https://doi.org/10.17221/162/2022-PSE

Soil weed seedbank under different cropping systems of middle Indo-Gangetic Plains

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Citation: Sharma P., Singh M.K., Verma K., Prasad S.K. (2022): Soil weed seedbank under different cropping systems of middle Indo-Gangetic Plains. Plant Soil Environ., 68: 542–551.

Abstract: Trees on agricultural fields can have a positive or negative impact on weed seedbank (WSB) due to diverse environmental and soil characteristics. Therefore, soil samples were drawn in six cropping systems [two agroforest systems (AFS): guava, mango; three horticulture systems (HCS): guava, mango, Indian gooseberry; and annual crop system (ACS)] at two landscape positions (lowland and upland) and two soil depths (0–15 cm and 15–30 cm) using factorial randomised block design each replicated three times. Results showed that guava-AFS had the highest WSB of different categories in general and individual weed species in particular, except for *Eragrostis pilosa* and *Dactyloctenium aegyptium*. Simultaneously, guava-AFS also showed the maximum Shannon-Weaver, species richness and Simpson index and was low in Whittaker statistics (β_W). The species evenness varied non-significantly with the cropping systems. Similarly, the landscape position had no discernible effect on any weed diversity indices; however lowland landscape position was dominated by *Cyperus* spp. and *E. pilosa*, while the upland by *Phyllanthus niruri*. Furthermore, with the exception of β_W, the WSB and diversity indices were found to be higher on the topsoil (0–15 cm). Our study establishes that the AFS system in the semi-arid sub-tropics has a more diverse WSB indicating a healthy system, as opposed to HCS, which has a dominance of certain weed species, opening the door for more severe infestation of invasive weed species.

Keywords: annual cropping system; seed distribution; spatial distribution patterns; weed density; weed ecology; weed population dynamics

Under the situation of climate change, extreme climatic events and growing demographic pressure, the monoculture, i.e., the annual cropping system (ACS) or the horticulture system (HCS), faces many challenges and constraints (CAFRI 2015). So, there is a need to focus on better land utilisation and diversification of agroecology with the introduction of the agroforest system (AFS), which not only sustains the farmer's livelihood through economic benefits but also enhances resilience through the provision of ecosystem services (Sharma et al. 2022). However, shifting in the cropping system can manipulate the weed composition and distribution in the cropped area of an AFS (Rizvi et al. 1999), simultaneously, the weed seedbank (WSB) (Deiss et al. 2018). Actually, trees modulate the germination as well as growth and development of weeds through allelopathy (Rizvi et al. 1999). Although previous literature reveals the discrepancy in the intensity of weed infestation in agroforestry in comparison to other agroecological systems (Deiss et al. 2017, 2018).

Simultaneously, despite a massive advancement in weed management practices, in India, weeds are still the major biotic factor reducing the crop yield by

https://doi.org/10.17221/162/2022-PSE

13.8–35.8% in the rainy season and 18.6–25.3% in the winter season, accounting for an economic loss of more than USD 11 billion annually (Gharde et al. 2018). Therefore, efficient weed management under the scenario of changing cropping system requires a better understanding of the spatial and temporal WSB dynamics (Koocheki et al. 2009). WSB includes the reserve of viable seeds, propagules or any reproductive material in the soil, which is the primary source of weed infestation and regulates the weed diversity in any cropping system (Singh-Manpreet et al. 2015). In fact, WSB dynamics can produce a better synoptic view of the cropping system's influence on weeds rather than above-ground vegetation (Srivastava and Singh 2014) and simultaneously forecast the probable weed menace (Forcella 1992).

Furthermore, currently, most of the weed dynamics studies in different cropping system either quantifies the weed population dynamics by counting the above-ground germinated weeds (Shivran et al. 2017, Kumar et al. 2018) or WSB in response to different agronomic practices, like tillage, crop rotation, fertilisation or weed management (Lal et al. 2016, Sharma et al. 2020). A weed dynamics study based on the above-ground germinated weeds did not give the real picture of potential weed problems due to WSB in future.

Moreover, studies conducted worldwide reveal that there is huge variability in WSB composition and size. In fact, WSB size varies from a few thousand to a million seeds per m^2 due to the complex inter- and intra-specific interactions between the various system components and edapho-climatic factors (Lal et al. 2016). Most often, the WSB studies have been conducted in the agricultural ecosystem rather than in the tree-based ecosystems, like forest or agroforestry; thus, it is a long-standing concern (Carrillo-Anzures et al. 2009). Furthermore, the literature showed a paucity of research conducted on understanding the WSB dynamics under variable cropping systems, especially in the semi-arid region of the Indian subcontinent. Additionally, in the WSB dynamic studies, weed diversity indices (WDI) are used less frequently; however, these indices help understand the weed community and its interaction with high flexibility (Otto et al. 2012), which is crucial for biodiversity maintenance.

