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Field Surveys of Bush Lima Bean Reveal Shortcomings in Weed Management

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***Abstract.* To understand the scope of weed problems in commercial lima bean (*Phaseolus lunatus* L.) production, lima bean fields were surveyed for weeds that escaped control near the time of crop harvest (hereby called residual weeds) from 2019 to 2022 in the Mid-Atlantic and the Midwest, two major production regions of the United States. Overall weed abundance was determined based on relative density, frequency, and uniformity throughout surveyed fields. Density was the number of individual plants in overall quadrats in fields with that weed. Frequency was the number of fields with that weed species recorded in overall surveyed fields. Uniformity was the number of quadrats with a particular weed species in overall quadrats. Approximately 52 weed species were observed, and differences in weed communities were observed between the Mid-Atlantic and Midwest regions. Significant weeds in the Mid-Atlantic region included common chickweed [*Stellaria media* (L.) Vill], amaranth species (*Amaranthus* spp.), and morningglory species (*Ipomoea* spp.). Significant weeds in the Midwest region were foxtail species (*Setaria* spp.), common lambsquarters (*Chenopodium album* L.), and amaranth species. Crop management practices used in the fields were obtained from collaborating farmers and vegetable processors. Widely adopted mechanical weed control methods included spring (preplant) tillage and interrow cultivation. Common herbicides included preemergent applications of *S*-metolachlor and halosulfuron-methyl. Bentazon was the most common herbicide applied postemergence. Classification and regression tree modeling were used to determine linkages among residual weeds and management factors. Despite the adoption of multiple chemical and mechanical weed control methods, this survey revealed extensive weed problems in many production fields. Greater diversification of integrated weed management systems is needed, especially for the control of amaranth species. This survey will help guide future research efforts for weed control in lima bean production.**

Weed interference constitutes a major threat and expense in most crop production systems. A core component of weed management is knowledge of the weed community because the effectiveness of management tactics depends, in part, on the species (Harper 1977; MacLaren et al. 2020; Nichols et al. 2015). Furthermore, weed communities are the result of management practices that were previously used (Bhowmik 1997; Dewey and Andersen, 2004). Weed surveys can be a valuable initial step toward identifying shortfalls in crop production systems (Bhowmik 1997; Dewey and Andersen 2004; Hanzlik and Gerowitt 2016; McCully et al. 1991; Thomas 1985) and the needs for future research (Acker et al. 2000; Hanzlik and Gerowitt 2016; Thomas and Dale 1991; Webster and Coble 1997; Williams et al. 2008).

Bush lima bean (*Phaseolus lunatus* L.) is a vegetable crop grown for processing as a canned or frozen product. Production in the United States spans 24,400 ha valued at $22 million (NASS 2018). Domestic production accounts for approximately 90% of lima bean consumption in the United States (Economic Research Service 2024). The majority of lima bean production in the United States occurs in the Mid-Atlantic and Midwest regions, including the states of Delaware, Illinois, Maryland, Minnesota, and Wisconsin (National Agricultural Statistics Service 2022). The crop is typically grown under contract between a food processor and grower (Kee et al. 1997). Nutritionally, lima bean is an excellent source of protein (Temegne et al. 2021).

There are two main growth forms of lima bean: an indeterminate vine-type and a determinate bush-type. Commercial production uses bush-type cultivars because of the shorter time to harvest and smaller growth habit suitable for mechanical harvest (Temegne et al. 2021).

Bush-type lima bean is an approximately 80-d crop that can be planted over a wide range of dates. Weed interference can be a major limiting factor to lima bean production (Beiermann et al. 2022b; VanGessel et al. 2000). Weeds compete with lima bean for moisture, light, and nutrients. Weed interference in lima bean can result in yield losses greater than 30%, whereas weed interference in dry bean can result in yield losses greater than 70% (Sankula et al. 2024; Soltani et al. 2018). Moreover, weeds such as amaranth species and velvetleaf can serve as hosts for diseases of lima bean, notably white mold, which is the most problematic disease in lima bean production (Blessing et al. 2003; Heffer 2007). Weeds can interfere with harvest and reduce crop quality by introducing foreign and potentially toxic material into the harvest load, which sometimes results in the harvested crop being rejected by the food processor (Kee et al. 1997; Glaze and Mullinix 1984; VanGessel et al. 2000). Individual weed plants observed late in the growing season, hereafter called residual weeds, either survived management tactics or emerged after management became ineffective. Because of different geographic regions of lima bean production and the range of planting dates used, the weed community is expected to vary widely across fields and regions.

