Weed Science

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Weed communities of snap bean fields in the United States

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Abstract

Weeds are one of the greatest challenges to snap bean (*Phaseolus vulgaris* L.) production. Anecdotal observation posits certain species frequently escape the weed management system by the time of crop harvest, hereafter called residual weeds. The objectives of this work were to (1) quantify the residual weed community in snap bean grown for processing across the major growing regions in the United States and (2) investigate linkages between the density of residual weeds and their contributions to weed canopy cover. In surveys of 358 fields across the Northwest (NW), Midwest (MW), and Northeast (NE), residual weeds were observed in 95% of the fields. While a total of 109 species or species-groups were identified, one to three species dominated the residual weed community of individual fields in most cases. It was not uncommon to have >10 weeds m^{-2} with a weed canopy covering >5% of the field's surface area. Some of the most abundant and problematic species or species-groups escaping control included amaranth species such as smooth pigweed (*Amaranthus hybridus* L.), Palmer amaranth (*Amaranthus palmeri* S. Watson), redroot pigweed (*Amaranthus retroflexus* L.), and waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer]; common lambsquarters (*Chenopodium album* L.); large crabgrass [*Digitaria sanguinalis* (L.) Scop.]; and ivyleaf morningglory (*Ipomoea hederacea* Jacq.). Emerging threats include hophornbeam copperleaf (*Acalypha ostryifolia* Riddell) in the MW and sharppoint fluvellin [*Kickxia elatine* (L.) Dumort.] in the NW. Beyond crop losses due to weed interference, the weed canopy at harvest poses a risk to contaminating snap bean products with foreign material. Random forest modeling predicts the residual weed canopy is dominated by *C. album*, *D. sanguinalis*, carpetweed (*Mollugo verticillata* L.), *I. hederacea*, amaranth species, and *A. ostryifolia*. This is the first quantitative report on the weed community escaping control in U.S. snap bean production.

Introduction

Snap beans are cultivars of common bean (*Phaseolus vulgaris* L.) grown for their young and unripe fruits (pods). More than 80% of snap bean is grown commercially for processing, with the remainder grown for the fresh market (Davis et al. 2023). Two-thirds of processed snap bean is canned and one-third is frozen (USDA-NASS 2024). Snap bean in the United States is grown for processing in the Northeast (NE), the Midwest (MW), and the Northwest (NW) (USDA-NASS 2024). In the last decade, snap bean grown for processing has decreased ~30% (USDA-NASS 2024). Declining production is attributed to increased snap bean imports and changing consumer preference toward fresh and frozen products (Davis et al. 2023).

Among the biggest challenges in row crop production in North America are weeds, whose competition for resources, costs of control, and harvest interference equate to an estimated US $44 billion in economic losses annually (Soltani et al. 2016, 2017). In snap bean production, competition from weeds escaping control causes up to 80% in direct yield loss (Odero and Wright 2018; Qasem 1995). Certain species cause greater harm by contaminating the harvested product. For instance, berries of nightshade species (*Solanum* spp.) can lead to entire harvested loads being rejected by processors (Peachey 2019). Consumers, vegetable processors, and food inspectors alike have a low tolerance for weedy vegetation (i.e., foreign material) in snap bean products. Despite the significance of weeds in snap bean production, detailed knowledge of specific weed problems in snap bean is limited to anecdotal observations. Weed species or species-groups observed in snap bean trials and other reports in the 21st century include

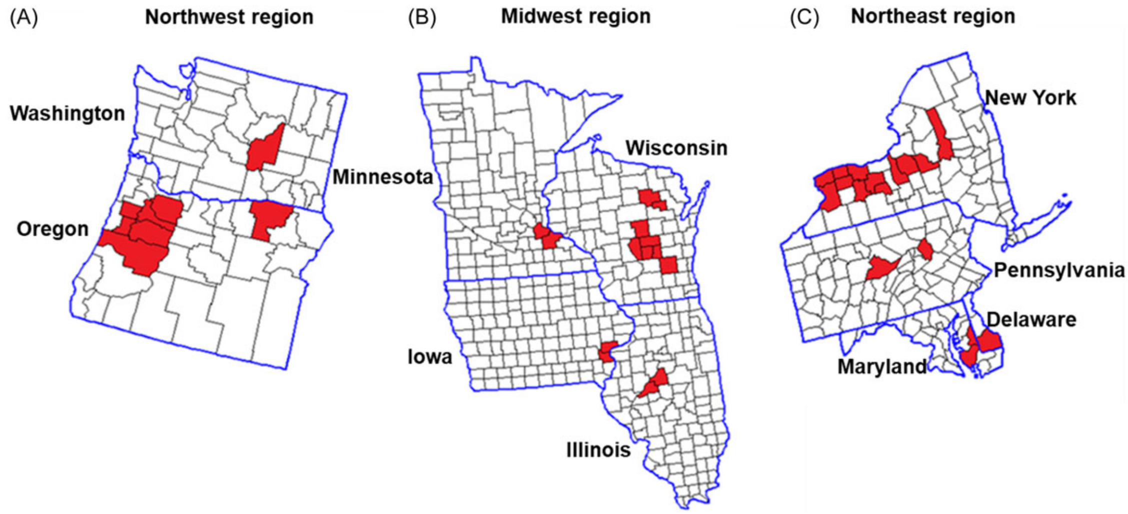

Figure 1. Counties of surveyed snap bean fields in the (A) Northwest, (B) Midwest, and (C) Northeast regions of the United States.

amaranth species (*Amaranthus* spp.), common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), nutsedge species (*Cyperus* spp.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], morningglory species (*Ipomoea* spp.), common purslane (*Portulaca oleracea* L.), wild radish (*Raphanus raphanistrum* L.), and hairy nightshade (*Solanum physalifolium* Rusby) (Aguyoh et al. 2003a, 2003b; Bailey et al. 2003; Boyhan et al. 2013; Bradley et al. 2007; Peachey 2019; Peachey et al. 2004; Van Wychen 2022).

Quantitative knowledge of weed community structure is fundamental to understanding the scope of weed issues and directing future management and research efforts in numerous row crops (Frick and Thomas 1992; Froud-Williams and Chancellor 1982; Rydberg and Milberg 2000; Salonen et al. 2001; Thomas 1985; Thomas and Dale 1991; Williams et al. 2008). Weeds observed late in the crop growing season, hereafter called residual weeds, are the cumulative result of unsuccessful weed management. Differences in residual weeds occurring across growing regions reflect the influence of variable environmental conditions and management practices. These residual populations also contribute to the weed seedbanks of their respective fields. Collectively, the canopy of the weed community at harvest represents the greatest threat to contaminating a snap bean product with foreign material. The objectives of this work were to (1) quantify the residual weed community in snap bean grown for processing across the major growing regions in the United States and (2) investigate linkages between the density of residual weeds and their contributions to the weed canopy cover.