With these backdrops, this paper aims to compare the impact of different agroforest, horticulture and annual cropping systems on the WSB dynamics in the semi-arid sub-tropical zone of the middle Indo-Gangetic Plains.

MATERIAL AND METHODS

Experimental location and climatic information. The experimental site was located at the RGS-Campus, Banaras Hindu University, Mirzapur (U.P.) and adjacent areas (elevation varies from 80–356 m a.s.l., 25°5'–25°6'N and 82°35'–82°59'E) situated in the middle Indo-Gangetic Plains. This area belongs to agro-climatic zone III A (semi-arid eastern plain zone), which receives erratic rainfall and is invariably poor in soil fertility; moreover, most of the crops are grown under rainfed conditions. The climatic condition of the region was characterised by semi-arid to sub-humid, with May and June being the hottest months (31.08–36.05 °C), while December and January were the coldest months (13.8–18.6 °C). The region received an annual rainfall of 1 068.55 mm/year, of which nearly 88% was received from June to September. However, the mean daily potential evapotranspiration was 6.45 mm/day.

Trial establishment and soil sampling. The experiment was laid out in a three-factor randomised complete block design. The first factor comprised of the six cropping systems, having three major systems, viz.; two-agroforest systems (AFS) [guava (*Guava guajava* L.) + mungbean (*Vigna radiata* (L.) R. Wilczek) followed by (*fb*) wheat (*Triticum aestivum* L.) and mango (*Mangifera indica* L.) + mungbean *fb* wheat], three-horticulture system (HCS) [guava, mango and Indian gooseberry (*Phyllanthus emblica* L.)] and one annual cropping system (ACS) [mungbean *fb* wheat] and each treatment replicated thrice. The details of the structure and composition of cropping systems are presented in Table 1. Mungbean-wheat cropping system was followed under both agroforestry and annual cropping system. In the conventional tilled field, during the *Kharif* (wet season), the mungbean (cv. Samrat) was grown in ACS and AFS with a seed rate of 15 kg/ha during the first fortnight of July, i.e. with the onset of monsoon. However, the weeds were managed with the post-emergence application of imazethapyr 200 g a.i. (active ingredient)/ha. At maturity, the crop was manually harvested on the first week of October, having a grain yield varying from 0.6–0.8 t/ha. Subsequently, during the *Rabi* (winter season) season, the wheat (cv. HD 2967) was sown in a conventional tilled field during the second fortnight of November with a 100 kg/ha seed rate. Weeds were managed by post-emergence application of a pre-mixed formulation of sulfosulfuron + metsulfuron (32 g/ha). The crop was manually harvested

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Table 1. Structure and composition of prevalent cropping systems in the semi-arid sub-tropical zone of middle Indo-Gangetic Plains

System	System type	Woody perennial inter- and intra-row spacing (m)	Annual intercrop/ sole crop inter-row spacing (cm)	Age of woody perennial	Ploughing frequency	Months of plowing
AFS	Guava + MB *fb* W	7 × 7	30 and 22.5	12	2	July and November
	Mango + MB *fb* W	10 ×10	30 and 22.5	19	2	July and November
HCS	Guava	6 × 6	–	12	1	July
	Mango	9 × 9	–	30	1	July
	Indian gooseberry	12 × 12	–	25	1	July
ACS	MB *fb* W		30 and 22.5	–	3	July and November

AFS – agroforest system; HCS – horticulture system; ACS – annual cropping system; MB – mungbean; W –wheat; *fb* – followed by cv. Samrat of MB, cv. HD-2967 of wheat

in the last week of April and yielded 3.5–4.0 t/ha grain. Further, no herbicidal weed control practices were adopted in the HCS system; however, weeds were hand weeded with a *khurpi* (a mechanical hand tool) at the flowering stage of the crop. Moreover, no pruning was performed in the mango-AFS, mango-HCS and Indian gooseberry-HCS. In guava-AFS and guava-HCS, pruning was performed in mid-May, with 25% of the shoot removed. The second and third factors comprised of two-landscape positions (lowland and upland) and two soil depths (0–15 cm and 15–30 cm), respectively.

The soil was also analysed for different physico-chemical parameters as per the standard procedure described by Arora et al. (2018). The soil was sandy clay loam in texture (typic: ustochrept; order: inceptisol), having neutral soil reaction, low in available nitrogen (N) and organic carbon (OC) content, whereas medium in available phosphorus (P) content (Table 2). A comparison of the soil characteristic

Table 2. Physico-chemical properties of the soil of different cropping systems under diverse landscapes and soil depth

