyssopifolia* L.	Annual	271 [iv]	267	287	223	207	128	336	278
12. *Monochoria hastata* L.	Annual	309 [ii]	289 [iii]	-	-	210	201	-	-
13. *Rotala ramosior* (L.) Koehne.	Annual	-	-	-	-	-	-	301	-
14. *Solanum torvum* Sw.	Perennial	-	-	318 [v]	217	-	-	409 [v]	437 [v]
15. *Spilanthes acmella* Murr.	Annual	270	-	-	-	139	-	85	-
16. *Digitaria sanguinalis* L.	Annual	212	343 [ii]	-	-	147	297 [ii]	190	380
17. *Echinochloa colonum* L.	Annual	270	248	212	264 [v]	159	270 [iv]	348	359
18. *E. crusgalli* L.	Annual	-	-	-	-	-	-	340	-
19. *Eleusine indica* L.	Annual	213	-	-	-	265 [v]	189	474 [iii]	327
20. *Leersia hexandra* L.	Perennial	-	-	372 [ii]	-	-	-	-	-
21. *Cyperus difformis* L.	Annual	283	-	-	-	158	117	370	359
22. *C. iria* L.	Annual	340 [i]	-	-	-	234	131	268	347
23. *C. rotundus* L.	Perennial	-	-	284	208	309 [iv]	589 [i]	494 [ii]	521 [iii]
24. *Fimbristylis miliacea* L.	Annual	264 [v]	246	-	-	146	147	245	286
Number of weed species		14 [bcd]	11 [cd]	10 [cd]	9 [e]	17 [ab]	15b [c]	19 [a]	16 [ab]
Weed density (plants m^{-2})		3708 [cd]	2956 [e]	2966 [e]	2365 [f]	4153 [c]	3427 [d]	6881 [a]	6064 [b]
Diversity index (H′)		2.61	2.39	2.35	2.28	2.78	2.76	2.95	2.93
Dominance index (SI)		0.53	0.51	0.63	0.63	0.55	0.51	0.53	0.49

* 1–15 = broadleaf, 16–20 = grass, 21–24 = sedge, CT = conventional tillage, SP = strip planting, BP = bed planting, NT = no tillage, M_{20} = 20% mulch, M_{50} = 50% mulch, i–v = five most dominant species, - = absent. Values are means of four replicates. The means with similar letters (a–f) do not differ significantly at $p \leq 0.05$. Co-efficient of variance (CV) and standard errors (SE±) for the number of weed species were 22.7% and 1.11, respectively; and for weed density (plants m^{-2}) values were 29.6% and 563, respectively.

The diversity and dominance indices of CT were lower than those of BP, indicating the evenly distributed, less diversified weed seedbank in CT. Mostly, the annual species was found to dominate the CT. *Euphorbia parviflora, Cyperus iria, Monochoria hastata, Jussia deccurence, Digitaria sanguinalis, Lindernia antipoda*, *L. hyssopifolia*, and *Fimbristylis miliacea* were the dominant weed species (Table 1). A retention of 50% residue with all the tillage types decreased the diversity and dominance of the weed species in the seedbank (Table 1).

In Digram, after the SP + 50% residue, 18 species emerged, while BP with 20% and 50% residue produced 25 and 23 weed species, respectively. Overall, there were fewer weed species in SP, followed by BP and CT. A retention of 50% residue produced 21% fewer weed species numbers than 20% residue mulch in SP. This reduction was 19% in CT and 8% in BP (Table 2).

Table 2. Seedbank composition and weed density (plants m^{-2}) as affected by tillage and residue mulch treatments in Digram after 5 years.