Materials and Methods

Description of Survey Area and Survey Methodology

Surveys of weeds in snap bean fields were conducted in 2019 to 2023 across the NW, MW, and NE regions. The authors collaborated with vegetable processors in each region to identify candidate fields. Fields were selected from counties that were among the leading snap bean producers for each state (USDA-NASS 2024; Figure 1). Furthermore, surveys were conducted across a broad period of snap bean harvest, from June through October.

Surveys were conducted within 1 wk before harvest. The survey methodology utilized the approach described by Thomas (1985) with slight modifications. In each field, 30 quadrats, or 1 quadrat ha $^{-1}$ on fields ≤20 ha, were placed randomly along a 300- to 500-m loop across the field. The minimum quadrat size was 0.5 m^2 (1-m length and 0.5-m width), and quadrats were placed parallel to the crop rows. Field areas within 20 m of the field edge were avoided. In each quadrat, residual weeds were enumerated by species. Weed species belonging to the same genus were similar in appearance in the seedling stage.

Quantifying the contribution of each weed species or species-group to the overall weed canopy at the time of crop harvest was not practical. Therefore, a visual estimate of the total cover of the weed community canopy, expressed as a percentage of the quadrat, was recorded in each quadrat.

Data Analysis

Quantitative indices of field frequency, mean field density, mean occurrence field density, mean field uniformity, and mean occurrence field uniformity were calculated (Thomas 1985). Field frequency (F) is the number of fields in which a species or species-group occurred, expressed as a percentage of the total number of fields. Mean field density (MFD) is the average number of individuals of a species or species-group k m^{-2} across all fields. Mean occurrence field density (MOFD) is the average number of individuals of a species or species-group k m^{-2} in fields where the species or species-group k occurred. Mean field uniformity (MFU) is the average number of quadrats in which a species or species-group k occurred across all fields, expressed as a percentage of all quadrats. Mean occurrence field uniformity (MOFU) is the average number of quadrats in which a species or species-group k occurred, expressed as a percentage of quadrats in fields where species or species-group k occurred. Total weed cover of all quadrats was averaged for each field to obtain the mean weed cover (MWC).

To rank the contribution of a species or species-group, F, MFD, and MFU were combined into a single index called relative abundance (RA) (Thomas 1985). RA assumes F, MFD, and MFU all have equal contribution to the weed community and has no units. Every weed species or species-group k value of F, MFD, and MFU was divided by its respective sum values of F, MFD, and MFU

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of all species or species-groups. The obtained values of each species or species-group k represent the relative values of F, MFD, and MFU, and the relative values of all species or species-groups is 100. Therefore, as there are three indices, the total value of RA of all species or species-groups is 300.

The Simpson index was used to characterize the diversity of the weed community (Simpson 1949). The Simpson index is defined as the probability that two individuals chosen at random and independently from an infinitely large population will belong to the same group. In this instance, the group represents a weed species or species-group. The index value is expressed as a reciprocal called Simpson's reciprocal index (SRI). Higher values of the index represent more diversity, with the lowest value being 1 (representing a community dominated by only one species) and the highest value being the total number of species in the community, which are all evenly distributed. Hence, the SRI is seen as a dominance index by giving more weight to the dominant species of the community (Kent 2012).

Distributions of the data did not meet the assumptions of normality and homoscedasticity necessary to conduct the parametric t-test; therefore, the nonparametric Wilcoxon-Mann-Whitney U-test was utilized (Fay and Proschan 2010; Mann and Whitney 1947) to compare regions for SRI, MFD, MFC, and MFU.

A random forest algorithm was used to gain insight into relationships between density of each species or species-group and weed cover (Breiman 2001). Random forest is a classifier consisting of a collection of tree-structured classifiers wherein each tree casts a unit vote for the most popular class of input. Random forest is nonparametric, so classical regression assumptions relating to data structure and distribution are not required. The goal of this approach was to determine the weed species or species-group that best predicted weed cover. Species or species-groups contributing to weed cover provide additional information on the significance of a weed species or species-group in the weed community (Kent 2012; Nkoa et al. 2015). This is particularly important for a crop like snap bean, for which weedy vegetation at crop harvest can contaminate the food product.

The package RANGER in R statistical software (v. 4.3.2; R Core Team 2023) was used for the random forest analysis. Tuning parameters were set so that the model with the lowest root mean-square error and highest goodness of fit (pseudo-R^2) values could be fit. The number of individual regression trees was set to 1,000, as suggested by Breiman (2001), while the optimal number of independent variables randomly selected as candidates for each split in the trees was set to 55, and the minimum optimal number of observations in each terminal node was set to 5. Across all regions, 9,999 quadrat samples were collected; however, due to missing data, the actual sample size was 8,178 quadrats. The dataset used for training the model was 80% of the whole sample size (6,542 quadrats), while the remaining 20% (1,636 quadrats) was used as a test set for checking the accuracy of the trained model. Before model fitting, the values of all variables were both scaled and transformed with the Yeo-Johnson transformation (Yeo and Johnson 2000). Due to certain randomization aspects of the algorithm, it is only possible to determine how important certain predictors were in the model, not necessarily what kind of relationship they have with the response variable. The "importance" of the predictor variable is defined as permutation importance, which considers the positive effect it had on the prediction performance (Breiman 2001). Partial dependence plots were used to visualize model relationships.

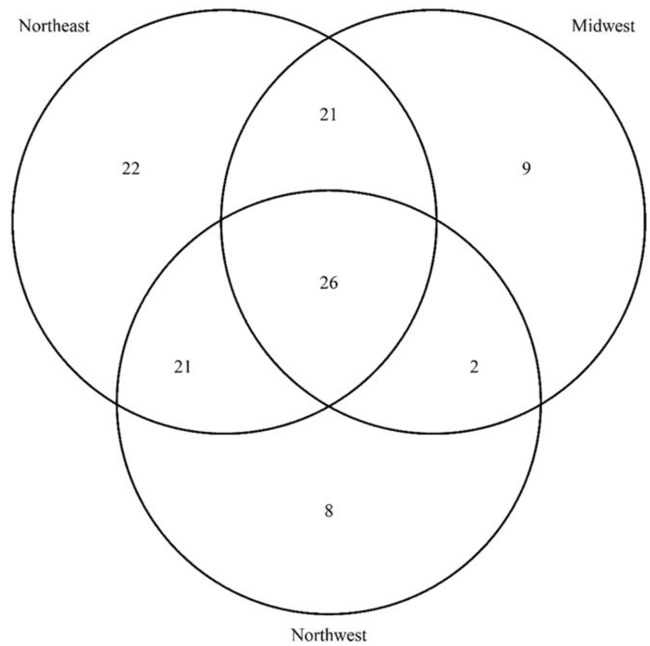

Figure 2. Venn diagram of the number of unique and shared weed species or species-groups among Northwest, Midwest, and Northeast regions of the United States.