Treatment	Bulk density (t/m^3)	pH	Electric conductivity (dS/m)	Organic carbon (%)	Available N (kg/ha)	Available P
Cropping system						
Guava-AFS	1.44^{c}	7.23^{a}	0.26^{ab}	0.35^{c}	165.03^{d}	18.15^{b}
Mango-AFS	1.42^{d}	7.31^{a}	0.24^{bc}	0.39^{b}	201.68^{b}	18.88^{b}
Guava-HCS	1.40^{e}	6.89^{b}	0.26^{ab}	0.42^{a}	188.10^{bc}	19.04^{b}
Mango-HCS	1.39^{e}	6.85^{b}	0.22^{bc}	0.44^{a}	236.17^{a}	21.47^{a}
Indian gooseberry-HCS	1.47^{b}	6.86^{b}	0.20^{c}	0.32^{d}	184.97^{c}	18.41^{b}
ACS	1.55^{a}	7.28^{a}	0.30^{a}	0.24^{e}	136.89^{e}	15.59^{c}
CD ($P \leq 0.05$)	0.01	0.20	0.04	0.02	16.61	0.94
Landscape position						
Lowland	1.42^{b}	7.18^{a}	0.22^{b}	0.38^{a}	198.90^{a}	19.73^{a}
Upland	1.47^{a}	6.95^{b}	0.27^{a}	0.34^{b}	172.05^{b}	17.45^{b}
CD ($P \leq 0.05$)	0.01	0.11	0.02	0.01	9.59	0.54
Soil depth (cm)						
0–15	1.42^{b}	6.91^{b}	0.27^{a}	0.38^{a}	204.82^{a}	17.53^{b}
15–30	1.47^{a}	7.23^{a}	0.23^{b}	0.33^{b}	166.13^{b}	19.65^{a}
CD ($P \leq 0.05$)	0.01	0.11	0.02	0.01	9.59	0.54

Mean values in the same column followed by a different letter differ significantly at $P \leq 0.05$. AFS – agroforest system; HCS – horticulture system; ACS – annual cropping system; CD – critical difference

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showed the highest OC, available N and P in the mango-HCS while the least in the ACS. However, the ACS recorded the highest bulk density and electric conductivity. Likewise, the lowland landscape position and topsoil layer (0–15 cm) recorded higher fertility (higher OC, available N, P) as compared to the upland and deeper soil layer, respectively. In upland soil leaching of base material resulted in lower pH, soil fertility and OC due to erosion, thereby recording the higher bulk density, whereas the inverse was true for lowland soil. Further, the topsoil showed higher OC content, which led to higher soil fertility as well as lower bulk density, as compared to the deeper soil profile.

For the WSB study, a total of seventy-two samples were drawn, with a 5-cm diameter auger, as per the methodology proposed by Forcella et al. (2003) on 30^{th} June 2017, and packed in air-tight sampling bags. Each soil sample was air-dried independently and sieved through a 2 mm screen to break up the big clouds and remove big pebbles, root pieces, and other debris, indicating that majority of the weed seeds were smaller than 2 mm. The sieved material was thinly spread over the aluminium trays (3–5 cm depth), placed randomly at the top of the rack (about two meters in height) in an open area covered with nylon net (3 cm mesh-seized) and nylon transparent sheet (2 mm). The trays were kept perforated and watered regularly to preserve the soil moisture content close to the field capacity. After the termination of the new weed seed emergence, i.e., nearly 100 days, dried soil was scratched in the tray and watered alternately to mimic the real field conditions to further initiate the weed seed emergence. Typically, all the emerged weeds had the emergence phase in the monsoon season (June to September).

Observation. For the quantification of the WSB, once a week, the emerged seedlings from each soil sample were visually identified, classified and counted separately and later classified into sedges, grasses, broadleaved weeds (BLWs) and expressed as density (number per m^2), by considering the surface area of the auger. The seedlings of doubtful identity were transplanted into another pot until their identity was verified and then discarded. "Composite List of Weeds", published by Weed Science Society of America, available online (http://wssa.net/), was used for the botanical nomenclature of weeds. However, weed species not available in the "Composite List of Weeds" were verified by Xu and Deng (2017) and Walia (2016). From the data of emerged weed, the weed community structure was analysed using the WDI like, Shannon-Weaver (H'), species richness (D_{Mg}), species evenness (J'), Simpson index (λ) and Whittaker statistics (β_W) as per the methodology used by Sharma et al. (2020).

Statistical analysis. Data on emerging WSB from different treatments were statistically analysed using the procedure suggested by Gomez and Gomez (1984). Bartlett's test was used to test the homogeneity of the treatment variance. Heterogeneous WSB data were square-root transformed [$\sqrt{(x + 0.5)}$] to produce a near-normal distribution. *F*-test was performed to test the significance of the treatment effect. The critical difference was estimated at a 5% probability level for the significant *F*-test. Moreover, to assess the variation in the WSB abundance as a function of cropping system, landscape position and soil depth, multivariate analysis viz., principal component analysis (PCA) and cluster analysis were carried out, based on the Pearson correlation coefficient index using XLSTAT 2020.5.1 (Addinsoft 2020).