Weed Type, Species, and Life Cycle *		CT		SP		BP	
		M_{20}	M_{50}	M_{20}	M_{50}	M_{20}	M_{50}
1. *Amaranthus viridis* L.	Annual	154	139	211	176	237	115
2. *A. spinosus* L.	Annual	148	123	187	103	205	231
3. *Chenopodium album* L.	Annual	149	-	122	-	199	-
4. *Commelina benghalensis* L.	Annual	172	144	163	-	187	-
5. *Cyanotis axillaris* Roem.	Annual	106	154	-	190	-	78
6. *Dentella repens* L.	Annual	161	172 [iv]	141	-	230 [v]	129
7. *Eclipta alba* L.	Annual	159	119	-	173	-	321
8. *Euphorbia parviflora* L.	Annual	157	135	-	-	-	189
9. *E. hirta* L.	Annual	159	-	101	145	207	138
10. *Gomphrena sessilis* L.	Perennial	141	99	209	109	186	462 [i]
11. *Hedyotis orymbose* Lamk.	Annual	123	134	144	-	325 [iii]	247 [v]
12. *Jussia deccurence* Walt.	Perennial	138	-	258	213 [iv]	374 [i]	258 [iv]
13. *Lindernia hyssopifolia* L.	Annual	168 [v]	147	156	-	198	176
14. *L. antipoda* Alston.	Annual	182 [ii]	101	141	-	259 [iv]	-
15. *Monochoria hastata* L.	Annual	176 [iv]	124	196	137	222	212
16. *M. vaginalis* Burm.	Annual	177 [iii]	136	-	-	-	99
17. *Physalis minima* L.	Annual	139	151	-	-	-	-
18. *Rotala ramosior* (L.) Koehne.	Annual	132	-	222	184	219	189
19. *Solanum torvum* Sw.	Perennial	-	131	269 [iii]	107	-	299 [iii]
20. *Sphenoclea zeylanica* Gaertn.	Annual	147	128	-	-	137	-
21. *Spilanthes acmella* Murr.	Annual	137	137	-	-	153	232
22. *Digitaria sanguinalis* L.	Annual	149	135	-	87	-	241
23. *Echinochloa colonum* L.	Annual	124	-	245 [v]	199	103	222
24. *E. crusgalli* L.	Annual	116	-	174	208 [v]	78	-
25. *Eleusine indica* L.	Annual	158	144	229	101	111	301 [ii]
26. *Leersia hexandra* L.	Perennial	137	117	283[ii]	-	104	-
27. *Cyperus difformis* L.	Annual	149	163 [v]	111	-	143	-
28. *C. iria* L.	Annual	105	181 [iii]	-	-	114	-
29. *C. rotundus* L.	Perennial	-	-	256 [iv]	321[i]	354 [ii]	241
30. *Eleocharisatro purpurea* Re.	Annual	152	196 [i]	106	152	207	211
31. *Fimbristylis miliacea* L.	Annual	228 [i]	185 [ii]	289 [i]	263 [iii]	219	146
32. *Scripus supinus* L.	Perennial	142	169	132	302 [ii]	233	158
Number of weed species		29[a]	25 [b]	23 [bc]	18 [d]	25 [b]	23 [bc]
Weed density (plants m^{-2})		4485 [b]	3564 [c]	4316 [b]	3170 [d]	5004 [a]	4895 [a]
Diversity index (H′)		3.09	3.06	3.01	2.83	3.39	3.20
Dominance index (SI)		0.41	0.39	0.59	0.59	0.50	0.48

* 1–21 = broadleaf, 22–26 = grass, 27–32 = sedge, CT = conventional tillage, SP = strip planting, BP = bed planting, M_{20} = 20% mulch, M_{50} = 50% mulch, i–v = five most dominant species, - = absent. Values are means of four replicates. The means with similar letters (a–d) do not differ significantly at $p \leq 0.05$. Where, co-efficient of variance (CV) and standard error (SE±) for the number of weed species were 19.2% and 1.86, respectively; and for weed density (plants m^{-2}) values were 17.3% and 298, respectively.

In the CT + 20% residue, 29 weed species were found, while the CT + 50% residue had 25 weed species (Table 2). On the other hand, the SP + 20% residue produced 23 weed species. Based on the importance value of the five most dominant species, the annuals were dominant over the perennials.

Overall, the highest number of weed species and weed plant density in the seedbank were found under the BP + 20% residue, but the richest composition of species was found in the CT + 20% residue. The SP + 50% residue has the lowest species richness and the lowest species density m^{-2}. A retention of 50% residue was beneficial in reducing both the species richness and density under all the tillage systems (Table 2). The lowest and highest values of diversity index (2.82) and dominance index (0.63) in the seedbank with 50% residue and SP indicated the least diversified population, but there was a dominance of some of the following weed species: *Cyperus rotundus*, *Scripus supinus*, *Fimbristylis miliacea*, *Jussia deccurence,* and *Echinochloa crusgalli*. The SP + 20% residue had comparable values of diversity index (3.01) and dominance index (0.47), respectively. Admixtures of *Fimbristylis miliacea*, *Leersia hexandra*, *Solanum torvum*, *Cyperus rotundus*, and *Echinochloa colonum* dominated the seedbank in this practice. In terms of the five most dominant species, the perennial species were dominant over the annual species (Table 2).

The highest diversity index (3.39) in the BP + 20% residue (5,004 plants m^{-2} comprising 25 species), plus the dominance index of 0.50, indicated the most diversified composition of weed seedbank, followed by the BP + 50% residue (23 species produced 4,895 plants m^{-2}). The mixture of perennial and annual species made the seedbank the most diverse, but it was dominated by perennial weeds: *Jussia deccurence*, *Cyperus rotundus*, *Hedyotis corymbosa*, *L. antipoda*, *Dentella repens*, *Eleusine indica*, and *Solanum torvum* (Table 2).