Results and Discussion

Overview

A total of 358 snap bean fields were surveyed. The majority (57%) were from the MW region, followed by the NE (23%) and the NW (20%). Fields from these three regions reflect the wide range of environmental conditions where snap bean is grown for processing in the United States. The MW and NE mostly have a humid continental climate (Köppen climate types Dfa and Dfb) with temperatures that vary greatly from summer to winter and appreciable precipitation (Paleontological Research Institution 2022; Wall and Parrish 2014). In the NW, the vast majority of the fields were surveyed in the western part of Oregon state, which has a warm-summer Mediterranean climate (Köppen climate type Csb) characterized by warm and dry summers and mild to cool and wet winters (Zabel et al. 2014).

A total of 109 residual weed species or species-groups representing 31 plant families were observed. The NE had the most weed species or species-groups and families, 90 and 30, respectively. The MW had 58 weed species or species-groups from 24 families. The NW had 57 species or species-groups from 20 families. There were 26 shared weed species or species-groups among the three regions, 21 shared species or species-groups between NE and MW, and NE and NW, and only 2 shared species or species-groups between MW and NW (Figure 2). There were 22 species or species-groups that occurred only in the NE region, while there were 9 and 8 species or species-groups occuring only in the MW and NW regions, respectively. Even though the number of observed residual weed species or species-groups exceeds 100, in ecological surveys of plant communities, it is usual for only a few species to dominate individual sites (Kent 2012), particularly in agroecosystems where intense selection pressure from management influences the weed community (Storkey and Neve 2018). This is evidenced in the diversity of weed communities, as characterized by field SRIs. While several species or species-groups

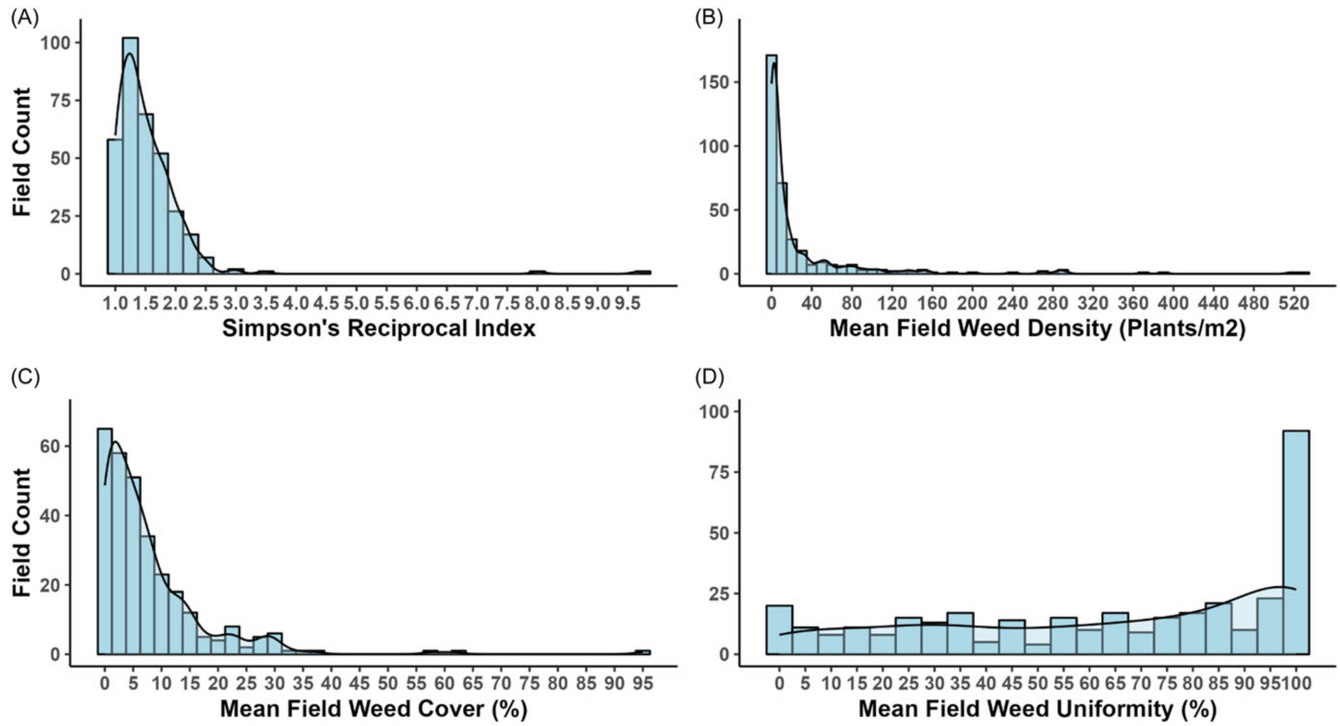

Figure 3. Density distribution plots of (A) Simpsons's reciprocal index, (B) mean field weed density, (C) mean field weed uniformity, and (D) mean field weed cover across regions.

were observed throughout each region, most individual fields had an SRI of 1 to 3 (Figure 3A), indicating that one to three species often dominated the residual weed community.

A majority (95%) of fields had residual weeds at the time of snap bean harvest. Several quantitative indices used to characterize the weed community were skewed right. For instance, it was not uncommon to have MFD >10 plants m^{-2} and MWC > 5% (Figure 3B and 3C, respectively). The extent to which these residual weed communities resulted in yield losses or contaminated harvested product is unknown. However, incomplete weed control during crop flowering can exacerbate the effects of adverse weather on crop yield (Konsens et al. 1991; Landau et al. 2021, 2022).

There were some important specific distinctions in the residual weed community of each production region. Diversity was highest (P-value < 0.01) in the MW and NE (median SRI values of 1.46 and 1.40, respectively) compared with the NW (median SRI value of 1.22) (Figure 4A). This was due to several fields in the MW and NE having more than two dominant weed species or species-groups. The MW had a higher median MFD (10.8 plants m^{-2}), MWC (6.6%), and MFU (86.7%) than the other two regions (P-value < 0.01) (Figure 4B–D). Collectively, the NW had among the smallest residual weed communities for every metric measured.