RESULTS

The WSB was composed of twelve weed species, of which eight were the BLWs, namely *Ammannia baccifera* L. (AMBA), *Anagallis arvensis* L. (ANAR), *Euphorbia hirta* L. (EUHI), *Launaea asplenifolia* Hook. f. (LAAS), *Ludwigia hyssopifolia* (G. Don) Exell (LUHY), *Oldenlandia corymbosa* L. (OLCO), *Phyllanthus niruri* L. (PHNI2), *Portulaca oleracea* L. (POOL); three were grasses viz., *Dactyloctenium aegyptium* (L.) Willd (DAAE), *Digitaria sanguinalis* (L.) Scop. (DISA), *Eragrostis pilosa* (L.) P. Beauv. (ERPI2); and one species of sedges (*Cyperus* spp.) (Table 3). In terms of density, BLWs dominated the WSB (50–80%), followed by the sedges (11–30%) and grasses (8–20%), while the species-specific relative composition revealed PHNI2 dominated the WSB (25–36%) followed by *Cyperus* spp. (11–30%), ANAR (6–20%), DISA (3–15%) and others.

Cropping system. Cropping systems significantly affected the WSB dynamics. Guava-AFS recorded the highest WSB of all the weeds species, except the seedbank (SB) of grasses and ERPI2 (Table 4), while the minimum WSB was noticed in the mango-HCS (sedges, BLWs, total weed density, ANAR, OLCO and PHNI2) or guava-HCS (grasses, AMBA, ERPI2, EUHI). Despite the PHNI2 dominated the guava-AFS, it showed statistically at par with the SB of mango-AFS, Indian gooseberry-HCS and ACS.

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Table 3. Weed species recorded in the soil seedbank

Botanical name	US Code/Code	Family	Common name
Ammannia baccifera L.*	AMBA	Lythraceae	Common ammannia
Anagallis arvensis L.	ANAR	Primulaceae	Scarlet pimpernel
Cyperus spp.	–	Cyperaceae	Sedge
Dactyloctenium aegyptium (L.) Willd	DAAE	Poaceae	Crow foot grass
Digitaria sanguinalis (L.) Scop.	DISA	Poaceae	Large crabgrass
Eragrostis pilosa (L.) P. Beauv.	ERPI2	Poaceae	Indian love grass
Euphorbia hirta L.	EUHI	Euphorbiaceae	Garden spurge
Launaea asplenifolia Hook. f.**	LAAS	Asteraceae	Jangli Gobhi
Ludwigia hyssopifolia (G. Don) Exell *	LUHY	Onagraceae	Water Primrose
Oldenlandia corymbosa L.	OLCO	Rubiaceae	Old world diamond flower
Phyllanthus niruri L.	PHNI2	Phyllanthaceae	Niruri
Portulaca oleracea L.	POOL	Portulacaceae	Common purslane

Botanical nomenclature and US code (except for * and **) are listed as per "Composite List of Weeds" published by Weed Science Society of America and available online (http://wssa.net/).* and ** botanical nomenclature listed as per Xu and Deng (2017) and Walia (2016), respectively and accordingly code was made

A minimum SB of PHNI2 was observed in the mango-HCS and guava-HCS. The WSB of the total weed, BLWs, AMBA, EUHI and OLCO followed an almost similar trend of dominance in guava-AFS, followed by the mango-AFS, ACS and others. Likewise, the SB of sedges dominated the guava-AFS and was sta-

Table 4. Effect of cropping system, agro-ecosystem and soil depth on the density of weeds in the soil seedbank