In the CT + 20% residue, 29 species comprising 4,485 plants m^{-2} were measured, with diversity and dominance indices of 3.09 and 0.41, respectively. As a result, this seedbank is more diverse than the CT + 50% residue (25 species produced 3,564 plants m^{-2}) and the SP treatments (Table 2). Mostly, the following annual weeds enriched the CT seedbank: *Fimbristylis miliacea*, *Eleocharisatro purpurea*, *Lindernia antipoda*, *Cyperus iria*, *Monochoria hastata*, *M. vaginalis*, *Lindernia hyssopifolia*, *Dentella repens*, and *Cyperus difformis*. Relatively lower values of both the indices were found in 50% residue retention than 20% (Table 2).

3.2. Effect of Tillage and Residue Levels on the Similarity Co-efficient of SØrensen

In Beluapara, the SP produced only 33% similarity of weed species with CT, but 52 and 69% similarity of weeds with BP and NT, respectively. Moreover, BP had 96 and 88% similar weeds to CT and NT, respectively. On the other hand, NT produced 79% similarity to CT, of weeds in the seedbank, and 88% similarity with BP (Table 3). We found 86% similarity in weeds in the seedbank in 20% and 50% residue retention (Table 4).

Table 3. Effect of tillage practices on the SØrensen's qualitative and quantitative similarity index (%) of the weed seedbank after 3 years in Beluapara and 5 years in Digram.

			SØrensen's Qualitative Similarity Index (%)			
	Tillage Practices		**CT**	**SP**	**BP**	**NT**
SØrensen's Quantitative Similarity Index (%)	Beluapara	CT *	-	33	96	79
		SP	28	-	52	69
		BP	84	44	-	88
		NT	67	61	75	-
	Digram	CT	-	53	89	-
		SP	49	-	82	-
		BP	87	76	-	-

* CT = conventional tillage, SP = strip planting, BP = bed planting, NT = no tillage.

Table 4. Effect of residue levels on the SØrensen's qualitative and quantitative similarity index (%) of the weed seedbank after 3 years in Beluapara and 5 years in Digram.

			SØrensen's Qualitative Similarity Index (%)	
	Residue Levels		$\mathbf{M_{20}}$	$\mathbf{M_{50}}$
SØrensen's Quantitative Similarity Index (%)	Beluapara	M_{20} *	-	86
		M_{50}	81	-
	Digram	M_{20}	-	77
		M_{50}	64	-

* M_{20} = 20% mulch, M_{50} = 50% mulch.

The composition of the weed seedbank in SP in Digram comprised a 53% and 82% similarity to that of CT and BP, respectively, while BP had 89% similar weeds to CT (Table 3).

A retention of 50% crop residues produced 77% weed similarity in the seedbank to 20% residue (Table 4).

The quantitative similarity index had a lower value at both the sites than the qualitative index (Tables 3 and 4), meaning that there was more similarity in the species composition than in the number of common species. Based on the results, the SP and CT seedbanks were the least similar in terms of weed species composition. Moreover, the weed composition in CT and BP was the most similar, followed in order by CT and NT, SP and NT, and SP and BP.

3.3. Effect of Different Tillage and Residue Retention on the Plant Abundance of Different Weed Types

In Digram, the BP + 20% residue generated the highest total weed density, followed by CT and SP, both with 20% residue. On average, the SP + 50% residue had 237 fewer weeds m^{-2} than the CT + 20% residue, but the BP + 20% residue had 776 more weeds m^{-2} than the CT + 20% residue (Table 5). The highest weed density resulted in the highest weed biomass in the BP + 20% residue, followed by the CT + 20% and 50% residue, while the lowest biomass of weeds was in the SP + 50% residue (Figure 1). The retention of 50% residue produced 610 fewer weeds m^{-2} than 20% residue that led to a 39% reduction in weed biomass with 50% residue (Figure 1). Broadleaf weeds were the most dominant in all types of tillage, while grass weeds outnumbered the sedges in BP, but the reverse was found in SP. Annuals led over perennials in the CT + 20% residue, but perennials led over annuals both in SP and BP with 50% residue (Figure 2).

Table 5. Effect of different tillage and residue mulch on the abundance (no. m^{-2}) of different weeds in Digram after 5 years and in Beluapara after 3 years.