Weed Community Composition

Amaranth species and *C. album* were among the most abundant species or species-groups observed in the NW (Table 1), MW (Table 2), and NE (Table 3). Waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] is a threat to snap bean production, because the stems break into pod-sized fragments at crop harvest and contaminate harvested product (R Pequinot, personal communication). Aguyoh and Masiunas (2003b) noted that redroot pigweed (*Amaranthus retroflexus* L.) was becoming more common in MW snap bean production and showed the weed caused >50% yield loss when crop and weed emergence coincided. Other amaranth species observed in the survey of growers' fields included smooth pigweed (*Amaranthus hybridus* L.) and Palmer amaranth (*Amaranthus palmeri* S. Watson). Amaranth species will continue to be an issue in snap bean production due to their high level of adaptability, widespread herbicide resistance, enormous seed production, and presence throughout the growing season due to discontinuous germination. *Chenopodium album* has been identified as a troublesome weed in snap bean production in New York (Van Wychen 2022) and Oregon (Peachey 2019). *Chenopodium album* has been the object of study in snap bean dating to the mid-1980s (Vencill et al. 1990; Wilson and Hines 1987). Wilson and Hines (1987) evaluated the use of acifluorfen for postemergence control of *C. album* in snap bean production. Meanwhile, Vencill et al. (1990) evaluated the effectiveness of imazethapyr use in snap bean production. Both the works of Wilson and Hines (1987) and Vencill et al. (1990) had the goal of finding new herbicide options for *C. album* control in snap bean production, since it was noted as a predominant weed in snap bean production in Virginia.

Nightshade species such as black nightshade (*Solanum nigrum* L.), *S. physalifolium*, and eastern black nightshade (*Solanum ptychanthum* Dunal) were observed throughout the United States, ranking as high as fourth and third in relative abundance in the NW (Table 1) and MW (Table 2), respectively. Peachey (2019) reported these species as being very troublesome in Oregon, as their berries, toxic to humans, can contaminate the harvested product, leading to entire harvested loads being rejected at processing facilities.

Across the United States, *D. sanguinalis* was one of the most abundant grass weeds in snap bean (Tables 1–3). In the early 2000s, *D. sanguinalis* was observed as a weed in MW snap bean production and could cause >50% yield loss at densities as low as 2

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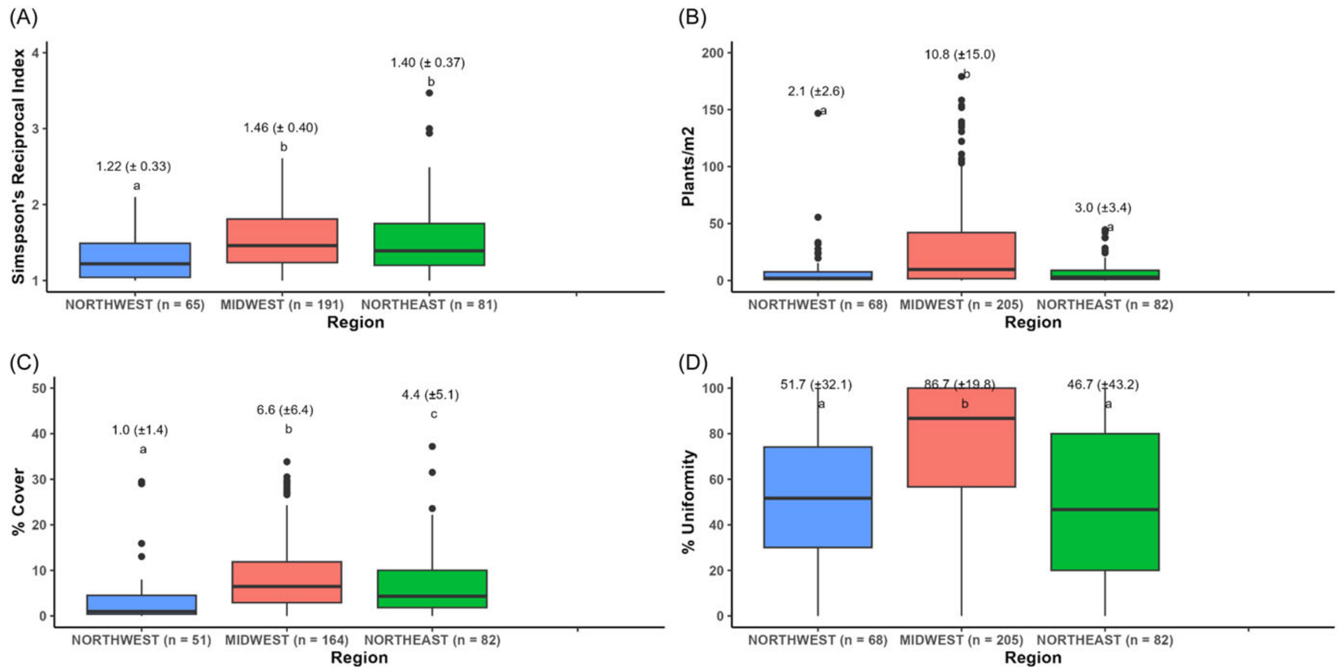

Figure 4. Distributions of (A) Simpson's reciprocal index, (B) mean field weed density, (C) mean field weed cover, and (D) mean field weed uniformity by region. Values above each box-and-whisker plot represent median values with median absolute deviation in parentheses.

plants m^{-2} (Aguyoh and Masiunas 2003a). In the MW and NE regions, MOFD of *D. sanguinalis* exceeded >12 plants m^{-2}, suggesting the weed may be widely troublesome.

Common chickweed [*Stellaria media* (L.) Vill.] was often observed in snap bean throughout the United States (Tables 1–3). *Stellaria media* was mainly observed in the seedling stage in fields surveyed late in the growing season (P.P., personal observation). Because *S. media* is a winter annual, the relatively high MOFD of its seedlings at crop harvest likely presents a minimal threat to snap bean production. Additional winter annuals that were often observed in the seedling stage in late-harvested snap bean fields of two or more regions included henbit (*Lamium amplexicaule* L.) and shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.].

Carpetweed (*Mollugo verticillata* L.) and ivyleaf morningglory (*Ipomoea hederacea* Jacq.), present in the MW and NE regions, were among the most abundant species in those two regions (Tables 2 and 3, respectively). *Mollugo verticillata* was the most abundant species in the MW. The prostrate growth habit of *M. verticillata* coupled with its relatively small plant size points to *M. verticillata* being not acutely problematic. In contrast, *Ipomoea* species are problematic in snap bean production because they vine around the crop and can interfere with harvest. *Ipomoea* species also are problematic in snap bean fields in the U.S. Southeast (Boyhan et al. 2013).