Treatment	Density of weeds (number/m^2)											
	grasses	sedges	BLWs	Total	AMBA	ANAR	DAAE	DISA	ERPI2	EUHI	OLCO	PHNI2
Cropping system												
Guava-AFS	51.87^{a}	62.41^{a}	224.93^{a}	339.22^{a}	21.04^{a}	46.04^{a}	17.50	29.25^{a}	5.13^{b}	29.99^{a}	40.09^{a}	64.80^{a}
Mango-AFS	45.72^{ab}	41.53^{bc}	161.57^{b}	248.81^{b}	6.95^{bc}	33.70^{ab}	19.22	12.75^{bc}	13.75^{a}	11.60^{bcd}	30.35^{b}	62.29^{a}
Guava-HCS	22.05^{b}	32.39^{cd}	90.39^{c}	144.83^{d}	2.53^{c}	24.64^{b}	10.60	8.93^{bc}	2.53^{b}	2.53^{d}	12.21^{d}	39.10^{bc}
Mango-HCS	38.36^{ab}	18.28^{e}	84.23^{c}	140.87^{d}	3.31^{c}	10.75^{c}	14.80	21.03^{ab}	2.53^{b}	15.98^{b}	8.78^{d}	34.50^{c}
Indian gooseberry-HCS	25.34^{b}	29.86^{d}	142.39^{b}	197.59^{c}	2.53^{c}	22.67^{bc}	18.46	2.53^{c}	4.35^{b}	4.41^{cd}	16.62^{cd}	50.95^{ab}
ACS	53.89^{a}	52.62^{ab}	130.31^{b}	236.82^{bc}	11.38^{b}	25.77^{b}	25.06	25.06^{ab}	6.95^{ab}	14.10^{bc}	24.41^{bc}	49.70^{abc}
CD ($P \leq 0.05$)	24.57	11.27	34.21	48.55	6.98	13.54	ns	13.90	7.55	11.37	9.44	15.96
Landscape position												
Lowland	44.20	42.89^{a}	136.30	223.39	6.86	23.91	17.65	18.20	8.35^{a}	14.06	23.18	42.45^{b}
Upland	36.88	36.14^{b}	141.64	212.66	9.05	30.62	17.56	13.93	3.40^{b}	12.15	20.97	58.00^{a}
CD ($P \leq 0.05$)	ns	6.51	ns	ns	ns	ns	ns	ns	4.36	ns	ns	9.21
Soil depth (cm)												
0–15	62.07^{a}	52.19^{a}	203.78^{a}	318.04^{a}	14.60^{a}	40.09^{a}	29.61^{a}	23.02^{a}	10.43^{a}	23.16^{a}	37.37^{a}	60.38^{a}
15–30	17.02^{b}	26.84^{b}	74.15^{b}	118.01^{b}	1.31^{b}	14.43^{b}	6.60^{b}	9.10^{b}	1.31^{b}	3.05^{b}	6.78^{b}	40.07^{b}
CD ($P \leq 0.05$)	14.18	6.51	19.75	28.03	4.03	7.82	7.70	8.03	4.36	6.57	5.45	9.21

Mean values in the same column followed by a different letter differ significantly at $P \leq 0.05$. Data are subjected to square root transformation ($\sqrt{x} + 0.5$). AFS – agroforest system; HCS – horticulture system; ACS – annual cropping system; BLWs – broad-leaved weeds; AMBA – *Ammannia baccifera*; ANAR – *Anagallis arvensis*; DAAE – *Dactyloctenium aegyptium*; DISA – *Digitaria sanguinalis*; ERPI2 – *Eragrostis pilosa*; EUHI – *Euphorbia hirta*; OLCO – *Oldenlandia corymbosa*; PHNI2 – *Phyllanthus niruri*; CD – critical difference; ns – non-significant

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tistically at par with the ACS, followed by others. However, the SB of DISA was recorded statistically below par with guava-AFS, ACS as well as mango-HCS. Furthermore, the SB of grasses dominated the ACS and was statistically similar to other systems, except guava-HCS and Indian gooseberry-HCS, in which the minimum grassy WSB was recorded. Likewise, the mango-AFS recorded the maximum SB of the ERPI2 and were statistically at par with the ACS, followed by the other cropping systems. Moreover, the SB of DAAE did not vary among the cropping system.

Cropping systems significantly influenced the WDI mainly, H', D_{Mg}, λ and β_W (Table 5). The highest H', D_{Mg} and λ were recorded under guava-AFS, and it was at par with the mango-AFS and ACS, while statistically similar and lowest H', D_{Mg} and λ were noticed in the HCS of mango, guava and Indian gooseberry. Conversely, the lowest β_W was observed under the guava-AFS, whereas the highest β_W was recorded in the mango-HCS, which was at par with guava and Indian gooseberry-HCS. Apart from the above, the cropping system did not significantly affect the J'.

Cluster analysis based on the Bray and Curtis distance indicated that the WSB under HCS of Indian gooseberry as well as guava were quite similar to the mango-HCS and were distinctly separated from the other three cropping systems (Figure 1). Further, the WSB under ACS showed more relevance to the mango-AFS, and both showed similarity with guava-AFS. PCA of WSB, based on the spatial representation (Figure 2), revealed that the principal axes 1 and 2 accounted for 48.27% and 21.23% of the total variation, respectively (cumulative value 69.50%). Further, the cropping system, soil depth and landscape position variation divided WSB into three groups: (1) OLCO, ANAR, EUHI2, *Cyperus* spp., AMBA, PHNI2, DISA; (2) LUHY, POOL, others, and (3) DAAE, LAAS, ERPI. Furthermore, the PCA also showed distinctiveness among the variable cropping systems.

Landscape position and soil depth. Landscape position variation significantly affected the SB of *Cyperus* spp., ERPI2 and PHNI2 (Table 4). The SB of *Cyperus* spp. and ERPI2 were dominated in the lowland; conversely, the upland was dominated by PHNI2. Generally, the predominant weed under upland was PHNI2 (36.79%), while the lowland was composed of approximately a similar dominance (about 23%) of *Cyperus* spp. and PHNI2.