Locations	Treatments	Broadleaf		Grass		Sedges	
		M_{20} *	M_{50}	M_{20}	M_{50}	M_{20}	M_{50}
Digram	Conventional tillage (CT)	2691 ^{b}	2257 ^{b}	1065 ^{a}	645 ^{b}	729 ^{bc}	662 ^{a}
	Strip planting (SP)	2460 ^{bc}	2028 ^{bc}	734 ^{b}	668 ^{b}	1122 ^{a}	474 ^{c}
	Bed planting (BP)	3136 ^{a}	3230 ^{a}	1067 ^{a}	1028 ^{a}	801 ^{b}	637 ^{b}
Co-efficient of Variance (CV (%))		12.4	25.5	20.1	27.5	23.7	17.3
Standard Error (SE±)		198	368	111	124	121	59
Beluapara	CT	2403 ^{b}	1567 ^{c}	774 ^{c}	591 ^{c}	531 ^{c}	798 ^{b}
	SP	1672 ^{d}	1514 ^{c}	737 ^{c}	496 ^{cd}	557 ^{c}	355 ^{d}
	BP	2367 ^{bc}	1919 ^{b}	914 ^{b}	857 ^{b}	872 ^{b}	651 ^{bc}
	No tillage (NT)	3440 ^{a}	3396 ^{a}	2271 ^{a}	1637 ^{a}	1170 ^{a}	1031 ^{a}
CV (%)		28.9	22.1	25.6	27.8	23.5	24.9
Standard Error (SE±)		182	221	184	129	75	71

* M_{20} = 20% residue, M_{50} = 50% residue. Values are means of four replicates. The means for each weed group with similar letters (a−d) do not differ significantly at $p \leq 0.05$.

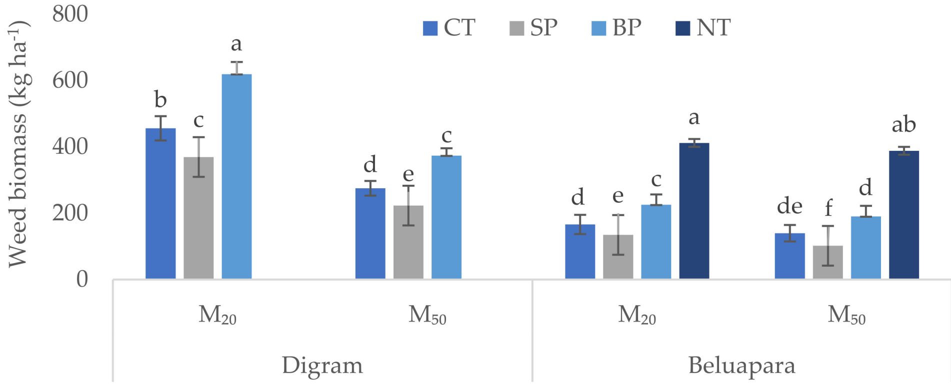

Figure 1. Effect of tillage practices and residue levels on the net weed dry biomass (kg ha^{-1}) at 30 days after emergence from soil collected from Digram after 5 years and Beluapara after 3 years. Values are means of four replicates. The means for each site with similar letters (a−f) do not differ significantly at $p \leq 0.05$. CT = conventional tillage, SP = strip planting, BP = bed planting, NT = no tillage, M_{20} = 20% residue, M_{50} = 50% residue. Whiskers mean the standard deviation.

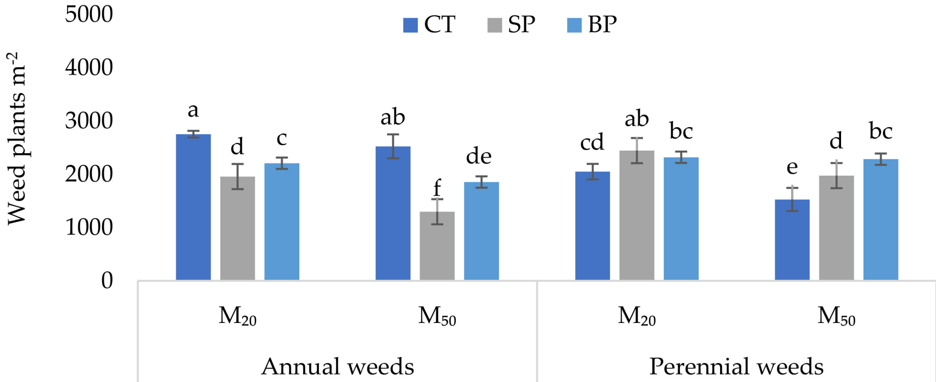

Figure 2. Density of emerged annual and perennial weeds from topsoil (0–15 cm) at 30 days after emergence from soil collected from Digram after 5 years under strip planting (SP), bed planting (BP) and conventional tillage (CT). Values are means of four replicates. The means with similar letters (a−f) do not differ significantly at $p \leq 0.05$. M_{20} = 20% residue, M_{50} = 50% residue. Whiskers mean the standard deviation.

In Beluapara, the lowest weed density was found in the SP + 50% residue, while the retention of 20% residue with NT produced the highest weed density, followed by the same residue level with BP and CT. On average, relative to the CT + 20% residue (1,668 weeds m^{-2}), SP has 560 fewer weeds m^{-2}, but BP and NT with 50% residue produced 386 and 2,639 more weeds m^{-2}, respectively (Figure 3). Furthermore, we recorded the highest weed biomass at the NT + 20% residue, followed by BP and CT. The SP + 50% residue produced the lowest biomass, which was 19% less biomass than the CT + 20% residue (Figure 1). In all types of tillage and residue levels, broadleaf led over sedges and grasses. Annuals were dominant over perennials in CT, but perennials led over annuals in SP, BP, and NT (Figure 3).