Quantitative knowledge of the residual weed communities in bush lima bean and how they are managed is poor. At the turn of the 21st century, morningglory species and acetolactate synthase (ALS)-resistant amaranth species were identified as some of the most problematic pest issues in lima bean for Mid-Atlantic production (Blessing et al. 2003). Although some herbicides are registered for the crop, the actual practices adopted by growers, including the use of nonchemical tactics, are unknown. Therefore, the objectives of this research were as follows: 1) quantify the residual weed communities in lima bean; 2) characterize weed management practices used by growers; and 3) identify linkages among management variables and

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weed ground coverage. We hypothesized that fields using a two-pass herbicide application system, namely a preemergence (PRE) herbicide application followed by postemergence (POST) herbicide application, would have fewer residual weeds than PRE-only or POST-only systems. Two-pass systems have been noted in other cropping systems to improve control by targeting different life stages of weeds and extending the duration of weed control (Craigmyle et al. 2013; Soltani et al. 2013).

Materials and Methods

Field surveys were conducted across 93 bush lima bean fields grown under contract within Delaware, Illinois, Maryland, Minnesota, and Wisconsin between 2019 and 2022 (Table 1). Collaborators from vegetable-processing companies identified fields each year, from which a subset was selected for surveying.

Survey protocol. Fields were surveyed within 1 week before harvest for residual weeds using the method described by Thomas (1985) with some adjustments. Population density of each weed species was quantified using 30 0.5-m^2 quadrats. Quadrats were placed randomly throughout the field along a polygon transversing the field, avoiding field edges by 20 m. Newly emerged weed species that were difficult to identify to species level were grouped into a single genus classification. At each quadrat, lima bean plant density was recorded. Weed ground coverage of the weed canopy in each quadrat was estimated as a percentage of the overall quadrat.

Soil samples were collected from each field by using a 20-cm soil corer at five locations within the field. Soil cores within each field were composited, air-dried, and homogenized before submission for analysis of soil physical properties. Analyzed soil properties included soil organic matter (SOM), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), particle size, pH, and cation exchange capacity.

Field management records were obtained from vegetable processors after harvest. Variables included cultivar, planting date, harvest date, row width, previous crop, use of spring or fall tillage, interrow cultivation, and hand weeding. Herbicide application records were collected.

Data analysis. Data of individual species or species groups were summarized by region using several quantitative measures. Frequency was the percentage of fields that had at least one observation of a given species. Uniformity of all fields was the total number of quadrats where the species was observed divided by the total number of quadrats surveyed. Occurrence uniformity was the total number of quadrats where the species was observed divided by the total quadrats of fields where the species occurred. Density of all fields was calculated by summing the number of all individual plants of a species and then dividing by all quadrats surveyed. Occurrence density was calculated by summing the number all individual plants of a species and then dividing by the number of surveyed quadrats in fields where the species was observed (McCully et al. 1991; Thomas 1985). Relative abundance, the contribution of each species to the community, was calculated based on the frequency of a species, uniformity of all fields, and density of all fields (Thomas 1985). Relative abundance of all weeds sums to a total value of 300 and has no units.

To characterize relationships between weed ground coverage and management practices, the machine learning method classification and regression tree (CART) and statistical software (R version 4.3.1) (R Core Team 2024) were used. The CART analysis has advantages over other statistical methods because it can handle incomplete data and is nonparametric; therefore, it does not require assumptions of data distributions (De'ath and Fabricius 2000).

The CART analysis was conducted using the *rpart* package in R (Therneau et al. 2022). The CART takes one dependent variable and splits it into two groups based on a range of given independent variables. The value at which the data are split depends on the distribution of the data (De'ath and Fabricius 2000). The model was pruned using the "1-se" rule and selecting the model with the least splits within 1 standard error of the model with the lowest error (Breiman et al. 2017). Average percent weed ground coverage of each field was the dependent variable. Six predictor variables were chosen for analysis, including region, presence of spring/fall tillage, cultivar, planting date, soil texture class, and whether a PRE or POST herbicide application was made.