Soil depths appreciably influenced the WSB. In general, the WSB decreased with the soil depth. In topsoil

Table 5. Effect of different cropping systems, agro-ecosystem and soil depth on the weed diversity indices

Treatment	Weed diversity indices				
	Shannon Weaver (H')	Species evenness (J')	Species richness (D_{Mg})	Simpson index (λ)	Whittaker statistics (β_W)
Cropping system					
Guava-AFS	1.49^{a}	0.85	1.27^{a}	0.71^{a}	2.36^{c}
Mango-AFS	1.40^{a}	0.87	1.14^{ab}	0.68^{a}	2.73^{bc}
Guava-HCS	1.07^{bc}	0.86	0.75^{c}	0.59^{abc}	3.74^{abc}
Mango-HCS	1.00^{c}	0.73	0.72^{c}	0.52^{c}	4.96^{a}
Indian gooseberry-HCS	1.13^{bc}	0.69	0.97^{bc}	0.55^{bc}	4.22^{ab}
ACS	1.32^{ab}	0.85	1.11^{ab}	0.67^{ab}	2.88^{bc}
CD ($P \leq 0.05$)	0.25	ns	0.25	0.12	1.68
Landscape position					
Lowland	1.26	0.81	1.03	0.62	3.47
Upland	1.21	0.81	0.96	0.62	3.49
CD ($P \leq 0.05$)	ns	ns	ns	ns	ns
Soil depth (cm)					
0–15	1.64^{a}	0.87^{a}	1.42^{a}	0.75^{a}	1.98^{b}
15–30	0.83^{b}	0.76^{b}	0.56^{b}	0.49^{b}	4.98^{a}
CD ($P \leq 0.05$)	0.15	0.10	0.14	0.07	0.97

Mean values in the same column followed by a different letter differ significantly at $P \leq 0.05$. AFS – agroforest system; HCS – horticulture system; ACS – annual cropping system; CD – critical difference; ns – non-significant

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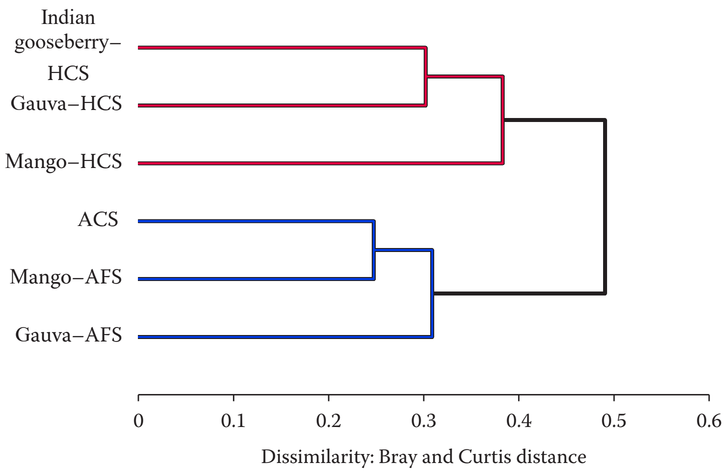

Figure 1. Cluster analysis of different cropping systems based on Bray-Curtis distance. AFS – agroforest system; HCS – horticulture system; ACS – annual cropping system

(0–15 cm), AMBA, ERPI2, EUHI, and OLCO deposited more than 90% of their total SB; moreover, *Cyperus* spp., BLWs, DISA, PHNI2 deposited 67–79% of their SB. Landscape position did not significantly affect the WDI; however, the soil depth did. WDI, mainly H', D_{Mg}, J' and λ followed an inverse relationship with the soil depth (Table 5); conversely, $β_W$ increased with the soil depth.

DISCUSSION

Cropping system. In the present study, the WSB assessment through the germination method clearly demonstrates that the cropping system considerably influences the WSB and subsequent species composition. The previous study also revealed that changes in the cropping system modify the ecosystem, causing the change in the WSB dynamics (Lal et al. 2016) through the alteration of the environment and soil (Plaza et al. 2011) along with the management practices (Koocheki et al. 2009). Further, the WSB study revealed that BLWs and sedges were dominated in the different cropping systems, of which PHNI2, ANAR, and OLCO are the predominant BLWs, DAAE and DISA are the predominant grasses. However, it is theoretically presumed that, under the AFS, the abundance of the weeds decreases due to the segregation in the WSB by the biophysical variation within the AFS (López-Pintor et al. 2013).