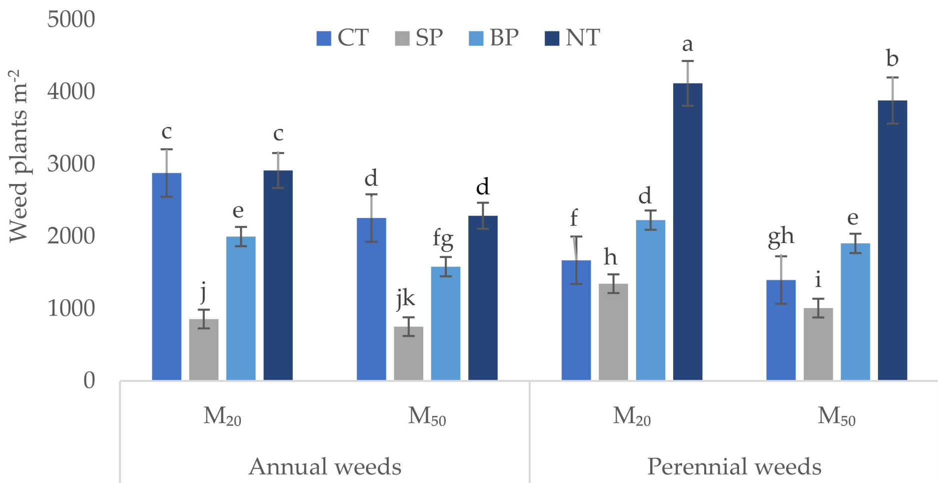

Figure 3. Density of emerged annual and perennial weeds from topsoil (0–15 cm) at 30 days after emergence collected from Beluapara after 3 years under strip planting (SP), bed planting (BP), no tillage (NT) and conventional tillage (CT). Values are means of four replicates. The means with similar letters (a−k) do not differ significantly at $p \leq 0.05$. M_{20} = 20% residue, M_{50} = 50% residue. Whiskers mean the standard deviation.

4. Discussion

After 3–5 years of CA experiments, the seedbank of the SP + 50% crop residue was characterized by a significantly lower density of broadleaf, grass, and sedge types, and gross weed biomass, than the CT + 20% residue at both the locations. In Digram, the SP + 50% residue produced 2,028 broadleaf, 668 grass, and 474 sedge weed plant m^{-2}, which was 25, 37, and 34% lower, respectively, than that of the CT + 20% residue. The reduction was 32−38% in Beluapara. The gross weed biomass of the SP + 50% residue was 51 and 39% lower than that of the CT + 20% residue; this was equivalent to 456 and 167 kg ha^{-1} in Digram and Beluapara, respectively. The CT + 20% residue represents the current farm practice in the intensive rice-based crop rotations in the Eastern Gangetic Plain (EGP), while the SP + 50% residue represents CA practice being recommended for smallholders [14]. Hence, these results suggest that the wider adoption of CA in the EGP will lessen the overall weed burden from crop management.

The suppression of the weed seedbank density and diversity after continuous SP + 50% residue for 3–5 years is attributed to minimal soil disturbance, plus the additive effect of reside retention for each of the three crops sown per year and the change in herbicide usage. Previous research suggests that a disturbance of about 80% of soil by CT [15] brings up dormant weed seeds from the deeper soil layers to the surface layer, which favors the higher germination of weed seeds and the emergence of weeds. The tilled soils of CT also offer a better germination medium for weed seeds, by increasing the aeration and temperature [1]. In the field, CT also allows seedlings to emerge from seeds that are buried deeper in the ground, compared to untilled soils in SP that may further increase the abundance of emerged weeds from the seedbank and alter the species composition in the weed seedbank of CT, relative to SP. However, in the present study, the soils were sampled to 15 cm depth in both CT and SP, and the soils were thoroughly mixed and spread to 3 cm depth. Hence, the present study may have overestimated the likely abundance of germinable weed seeds, by creating suitable germination conditions for seed that are normally buried too deep in CT, and especially in SP, to germinate and/or emerge. However, in another study, we found a lower weed density and biomass, and fewer weed species in the weed seedbank in soils sampled to only 0–5 cm under the SP + 50% residue retention, compared to CT after only 2 years [16]. Dormant seeds in CT become viable to germinate by scarification, ambient CO_2 concentrations, and higher nitrate concentrations, which may lead to the production of a higher weed emergence of new weed species in plowed soils [17]. By contrast, owing to the stronger germination stimulus near the soil surface of less disturbed or no-till soil, a higher proportion of weed seeds will germinate in untilled soil than after plowing [18]. This might have led to a larger composition of seedbank in the NT than CT, followed by BP and SP, in this study.