To test whether a two-pass herbicide application system reduced weed ground coverage more than a single-pass system, the Mann-Whitney-Wilcoxon test was performed. The Wilcoxon test was chosen after testing for normality with the Shapiro-Wilks test (all $\alpha = 0.05$).

Results

This research aimed to identify the scope of weed problems in bush lima bean production in the United States. The surveyed fields were representative of lima bean production in the United States. Totals of 59 and 34 fields from the Mid-Atlantic and Midwest regions, respectively, were surveyed. Delaware accounted for more than one-half of all surveyed fields, while fields in the Midwest were more evenly distributed across Illinois, Minnesota, and Wisconsin (Table 1).

A few species and species groups dominated the residual weed community of lima bean. The top six and seven weeds accounted for 71% and 67% of the relative abundance in the Mid-Atlantic (Table 2) and Midwest (Table 3) regions, respectively, with subsequent species contributing significantly less to relative abundance. Amaranth species were identified as the most frequently occurring weed in both regions, with presence found in more than one-half of all fields. Other notable weeds that were found in more than 10% of all fields included common chickweed, morningglory species, annual bluegrass, carpetweed, and henbit in the Mid-Atlantic region. Foxtail species, common lambsquarters, common purslane, and velvetleaf were found in more than 10% of fields in the Midwest region.

Various crop production and weed management practices were common in both regions. Common bush lima bean cultivars across regions were Cypress and Meadow (Tables 4 and 5). Planting dates ranged from late May to late July. Lima bean in the Mid-Atlantic region was always planted on 76-cm rows, but narrower rows were more common in the Midwest region. Harvest dates ranged from mid-August to early November. Although only reported in the Midwest region, field pea and some types of corn (field corn, sweet corn, or silage corn) were the most common crops planted before lima bean. Some fields in the Mid-Atlantic also planted field pea before planting lima beans (personal observation).

Some form of mechanical cultivation was used in most surveyed lima bean fields across both the Mid-Atlantic and the Midwest; 84% of fields reported spring tillage in the Mid-Atlantic region and no fields reported fall tillage the year before lima bean planting (Table 4).

Table 1. Geographic distribution of 93 lima bean fields surveyed from 2019 to 2022 in the United States.

	State distribution			County distribution		
Region	State	Fields, no.	Fields, %	County	Fields, no.	Fields, %
Mid-Atlantic	Delaware	51	54.8	Kent	2	2.2
				Sussex	49	52.7
	Maryland	8	8.6	Caroline	5	5.4
				Dorchester	3	3.2
Midwest	Illinois	15	16.1	Marshall	1	1.1
				Tazewell	2	2.2
				Whiteside	12	13
	Minnesota	5	5.4	McLeod	3	3.2
				Redwood	2	2.2
	Wisconsin	14	15.1	Columbia	1	2.2
				Green Lake	3	3.2
				Rock	4	4.3
				Wasushara	6	6.5

Table 2. Residual weeds observed near harvest of lima bean fields surveyed in the US Mid-Atlantic region from 2019 to 2022 (n = 59).