Further, it was hypothesised that trees lead to microclimate moderation vis-à-vis soil covering with litter, which

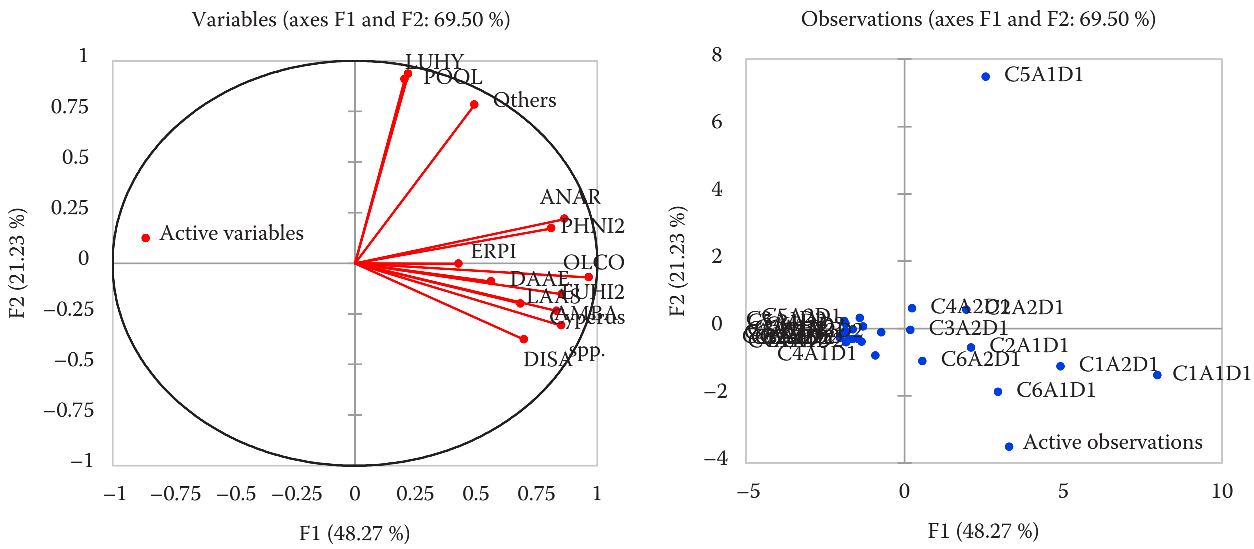

Figure 2. Principal component analysis showing community structure of the viable weed seed in soil and treatment combination. C1 – Guava-AFS; C2 – Mango-AFS; C3 – Guava-HCS; C4 – Mango-HCS; C5 – Indian gooseberry-HCS; C6 – ACS; A1 – lowland landscape position; A2 – upland landscape position; D1 – 0–15 cm soil depth; D2 – 15–30 cm soil depth

https://doi.org/10.17221/162/2022-PSE

improves the soil quality, thus enhancing crop growth and subsequently restricting weeds infestation (Pumariño et al. 2015). However, contrary to this hypothesis in the present study, the highest SB of sedges, BLWs and total weeds (including all individual species, except for grassy and ERPI2) was observed under AFS, specifically under the guava-AFS; this might be due to tree's ability to create a distinct ecological niche in the agricultural landscape (Tsonkova et al. 2012). Distinct ecological niche under trees is primarily associated with nutrient retrieval from beneath the crop rooting zone, reduction of nutrient losses and addition of soil organic matter (Buresh and Tian 1998), thereby improving the soil's physico-chemical and biological properties. Additionally, it also reduces the interception of direct solar radiation, thus modifying the microclimate. Improvement in soil properties and microclimate improves soil moisture retention as well as better condition for the proliferation of the crop (Hawke and Wedderburn 1994) and weeds, especially in the semi-arid region. Furthermore, in the alley-cropped AFS, the understory herbaceous strips serve as a reservoir for weeds and provide an opportunity for biodiversity conservation (Boinot et al. 2019). These results are in conformity with Shivran et al. (2017), which also showed a higher density of BLWs, sedges and total weeds in the green gram (*Vigna radiata*) based AFS over the green gram in ACS. Likewise, Deiss et al. (2017) also reported higher weed species diversity and concentration in AFS compared to the sole cropping system.

Furthermore, HCS, especially the mango-HCS, provide less conducive conditions for germinating all the weeds, except the DISA (highest in Indian gooseberry-HCS) and EUHI (in guava-HCS), mainly due to dense canopy and lack of regular soil disturbance. In general, under HCS, dense foliage attenuates light penetration within the canopy, which is essential for weed seed germination. Simultaneously, due to the lack of regular soil disturbance, most of the WSB remain on the topsoil, thus weed seeds are exposed to harsh environmental conditions, like, as high humidity and moist soil condition, which favours the microbial decay and predation (Liebman et al. 2001, Sharma et al. 2020). Although, the tree species influences the understory herbaceous strips differentially, including weed density and composition based on the denseness of the canopy, leaves characteristics, allelopathy and other factors (Rizvi et al. 1999, Harmand et al. 2003). Similarly, in the current experiment, Indian gooseberry-HCS recorded significantly higher WSB than the other two HCS; this might be attributed to two reasons, firstly, due to the deciduous nature of the tree and secondly, higher rate of leaves decomposition, similar to the *Leucaena leucocephala* which is less effective in reducing weed infestation (Kamara et al. 2000). Further, higher WSB under Indian gooseberry-HCS was followed by the guava-HCS which is semi-deciduous to evergreen in nature, whereas, least WSB in mango-HCS which is an evergreen tree having dense canopy that can produce 100% shade (Bally 2006) and secrete allelochemicals in root-rhizosphere (Kato-Noguchi and Kurniadie 2020), thereby provides a less favourable environment for weed infestation and deposition of WSB.