Portulaca oleracea was the 10th and 14th most abundant weed in the MW and NE regions, respectively (Tables 2 and 3, respectively). Early research by Vengris and Stacewicz-Sapuncakis (1971) showed *P. oleracea* emergence within 2 wk of snap bean emergence was detrimental to crop yield. Boyhan et al. (2013) noted the threat of *P. oleracea* in snap bean could be mitigated with the use of pendimethalin, trifluralin, and *S*-metolachlor.

Hophornbeam copperleaf (*Acalypha ostryifolia* Riddell) was observed in the MW and NE regions (Tables 2 and 3, respectively). The weed was found in Illinois fields with a high density of >11.5 plants m^{-2} on at least one-third of fields surveyed in the state (data not shown). Illinois fields had some of the latest plantings out of all surveyed (late July), and *A. ostryifolia* is known to germinate quickly in warmer temperatures throughout summer (Sosnoskie et al. 2020). The weed also has become widespread throughout the MW because of its innate tolerance to herbicides containing dicamba, which are commonly used in crops rotated with snap bean.

Aside from *D. sanguinalis*, additional annual grass species most abundant in one or more regions included annual bluegrass (*Poa annua* L.) and foxtail species such as giant foxtail (*Setaria faberi* Herrm.), green foxtail [*Setaria viridis* (L.) P. Beauv.], and yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.] in the NE and fall panicum (*Panicum dichotomiflorum* Michx.) in both the MW and NE. Despite the abundance of some of these grassy species, they can be easily controlled with the use of graminicides, as there are several products registered for that purpose in snap bean (CDMS 2024). However, it is important to note that the minimum time from application to harvest (PHI) for graminicides is 15 to 21 d, which means that these herbicides can only be used until the period of snap bean flowering (Anonymous 2018, 2020, 2021). Therefore, the observed residual grassy species are most probably those that emerged after the PHI, which should be monitored in the future so that later-emerging populations are not selected for.

Common groundsel (*Senecio vulgaris* L.) and sharppoint fluvellin [*Kickxia elatine* (L.) Dumort.] were additional shared species between the NW and NE. There are no previous reports on these species in snap bean production. *Senecio vulgaris* is a winter annual weed found throughout the NW and is adapted to wet

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Table 1. Top 30 weed species in the Northwest region arranged by relative abundance[a].

Rank	Latin binomial with authority	Common name	EPPO code	Lifeform	RA	F	MFD	MOFD	MFU	MOFU
						%	—no. m^{-2}—		——%——	
1	*Stellaria media* (L.) Vill.	Common chickweed	STEME	Annual	46.6	10.3	5.7	55.3	3.3	31.9
2	*Amaranthus* spp.	Amaranth species	AMASPP	Annual	40.9	50.0	2.5	5.0	11.7	23.3
3	*Chenopodium album* L.	Common lambsquarters	CHEAL	Annual	30.1	60.3	0.8	1.4	11.2	18.6
4	*Solanum* spp.	Nightshade species	SOLSPP	Annual	27.8	57.4	0.6	1.0	11.1	19.4
5	*Capsella bursa-pastoris* L.	Shepherd's purse	CAPBP	Annual	22.7	36.8	0.9	2.5	8.1	22.1
6	*Veronica hederifolia* L.	Ivyleaf speedwell	VERHE	Annual	14.4	17.6	1.0	5.5	3.6	20.6
7	*Trifolium* spp.	Clover species	TRFSPP		10.6	20.6	0.4	2.0	3.3	16.2
8	*Senecio vulgaris* L.	Common groundsel	SENVU	Annual	9.3	23.5	0.2	0.7	3.3	14.2
9	*Kickxia elatine* (L.) Dumort.	Sharppoint fluvellin	KICEL	Annual	8.9	16.2	0.3	1.9	3.2	19.7
10	*Medicago sativa* L.	Volunteer alfalfa	MEDSA	Perennial	8.4	7.4	0.4	4.9	3.9	52.7
11	*Convolvulus arvensis* L.	Field bindweed	CONAR	Perennial	7.5	19.1	0.1	0.5	2.8	14.6
12	*Lamium amplexicaule* L.	Henbit	LAMAM	Annual	7.1	8.8	0.4	4.2	2.5	27.8
13	*Persicaria pensylvanica* (L.) M. Gómez	Pennsylvania smartweed	POLPY	Annual	6.9	19.1	0.2	0.8	1.9	10.0
14	*Sonchus arvensis* L.	Perennial sowthistle	SONAR	Perennial	4.9	14.7	0.03	0.2	1.7	11.3
15	*Lolium* spp.	Ryegrass species	LOLSPP		4.8	13.2	0.1	0.6	1.6	11.9
16	*Digitaria sanguinalis* (L.) Scop.	Large crabgrass	DIGSA	Annual	3.1	8.8	0.03	0.3	1.1	12.2
17	*Tripleurospermum inodorum* (L.) Sch. Bip.	Scentless chamomile	MATIN	Annual	3.0	10.3	0.04	0.4	0.7	6.7
18	*Panicum miliaceum* L.	Wild proso millet	PANMI	Annual	2.8	8.8	0.03	0.3	0.8	9.4
19	*Brassica* spp.	Brassica species	BRSSPP		2.7	10.3	0.01	0.1	0.6	6.2
20	*Portulaca oleracea* L.	Common purslane	POROL	Annual	2.6	10.3	0.02	0.2	0.5	4.8
21	*Malva sylvestris* L.	High mallow	MALSI	Perennial	2.6	7.4	0.03	0.4	0.9	12.0
22	*Polygonum aviculare* L.	Prostrate knotweed	POLAV	Annual	2.6	8.8	0.02	0.2	0.7	7.8
23	*Beta vulgaris* subsp. *vulgaris*, Altissima Group	Volunteer sugar beet	BEAVP	Annual	2.5	7.4	0.03	0.3	0.8	11.3
24	*Sonchus oleraceus* L.	Annual sowthistle	SONOL	Annual	2.2	7.4	0.02	0.2	0.6	8.0
25	*Cirsium arvense* (L.) Scop.	Canada thistle	CIRAR	Perennial	2.1	7.4	0.02	0.2	0.5	7.3
26	*Echinochloa crus-galli* (L.) P. Beauv.	Barnyardgrass	ECHCG	Annual	1.9	4.4	0.02	0.5	0.8	17.8
27	*Lactuca serriola* L.	Prickly lettuce	LACSE	Annual	1.7	7.4	0.01	0.1	0.2	3.3
28	*Daucus carota* L.	Wild carrot	DAUCA	Perennial	1.2	4.4	0.01	0.2	0.3	6.7
29	*Eupatorium capillifolium* (Lam.) Small	Dogfennel	EUPCP	Annual	1.1	2.9	0.01	0.3	0.4	15.0
30	*Cirsium vulgare* (Savi) Ten.	Bull thistle	CIRVU	Perennial	1.1	4.4	0.004	0.1	0.2	4.4