The reduction in the number of weed species in SP might also be due to a cumulative effect of minimizing the weed seedbank status in the soil, by increasing non-viable or dormant weed seeds in the seedbank. Due to minimal soil disturbance (only 20% of the soil surface) in the upper soil layer in SP, most of the weed seeds remain on or close to the soil surface. They can lose viability, due to desiccation and an adverse climate [1]. The loss of seed viability in SP may also be attributed to increased seed dormancy in the undisturbed deeper soil layer, due to less oxygen pressure and darkness, which prevents the required germination triggers for these deeply buried seeds [19].

The surface accumulation of weed seeds in SP would increase predator (ants, insects, rodents, and birds) access to weed seeds, and could increase their removal rates. For example, common ground beetles or crickets can reduce weed seed emergence by 5 to 15% [20]. Overall, the adoption of SP may encourage seed losses via predation, by increasing the availability of seeds to predators, and by minimizing mortality and forced relocation of predators during tillage; therefore, reducing the weed seedbank size in SP. A higher dispersal of weed seeds may also lead to an increase in the seedbank in CT over SP, followed by BP and NT. Weed seeds traveled 2–3 m in the direction of full tillage, while in reduced tillage soils, the distance is negligible [21]. Reducing tillage in BP, and no tillage in SP and NT, therefore, reduced the physical spread of weed seeds both within and across fields. The reduced weed seedbank in SP, relative to NT, may also have occurred from additional weed seed burial, as strips cover about 20% of the surface area, but over successive plantings and years, they bury some seeds over most of the field.

The cumulative effect of herbicides applied probably also contributed to the lesser amount of weed seed set in the SP + 50% residue, followed by BP and NT, with and without residue. In the long-term CA plots, glyphosate and pendimethalin herbicide were used in all crops. Besides, ethoxysulfuron-ethyl was applied in rice, isoproturon in mustard, carfentrazone-ethyl + isoproturon in wheat, while fenoxaprop-p-ethyl was applied in jute, lentil, mungbean, and chickpea. These herbicides were previously reported to reduce seed set, which might have led to the reduction in weed pressure in SP, relative to CT. It was reported that a range of herbicides could reduce seed production and germination by several fold, depending on the biotypes. Glyphosate was found to suppress seed production by almost 100% in *Ambrosia artemisiifolia* L. [22]; pendimethalin herbicide decreased the seed germination of *Chenopodium album* L. by 31% [23]; and ethoxysulfuron-ethyl killed 98–100% of the seeds of *Echinochloa glabrescens* L. [24]. Moreover, carfentrazone-ethyl + isoproturon damaged 100% of the seeds of *Emex spinosa* L. [25], and fenoxaprop-p-ethyl ruined 97% of the seeds of *Phalaris minor* L. [26]. In addition, herbicide-induced seed dormancy has been reported in *Hordeum murinum* L., *Bromus diandrus* Roth., and *Lolium rigidum* Gaud. [15,27]. Hence, in the present study, herbicides could reduce the seed production and viability of weeds, thereby reducing the seedbank size in SP and, to a lesser extent, in BP and NT, relative to CT. Hossain et al. [28] reported a 30% lower weed density and 40% lower weed biomass in SP than CT, when a pre- and post-emergence herbicide was used to control weeds in SP.

A retention of 50% residue, both with SP and CT, reduced both the density and biomass of the seedbank weeds at both the locations. In Digram, the 50% residue reduced the gross density and biomass by 30% and 40% in SP, but 25% and 36% in CT, respectively. We found 27% less density and 24% less biomass in 50% residue than 20% residue in SP than in CT in Beluapara. Fewer aboveground weed taxa in 50% residue than 20% residue might be due to the effective suppression of germinated weeds, caused by the physical barrier of extra residue, lower soil temperatures, and allelochemicals released from decaying plant tissues in the field, as suggested by [29]. Moreover, reduced light penetration and cooler average soil temperatures in 50% residue, relative to 20% residue, could reduce weed seed germination or delay germination, damage of weed seeds, due to predation, and decomposition by macro and microbial populations [30]; delay emergence of etiolated plants that, in turn, produced fewer seeds, as stated earlier [31]. Comparatively higher and lower values of qualitative and quantitative similarity indices, respectively, in 50% residue than 20% signify a more diversified weed seedbank in the 50% residue than the 20% residue in this study.