Rank[i]	Common name	Latin name	EPPO code[ii]	Life cycle[iii]	Region[iv]	Frequency[v] %	Uniformity[vi] All fields %	Uniformity[vi] Occurrence %	Density[vii] All fields no./m^2	Density[vii] Occurrence fields no./m^2	Relative abundance[viii]
1	common chickweed	*Stellaria media* (L.) Vill	STEME	WA	A, M	20.3	13.4	60.8	3.8	17.3	60.4
2	amaranthus species	*Amaranthus* spp.	AMASPP	SA	A, M	54.2	19.9	34.6	0.8	1.4	44.5
3	morningglory species	*Ipomoea* spp.	IPOSPP	SA	A, M	49.2	12.2	26	0.2	0.5	29.4
4	carpetweed	*Mollugo verticillata* L.	MOLVE	SA	A, M	35.6	12.2	33.4	0.4	1.2	27.6
5	annual bluegrass	*Poa annua* L.	POAAN	SA	A	11.9	7.7	60	1.5	11.4	27
6	henbit	*Lamium amplexicaule* L.	LAMAM	WA	A, M	15.3	8.5	51.1	1	5.8	23.3
7	fall panicum	*Panicum dichotomiflorum* Michx.	PANDI	SA	A, M	20.3	3.4	15.9	0.1	0.3	10.1
8	field pansy	*Viola arvensis* Murray	VIOAR	WA	A	6.8	2.5	27	0.4	5.4	8.2
9	volunteer oat	*Avena sativa* L.	AVESA	SA	A	1.7	1.2	86.7	0.5	34.1	6.7
10	texas panicum	*Urochloa texana* (B.) Webster	PANTE	SA	A	15.3	2	12.9	0.1	0.6	7.5
11	nightshade species	*Solanum* spp.	SOLSPP	SA, P	A, M	15.3	1.4	25.9	0	0.3	6.1
12	horseweed	*Erigeron canadensis* L.	ERICA	SA, WA	A, M	11.9	2.5	19.6	0	0.3	6.4
13	volunteer barley	*Hordeum vulgare* L.	HORVX	SA	A	8.5	2.4	32.5	0.1	1.4	6
14	witchgrass	*Panicum capillare* L.	PANCA	SA	A, M	10.2	1.8	16.5	0.1	0.7	5.5
15	yellowcress species	*Rorippa* spp.	RORSPP	SA	A	6.8	2.2	34.3	0.1	1.9	5.5
16	large crabgrass	*Digitaria sanguinalis* (L.) Scopoli	DIGSA	SA	A, M	10.2	1.3	12.2	0	0.4	4.7
17	common purslane	*Portulaca oleracea* L.	POROL	SA	A, M	6.8	0.6	7.5	0	0.1	2.7
18	jimsonweed	*Datura stramonium* L.	DATST	SA	A	5.1	0.7	14.6	0	0.2	2.4
19	hairy galinsoga	*Galinsoga quadriradiata* Cav.	GASCI	SA	A	5.1	0.6	11.7	0	0.2	2.3
20	yellow woodsorrel	*Oxalis corniculata* L.	OXAST	SA	A	1.7	0.6	70	0.1	8.9	2
21	grape hyacinth	*Muscaria negelctum* T.	MUSRA	P	A	1.7	0.2	10	0.1	4.5	1.6
22	spurred anoda	*Anoda cristata* (L.) Schlechtendal	ANVCR	SA	A	3.4	0.5	13.2	0	0.2	1.6
23	copperleaf species	*Acalypha* spp.	ACCSPP	SA	A	3.4	0.3	15	0	0.5	1.4
24	yellow nutsedge	*Cyperus esculentes* L.	CYPES	P	A, M	1.7	0.6	30	0	0.4	1.1
25	false daisy	*Eclipta prostrata* (L.) Linnaeus	ECLAL	SA	A	1.7	0.3	15	0	0.6	0.9
26	hairy vetch	*Vicia villosa* Roth	VICVI	SA, WA	A	1.7	0.4	40	0	0.4	0.9
27	curly dock	*Rumex crispus* L.	RUMCR	SA	A	1.7	0.3	15	0	0.3	0.8
28	common cocklebur	*Xanthium strumarium* L.	XANST	P	A, M	1.7	0.2	2	0	0.3	0.8
29	rye cereal	*Secale cereale* L.	SECCE	SA	A	1.7	0.2	20	0	0.4	0.7
30	barnyardgrass	*Echinochloa crus-gali* (L.) P. Beauv.	ECHCG	SA	A, M	1.7	0.2	9.1	0	0.1	0.7
31	ragweed species	*Ambrosia* spp.	AMBSPP	SA	A, M	1.7	0.1	6.7	0	0.1	0.6
32	prickly sida	*Sida spinosa* L.	SIDSP	SA	A	1.7	0.1	10	0	0.1	0.6
	smooth pigweed	*Amaranthus hybridus* L.	AMACH	SA	A	55.9	18.8	32.8	0.8	1.3	.
	palmer amaranth	*Amaranthus palmeri* S.Wats.	AMAPA	SA	A, M	3.4	1.3	35	0	1	.
	common ragweed	*Ambrosia artemisiifolia* L.	AMBEL	SA	A, M	1.7	0.1	6.7	0	0.1	.
	ivyleaf morningglory	*Ipomoea hederacea* Jacq.	IPOHE	SA	A, M	28.8	9.4	32.7	0.2	0.6	.
	pitted morningglory	*Ipomoea lacunosa* L.	IPOLA	SA	A	1.7	0.1	4.8	0	0.1	.
	eastern black nightshade	*Solanum ptychanthum* Dunal	SOLAM	SA	A	5.1	0.5	8.2	0	0.1	.
	Horsenettle	*Solanum carolinense* L.	SOLCA	P	A	33.9	6.5	18.4	0.2	0.6	.