[a]Abbreviations: F, field frequency; MFD, mean field density; MFU, mean field uniformity; MOFD, mean occurrence field density; MOFU, mean occurrence field uniformity; RA, relative abundance.

environments (Aldrich-Markham 1994; Washington State Noxious Weed Control Board 2024). *Kickxia elatine* has been reported as a problematic weed in grass seed production areas of Oregon and is tolerant to many herbicides (Curtis et al. n.d.). Snap bean production in the NW is intensively irrigated and commonly rotated with grass seed crops (Pavlovic 2024), perhaps explaining the persistence of these weed species in snap bean.

Overall, many species that were previously reported in research and extension publications as being problematic in snap bean were also observed in the current surveys as well. Even though some of these reports are decades old, it still demonstrates that certain species or species-groups have been and continue to be problematic in snap bean. Most notable examples are *C. album* (Odero and Wright 2018; Peachey 2019; Talbert et al. 1997; Van Wychen 2022; Vencill et al. 1990; Wilson and Hines 1987) and *Amaranthus* spp. (Aguyoh and Masiunas 2003b; Lugo et al. 1995). Other noteworthy examples are *A. artemisiifolia* in the NE (Evanylo and Zehnder 1989; Bradley et al. 2007), *P. dichotomiflorum* and *Setaria* spp. in the NE (Teasdale and Frank 1982,1983), *S. physalifolium* in the NW (Peachey et al. 2004), and *D. sanguinalis* in the MW (Aguyoh and Masiunas 2003a). Other species or species-groups seem to have been more of a problem in the past before the introduction of certain herbicide active ingredients or management practices, as they were not so abundant in the survey. These are species or species-groups such as common cocklebur (*Xanthium strumarium* L.) (Neary and Majek 1990), Carolina horsenettle (*Solanum carolinense* L.) (Frank 1990), *Cyperus* spp. (Boyhan et al. 2013; William and Warren 1975), and *R. raphanistrum* (Boyhan et al. 2013). However, more importantly, the surveys also found several species or species-groups that have not been reported in snap bean previously but could be problematic in the future, such as *K. elatine* in the NW, *A. ostryifolia* in the MW, and annual bluegrass in the NE.

Relationship between Weed Density and Weed Cover

A machine learning algorithm, random forest, was used to determine the weed species or species-group that best predicted weed cover observed at crop harvest. The fitted random forest model had a pseudo-R^2 value of 0.60 (±0.01) and an accuracy of 78.3%. Several species densities were strongly associated with predicting weed cover (Figure 5). *Chenopodium album* was the most important predictor, with 100% permutation importance. Other important predictors included *D. sanguinalis* (70.7%), *M. verticillata* (46.8%), *I. hederacea* (43.2%), amaranth species (35.3%), and *A. ostryifolia* (34.9%). Other species had a permutation importance of <22%.

Table 2. Top 30 weed species in the Midwest region arranged by relative abundance[a].

Rank	Latin binomial with authority	Common name	EPPO code	Lifeform	RA	F	MFD	MOFD	MFU	MOFU
					—%—		—no. m^{-2}—		—%—	
1	*Mollugo verticillata* L.	Carpetweed	MOLVE	Annual	56.7	49.3	13.7	27.8	25.1	50.8
2	*Lamium amplexicaule* L.	Henbit	LAMAM	Annual	29.0	30.2	7.1	23.4	11.3	37.2
3	*Solanum* spp.	Nightshade species	SOLSPP		24.3	46.3	3.4	7.2	13.6	29.4
4	*Digitaria sanguinalis* (L.) Scop.	Large crabgrass	DIGSA	Annual	23.3	35.1	4.3	12.2	11.3	32.3
5	*Acalypha ostryifolia* Riddell	Hophornbeam copperleaf	ACCOS	Annual	22.3	30.7	4.4	14.5	10.5	34.1
6	*Chenopodium album* L.	Common lambsquarters	CHEAL	Annual	21.4	57.6	1.0	1.8	14.7	25.6
7	*Amaranthus* spp.	Amaranth species	AMASPP		19.3	57.1	1.2	2.1	11.1	19.5
8	*Stellaria media* (L.) Vill.	Common chickweed	STEME	Annual	17.6	22.4	3.5	15.4	8.9	39.6
9	*Ipomoea hederacea* Jacq.	Ivyleaf morningglory	IPOHE	Annual	15.6	42.0	0.7	1.7	10.9	25.9
10	*Portulaca oleracea* L.	Common purslane	POROL	Annual	14.5	36.1	0.9	2.4	10.2	28.2
11	*Panicum dichotomiflorum* Michx.	Fall panicum	PANDI	Annual	6.0	22.0	0.3	1.2	2.8	12.7
12	*Conyza canadensis* (L.) Cronquist (syn.: *Erigeron canadensis* L.)	Horseweed	ERICA	Annual	4.9	17.6	0.3	1.7	2.0	11.5
13	*Abutilon theophrasti* Medik.	Velvetleaf	ABUTH	Annual	4.8	19.0	0.1	0.6	2.3	12.2
14	*Ipomoea purpurea* (L.) Roth	Tall morningglory	PHBPU	Annual	4.7	20.5	0.1	0.3	2.0	9.7
15	*Setaria* spp.	Foxtail species	SETSPP		3.6	11.7	0.3	2.7	1.5	12.9
16	*Persicaria pensylvanica* (L.) M. Gómez	Pennsylvania smartweed	POLPY	Annual	3.2	9.3	0.1	1.5	2.0	22.0
17	*Capsella bursa-pastoris* L.	Shepherd's purse	CAPBP	Annual	3.0	8.3	0.2	2.0	1.9	22.5
18	*Ipomoea lacunosa* L.	Pitted morningglory	IPOLA	Annual	2.7	11.7	0.05	0.4	1.1	9.3
19	*Zea mays* L.	Volunteer corn	ZEAMX	Annual	2.2	9.8	0.04	0.4	0.7	7.5
20	*Oxalis stricta* L.	Yellow woodsorrel	OXAST	Perennial	1.5	7.3	0.0	0.4	0.4	5.3
21	*Solanum carolinense* L.	Carolina horsenettle	SOLCA	Perennial	1.5	5.4	0.07	1.2	0.7	12.4
22	*Panicum miliaceum* L.	Wild proso millet	PANMI	Annual	1.4	4.9	0.1	1.9	0.6	12.5
23	*Ambrosia artemisiifolia* L.	Common ragweed	AMBEL	Annual	1.3	4.9	0.02	0.4	0.7	14.2
24	*Cirsium arvense* (L.) Scop.	Canada thistle	CIRAR	Perennial	1.0	4.4	0.02	0.4	0.4	9.6
25	*Vicia* spp.	Vetch species	VICSPP		1.0	4.9	0.005	0.1	0.3	6.3
26	*Sinapis arvensis* L.	Wild mustard	SINAR	Annual	1.0	3.4	0.03	0.8	0.6	17.1
27	*Taraxacum officinale* F.H. Wigg.	Dandelion	TAROF	Perennial	1.0	4.4	0.01	0.2	0.4	8.4
28	*Trifolium* spp.	Clover species	TRFSPP		0.9	3.9	0.01	0.3	0.4	10.5
29	*Matricaria discoidea* DC.	Pineapple weed	MATMT	Annual	0.9	1.0	0.1	11.8	0.7	72.9
30	*Euphorbia* spp.	Spurge species	EPHSPP		0.8	3.9	0.01	0.2	0.3	7.0