Chauhan and Abugho [32] observed that the emergence of weeds declined with increasing residue, and resulted in less weed biomass than with the no-residue treatment under reduced tillage. Similarly, Ngwira et al. [33] found double the weed biomass in NT without surface residue than NT with surface residue, retained at 6 t ha^{-1}. There is evidence that NT + residue encourages seed predation, increasing predatory seed depletion by two- to three-fold [34,35], as compared to conventional methods. Allelopathic suppression of weed seed germination through surface residue may be more effective in NT because seeds are concentrated near the soil surface, where the retained residue can release allelopathic compounds. Although pre-emergence herbicides are reported to be intercepted by the residue, those weeds that over-grow the residue can be killed effectively with the application of post-emergence herbicides [1,36].

In Beluapara, the least diversified seedbank of the SP + 50% residue had the lowest Shannon index (2.28) and the highest Simpson index (0.63) values in weed composition, with a dominance of particular weed species. The seedbank of the CT + 20% residue, which represents current farmers' practice, was more diversified than the SP + 50% residue, with Shannon and Simpson indices of 2.61 and 0.52, respectively. Similarly, in Digram, the SP + 50% residue seedbank was the least diversified, in terms of the lowest and highest values of Shannon and Simpson indices of 2.83 and 0.59, respectively. The seedbank of the CT + 20% residue was more diversified (values 3.09 and 0.41, respectively) than the SP + 50% residue. In a similar study, which lasted only 2 years, Hossain et al. [16] reported a more diversified seedbank of CT without residue (with diversity and dominance indices of 2.93 and 0.54, respectively), relative to the SP + 50% residue (indices of 2.44 and 0.90, respectively), even though that study sampled soils to 5 cm depth rather than 15 cm. In another study, Cardina et al. [37] found a decrease in species diversity with the increasing number of tillage operations; their diversity indices were 0.6, 0.5, and 0.2 in NT, RT, and CT, respectively). Sekutowski and Smagacz [38] reported a higher and lower coefficient of Shannon and Simpson in CT (2.55 and 0.08, respectively) than RT (1.61 and 0.22, respectively). In contrast, Plaza et al. [39] discovered a more diversified RT seedbank (1.29) than CT, while NT was the least diversified (1.14), as did Woźniak [5], who reported a more diversified seedbank in RT (0.86) than CT (0.77). In another study, Feledyn-Szewczyk et al. [39] found that the least diversified NT seedbank was characterized by the lowest value of Shannon's diversity index (2.04) and a higher value of Simpson's domination index (0.18) than the RT (2.18, 0.18, respectively) and CT (2.41 and 0.11, respectively).

In Beluapara, a retention of 50% residue decreased the diversity index with NT (2.93), BP (2.76), SP (2.28), and CT (2.39), relative to 20% residue (values were 2.95, 2.78, 2.35, and 2.61, respectively). Here, the dominance indices of 50% residue with NT, BP, SP, and CT were 0.49, 0.51, 0.63, and 0.51, respectively, while the indices of 20% residues were 0.53, 0.55, 0.63, and 0.53, respectively. Similarly, in Digram, the diversity and dominance indices of 50% residue, along with BP, SP, and CT, were 3.20 and 0.48, 2.83 and 0.59, and 3.06 and 0.39, respectively, while with 20% residue, the indices were 3.39 and 0.50, 3.01 and 0.47, and 3.09 and 0.41, respectively. Similarly, Hossain et al. [16] discovered that 50% residue with CT and SP had a lower diversity index (2.89 and 2.44, respectively) than no-residue (2.93 and 2.49, respectively). However, they found a lower dominance index of 50% residue (0.90) than no-residue (0.91) in RT, but the reverse in CT (0.57 and 0.54, respectively). In Beluapara, relative to CT, the most similar species composition was found in BP (96%), followed by NT (79%), and the least similar in SP (33%). Similarly, in Diagram, the similarities in BP and SP were 89 and 53%, respectively. Our finding was supported by Feledyn-Szewczyk et al. [40], who found about a 78% similar weed species composition in

NT and RT, respectively. In another study, Zanin et al. [41] discovered 83 and 66% similar species compositions in NT and RT, respectively, relative to CT. In our study, the seedbank of 50% and 20% residue had 86 and 77% similar species compositions at the Beluapara and Digram sites, respectively. Hossain et al. [16] found 75% similar species compositions (qualitative values) in RT and CT, and 86% similar species compositions in 50% residue and no-residue.

In the present study, the following annual weeds led over perennials in CT: *Euphorbia parviflora*, *Cyperus iria*, *Monochoria hastata*, *Digitaria sanguinalis*, *Lindernia antipoda*, *L. hyssopifolia* and *Fimbristylis miliacea*; however, the following perennial weeds were more abundant than annuals in SP, BP, and NT: *Alternanthera denticulata*, *Leersia hexandra*, *Dentella repens*, *Jussia deccurence*, *Solanum torvum*, and *Cyperus rotundus*. Many studies support our study reporting that CT systems favor annuals, while reduced tillage systems favor perennial weeds [42]. Thomas et al. [43] also observed the proliferation of annual species in the traditional tillage. The ecological succession theory [4] also suggests the dominancy of perennials weeds in less-disturbed systems, because CT kills most of the underground vegetative reproduction structures (rhizomes, tubers, bulbs, runner, and stolon) of perennial weeds, while annual weeds, which reproduce mostly by seeds, tend to be more competitive. On the other hand, reduced tillage in ST and BP, and NT preserves viable rhizomes, tubers, bulbs, runners, and stolons, which favor perennial weeds in the soil weed seedbank.