However, the ACS of the semi-arid region receives sufficient light for weed seed stimulation, but the lack of soil moisture coupled with desiccating wind plays a key role in weed proliferation. Interestingly, compared to AFS and HCS, WSB under ACS was predominated by C4 weed species, like PHNI2, ERPI2, DISA, DAAE and *Cyperus* spp. because under hot and arid conditions, the C4 plants perform better, showing higher water use efficiency and producing more biomass, root growth and seeds than C3 plants (Varanasi et al. 2016). Further, the highest grasses WSB were recorded under ACS and were at par with guava-AFS and mango-AFS. This might be attributed to the SB of DAAE, despite the fact that DAAE was not considerably influenced by the cropping system. However, ACS has better illumination than AFS or HCS; this condition stimulates the germination of DAAE (Chauhan 2011), thus recording almost double the DAAE SB over HCS. In conformity with our findings, Kumar et al. (2018) also observed non-significant variation in grassy weed density among ACS and AFS.

The diversity of species within the weed community, as well as the nature of their relationships, is of agronomic importance (Derksen et al. 1995). The WDI values recorded in the present study are within the range of previously reported studies for various cropping systems (Derksen et al. 1995), like, H' value is consistent with the previously reported value, i.e., less than 2.0 (Sharma et al. 2020). Moreover, the non-significant variation in J' among cropping systems signifies no relative dominance of any species. Simultaneously, the appreciably lower D_{Mg} as well as H' index under the mango-HCS critically establish the reduced weed diversity with low WSB and was also confirmed by the low λ and high β_W, which raises a serious concern. It is important to mention that more diversity of weed community in any cropping system clearly reflects a less competitive environment as well as less chance for dominance by highly adapted

https://doi.org/10.17221/162/2022-PSE

herbicide resistance species. Moreover, higher weed diversity is indicative of wider sustainability, i.e., both the agronomic and environmental sustainability of the whole cropping system (Storkey and Neve 2018). Studies showed that enhanced weed diversity has a beneficial effect on the agroecological system functioning (Franke et al. 2009) as higher biodiversity is an indicator of a healthy ecosystem which enhances both productivity and stability of the system (Sharma et al. 2020). However, the low diversity in the mango-HCS may be due to limited light availability to the undergrown weeds, thus suppressing the growth of some weeds like sedges (*Cyperus* spp.) (Shetty et al. 1982) and ANAR (CABI 2021).

Landscape position and soil depth. In lowland landscape positions, the occurrence of temporary waterlogging during the rainy season for two to three days is common, which favours the growth of ERPI2 (Li et al. 2006); thus, a higher SB of ERPI2 was recorded. Apart from these, upland soils are poor in soil fertility and organic matter (Table 1) and have low moisture content (Adeli et al. 2020), which did not favour the growth of *Cyperus* spp. (Peerzada 2017) and ERPI2 (Li et al. 2006). PHNI2 dominated the upland because the drier upland condition has the preferential natural habitat of this weed (Saraswat 1980). Irrespective of the weed categories and species, maximum WSB was observed at the top 0–15 cm, which reduced with the depth. Likewise, the WDI, except β_W, also reported a similar trend. The top soil layer (0–15 cm) showed higher D_{Mg} and H' indices that indicate the existence of more diverse weed species; further, the higher λ signifies the dominance of some weed species in the topsoil as compared with the deeper layer. Usually, during the primary dispersal process, the seed rain from the plant at maturity occupies the top layer of soil (Singh-Manpreet et al. 2015); later on, through natural or manual tillage process, the seeds reach the deeper layer of the soil profile (Benvenuti et al. 2001). However, germination from the bottom layer (15–30 cm) of the soil profile is still associated with induced dormancy rather than suicidal germination because of excessive burial depth (Benvenuti et al. 2001). Overall, the study shows that the AFS have a larger and more diverse WSB, making the AFS more healthy agro-ecosystem than other systems. Furthermore, the predominance of certain weed species in the HCS with low WSB raises serious concerns about the sustainability of these systems. Simultaneously, ACS, an open cropping system, have a larger proportion of C4 weeds than either light (AFS) or fully shaded systems (HCS).

Acknowledgement. The authors are grateful to the Head of Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi (UP), for providing the necessary facilities during the study.

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Received: May 3, 2022
Accepted: November 10, 2022
Published online: November 28, 2022