[a]Abbreviations: F, field frequency; MFD, mean field density; MFU, mean field uniformity; MOFD, mean occurrence field density; MOFU, mean occurrence field uniformity; RA, relative abundance.

In all cases, higher weed density resulted in greater predicted weed cover (Figure 6). This is consistent with density–cover (density–biomass) relationships observed by others (Hardwick and Andrews 1983; Röttgermann et al. 2000; Weisberger et al. 2019). *Chenopodium album*, *D. sanguinalis*, *M. verticillata*, *I. hederacea*, *Amaranthus* spp., and *A. ostryifolia* cause problems at harvest and postharvest. Above an undefined threshold, their infestation can complicate and slow snap bean harvest. Even lower infestations can result in weed organs harvested with snap bean; their removal in the processing plant can be difficult and expensive (R Pequinot, personal communication).

This research documents the first quantitative report on the weed community escaping the weed management system in U.S. snap bean production. At crop harvest, weeds were present in approximately 95% of the surveyed fields. A total of 109 species or species groups were observed in 358 fields from Oregon to Delaware. In most cases, one to three species dominated the residual weed community. It was not uncommon to have >10 weeds m^{-2} with a weed canopy covering >5% of the field's surface area. Some of the most abundant and problematic species or species-groups escaping control included amaranth species (such as *A. hybridus*, *A. palmeri*, *A. retroflexus*, and *A. tuberculatus*), *C. album*, *D. sanguinalis*, and *I. hederacea*. *Acalypha ostryifolia* appears to be emerging as a problematic species in the MW region. This is the first report of *K. elatine* routinely escaping control in snap bean, particularly in the NW. Beyond crop losses due to weed interference, the weed canopy at harvest risks contaminating snap bean products with foreign material. Our modeling suggests the residual weed canopy is dominated by *C. album*, *D. sanguinalis*, *M. verticillata*, *I. hederacea*, *Amaranthus* spp., and *A. ostryifolia*. All these species or species-groups have been identified by processors as problematic with snap bean harvest and processing.

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Table 3. Top 30 weed species in the Northeast region arranged by relative abundance[a].

Rank	Latin binomial with authority	Common name	EPPO code	Lifeform	RA	F	MFD	MOFD	MFU	MOFU
						%	——no. m^{-2}——		———%———	
1	*Chenopodium album* L.	Common lambsquarters	CHEAL	Annual	51.6	69.5	1.8	2.6	18.7	26.9
2	*Amaranthus* spp.	Amaranth species	AMASPP		23.6	53.7	0.6	1.0	9.4	17.5
3	*Stellaria media* (L.) Vill.	Common chickweed	STEME	Annual	19.4	12.2	1.0	8.0	4.6	37.5
4	*Poa annua* L.	Annual bluegrass	POAAN	Annual	15.0	18.3	0.6	3.4	4.3	23.6
5	*Ipomoea hederacea* Jacq.	Ivyleaf morningglory	IPOHE	Annual	14.6	26.8	0.2	0.6	9.7	36.2
6	*Mollugo verticillata* L.	Carpetweed	MOLVE	Annual	13.8	15.9	0.5	2.9	5.8	36.5
7	*Digitaria sanguinalis* (L.) Scop.	Large crabgrass	DIGSA	Annual	11.8	28.0	0.2	0.8	5.3	18.8
8	*Setaria* spp.	Foxtail species	SETSPP		10.9	24.4	0.3	1.1	4.1	16.9
9	*Ambrosia artemisiifolia* L.	Common ragweed	AMBEL	Annual	10.4	24.4	0.2	1.0	4.2	17.2
10	*Panicum dichotomiflorum* Michx.	Fall panicum	PANDI	Annual	9.2	23.2	0.2	0.7	4.2	18.2
11	*Oxalis stricta* L.	Yellow woodsorrel	OXAST	Perennial	7.6	13.4	0.2	1.8	2.8	20.6
12	*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.	Smooth crabgrass	DIGIS	Annual	6.3	9.8	0.2	2.2	2.3	23.3
13	*Solanum carolinense* L.	Carolina horsenettle	SOLCA	Perennial	5.9	20.7	0.1	0.4	2.2	10.7
14	*Portulaca oleracea* L.	Common purslane	POROL	Annual	5.9	19.5	0.1	0.5	1.9	9.9
15	*Echinochloa crus-galli* (L.) P. Beauv.	Barnyardgrass	ECHCG	Annual	5.2	23.2	0.04	0.2	1.6	6.8
16	*Solanum* spp.	Nightshade species	SOLSPP		4.9	19.5	0.1	0.3	1.6	8.2
17	*Taraxacum officinale* F.H. Wigg.	Dandelion	TAROF	Perennial	4.5	12.2	0.1	0.6	1.9	15.7
18	*Acalypha ostryifolia* Riddell	Hophornbeam copperleaf	ACCOS	Annual	4.4	11.0	0.1	0.9	1.7	15.4
19	*Panicum* spp.	Panicgrass species	PANSPP		3.5	13.4	0.05	0.4	1.1	8.5
20	*Cyperus esculentus* L.	Yellow nutsedge	CYPES	Perennial	3.3	6.1	0.1	1.0	1.7	28.7
21	*Polygonum aviculare* L.	Prostrate knotweed	POLAV	Annual	3.1	11.0	0.1	0.5	0.9	7.8
22	*Abutilon theophrasti* Medik.	Velvetleaf	ABUTH	Annual	3.0	13.4	0.02	0.2	1.0	7.3
23	*Urochloa texana* (Buckley) R. Webster	Texas millet	PANTE	Annual	2.4	7.3	0.05	0.7	0.8	11.1
24	*Rumex crispus* L.	Curly dock	RUMCR	Perennial	2.4	11.0	0.01	0.1	0.8	7.0
25	*Hordeum vulgare* L.	Volunteer barley	HORVX	Annual	2.4	2.4	0.07	2.8	1.2	50.0
26	*Trifolium* spp.	Clover species	TRFSPP		2.4	9.8	0.02	0.2	0.8	8.3
27	*Pisum sativum* L.	Volunteer garden pea	PIBSX	Annual	2.3	7.3	0.03	0.4	0.9	12.2
28	*Cirsium arvense* (L.) Scop.	Canada thistle	CIRAR	Perennial	2.2	7.3	0.05	0.6	0.6	8.3
29	*Capsella bursa-pastoris* L.	Shepherd's purse	CAPBP	Annual	2.0	7.3	0.02	0.3	0.8	11.1
30	*Phytolacca americana* L.	Common pokeweed	PHTAM	Perennial	1.8	4.9	0.03	0.7	0.8	16.7