Herbicide application was found to be more effective to control perennial weeds under reduced or no-tillage systems in CA [44]. In-crop, preharvest, and postharvest herbicide applications can be used in perennial weed control schemes in crops. Regardless of the implementation method, retreatment once or twice a year is expected for effective control of perennial weeds. Using a knockdown herbicide, such as glyphosate, as in Roundup Ready maize, soybean, canola, and sugar beet is a highly successful method for controlling perennial weeds. Glyphosate-applied preharvest provided effective control of existing *Cirsium arvense* (Canada thistle). Postharvest herbicide applications were successful in treating new perennial weed growth. However, carefully designed herbicide programs are needed to combat perennial weeds in CA, while minimizing negative environmental effects and weed resistance to herbicide. Moreover, the persistence of herbicides in soils has an impact on the crop sequencing in CA rotations, especially when the herbicide is selective to the crop to which it is applied, but not to following crops [45,46]. This raises the issue of weed control tactic compatibility, since crop rotation is also a weed control method in CA [1]. Crop rotation disrupts the life cycle of weeds and reduces crop–weed specificity [47], thus decreasing weed persistence and its associated challenges. However, the efficacy of pre-emergence herbicides on the soil surface is diminished, due to crop residue interception [48]. This necessitates the use of a post-emergence herbicide. Crop residue can also be a source of weed seeds. However, the IWM approach of preventive weed management could effectively regulate perennial and annual weeds in CA [48,49].

5. Conclusions

The soil weed seed bank (number of weeds m^{-2}) decreased in SP by 13%, and increased in BP and NT by 19% and 76%, respectively, compared with CT. The number of weed species reduced in both SP and NT, by 24% and 11%, respectively, but increased in BP by 2%. The lowest similarity of weed communities was found in the seedbank between SP and CT, indicating significant divergence of the seedbanks after 3–5 years. The seedbank under CT was dominated by the following annual weeds: *Cyperus iria* (L.), *Digitaria sanguinalis* (L.), *Euphorbia parviflora* (L.), *Fimbristylis miliacea* (L.), *Lindernia antipoda* (L.), *L. hyssopifolia* (L.), and *Monochoria hastata* (L.). On the other hand, the seedbank of SP, BP, and NT was dominantly perennial weeds, especially the following: *Alternanthera denticulata* ((R.) Brown.), *Cyperus rotundus* (L.), *Dentella repens* (L.), *Jussia deccurence* (Walt.), *Leersia hexandra* (L.), and *Solanum torvum* (Sw.). A retention of 50% of cereal crop residues also reduced the weed seedbank species composition (16%)

and diversity (14%). We concluded that the continued strip planting-based conservation agriculture with 50% crop residue retention for 3–5 years reduced the weed seedbank size and diversity of weed species in the seedbank in contrasting rice-based cropping patterns. However, strip planting, bed planting, and no-tillage increased the proportion of perennial weeds in the weed seedbank, relative to the dominance of annual weeds in conventional tillage, and this may necessitate a change, over time, in weed control strategies. To verify this finding, a more extensive on-farm field study on the soil weed seedbanks under long-term conservation agriculture is suggested. Also, it is necessary to conduct research on the control of perennial weeds in conservation agriculture systems. Further research is also essential, in order to fully understand the complex relationships of weed species, and how they are affected by different tillage and residue mulch retention levels.

Author Contributions: Conceptualization, M.M.H., M.B. and M.M.R.; methodology, M.M.H. and A.H.; software, M.M.H.; validation, R.W.B., A.H. and M.B.; formal analysis, M.M.H. and M.M.R.; investigation, M.M.H., M.B., M.M.R.; resources, M.M.H.; data curation, M.M.H., M.B. and A.H.; writing—original draft preparation, M.M.H., R.W.B.; writing—review and editing, R.W.B., A.H. and M.E.H.; visualization, M.M.H. and A.H.; supervision, M.B., M.M.R.; project administration, M.B., R.W.B. and M.E.H.; funding acquisition, R.W.B.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Australian Centre for International Agricultural Research (ACIAR) project (LWR/2010/080), led by Murdoch University, Australia, and the APC was funded by Murdoch University.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are not publicly available, though the data may be made available on request from the corresponding author.

Acknowledgments: The authors thankfully acknowledge the research facilities provided by the department of Agronomy, Bangladesh Agricultural University.

Conflicts of Interest: The authors declare no conflict of interest.

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