[a]Abbreviations: F, field frequency; MFD, mean field density; MFU, mean field uniformity; MOFD, mean occurrence field density; MOFU, mean occurrence field uniformity; RA, relative abundance.

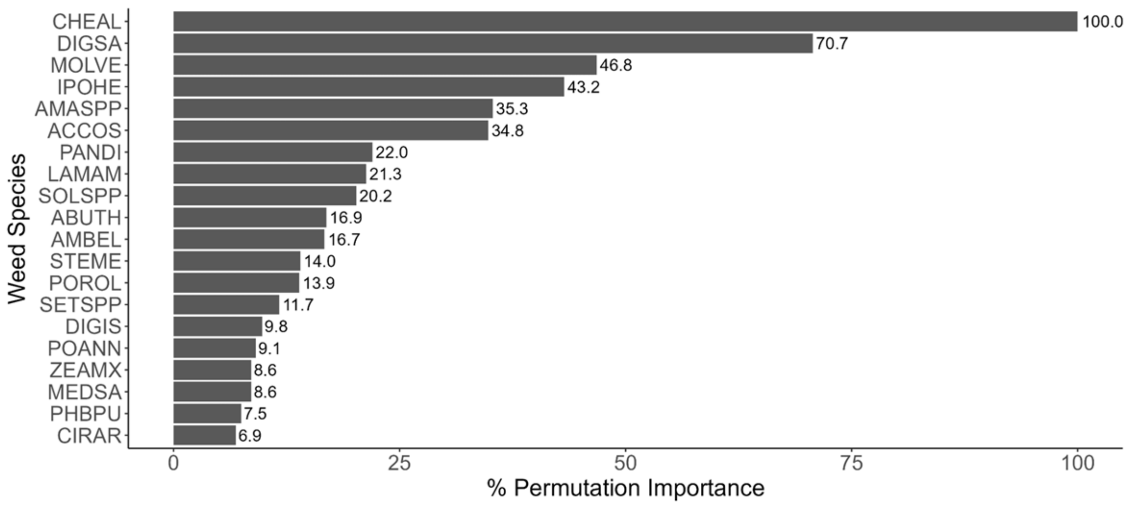

Figure 5. Random forest variable importance plot for predicting weed cover (%) based on weed density (plants m^{-2}). The 20 most important weed species or species-groups are shown. Weed species' EPPO codes are defined (scientific and common names) in Tables 1–3.

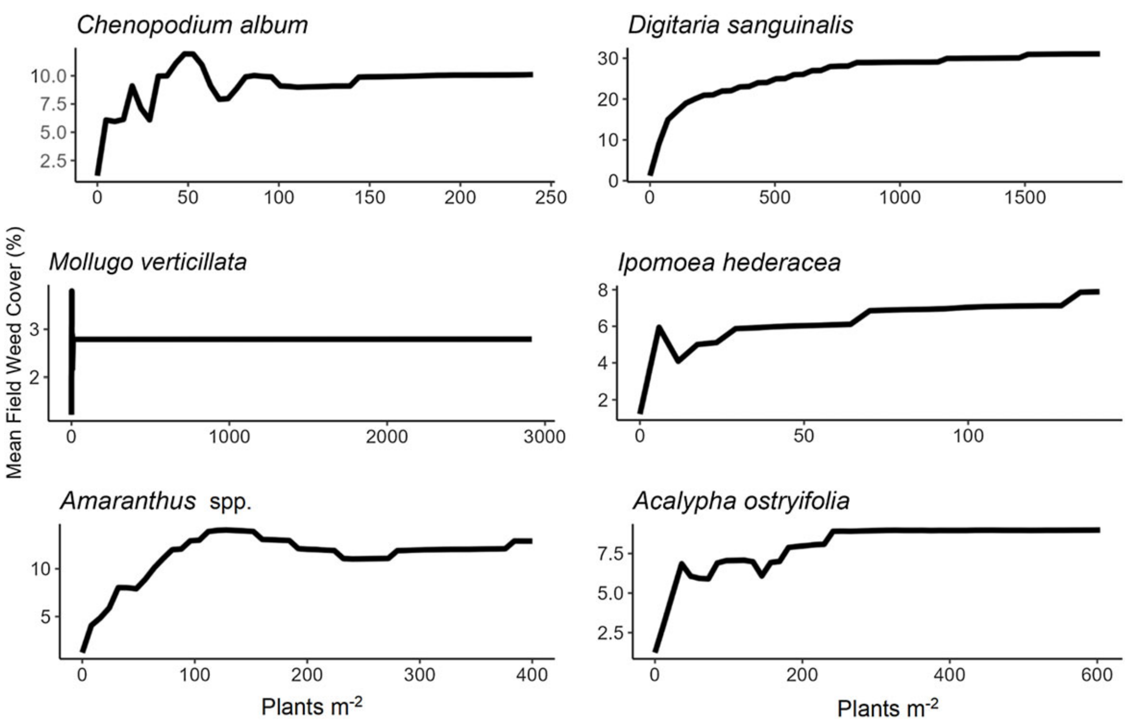

Figure 6. Partial dependence plots of the marginal effect of the weed species with the greatest importance in predicting mean field weed cover in the fitted random forest model.

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