[i] Ranked by relative abundance.
[ii] EPPO = European and Mediterranean Plant Protection Organization code, formerly known as a Bayer code.
[iii] P = perennial; SA = summer annual; WA = winter annual.
[iv] A = Mid-Atlantic; M = Midwest.
[v] Frequency was the percentage of fields with a species present based on within-quadrat observations.
[vi] Uniformity was determined by dividing the number of quadrats in which the species was observed by the total number of quadrats of all surveyed fields (all fields) or total number of quadrats of fields where the species was observed (occurrence fields); both were expressed as a percentage.
[vii] Density was the number of plants per square meter in all fields (all fields) or fields where the species was observed (occurrence fields).
[viii] Relative abundance ranks of the contribution of individual species in the overall weed community based on equal importance of unadjusted frequency, uniformity in all fields, and density in all fields. The total value for relative abundance of all species is 300.

Table 3. Residual weeds observed near harvest of lima bean fields surveyed in the US Midwest region from 2019 to 2022 (n = 34).

Rank[i]	Common name	Latin name	EPPO code[ii]	Life cycle[iii]	Region[iv]	Frequency[v] %	Uniformity[vi] All fields %	Uniformity[vi] Occurrence %	Density[vii] All fields no./m^2	Density[vii] Occurrence fields no./m^2	Relative abundance[viii]
1	foxtail species	*Setaria* spp.	SETSPP	SA	M	14.7	4.4	26	1.6	9.6	44.6
2	common lambsquarters	*Chenopodium album* L.	CHEAL	SA	M	35.3	8.8	24.6	0.4	1.1	29.4
3	amaranthus species	*Amaranthus* spp.	AMASPP	SA	A, M	55.9	7.6	17.4	0.3	0.6	29.3
4	velvetleaf	*Abutilon theophrasti* Medik.	ABUTH	SA	M	41.2	9.4	21	0.3	0.6	28.6
5	common purslane	*Portulaca oleracea* L.	POROL	SA	A, M	35.3	8	21.1	0.3	0.9	26.7
6	large crabgrass	*Digitaria sanguinalis* (L.) Scopoli	DIGSA	SA	A, M	17.7	6.3	31.1	0.4	1.9	21.4
7	common chickweed	*Stellaria media* (L.) Vill	STEME	WA	A, M	17.7	4.9	27.9	0.4	2.3	20
8	burcucumber	*Sicyos angulatus* L.	SIYAN	SA	M	11.8	3.4	26.6	0.2	1.4	11.2
9	carpetweed	*Mollugo verticillata* L.	MOLVE	SA	A, M	20.6	2.1	10.1	0.1	0.6	10.4
10	fall panicum	*Panicum dichotomiflorum* Michx.	PANDI	SA	A, M	23.5	1.1	5.4	0.1	0.3	8.6
11	field pennycress	*Thlaspi arvense* L.	THLAR	WA	M	14.7	2.2	15.2	0.1	0.5	8.2
12	wild-proso millet	*Panicum miliaceum* L.	PANMI	SA	M	11.8	2.3	17.5	0.1	0.4	7.1
13	ragweed species	*Ambrosia* spp.	AMBSPP	SA	A, M	17.7	1.9	23.6	0.1	0.1	6.9
14	Canada thistle	*Cirsium arvense* (L.) Scop.	CIRAR	P	M	11.8	1.5	12.2	0.1	0.5	6.1
15	morningglory species	*Ipomoea* spp.	IPOSPP	SA	A, M	8.8	1.7	16.7	0.1	0.5	5.5
16	volunteer corn	*Zea mays* L.	ZEAMX	SA	M	11.8	1	9.3	0.1	0.4	5.2
17	smartweed species	*Persicaria* spp.	POLSPP	SA	M	8.8	1	10.8	0.1	0.4	4.4
18	shepherds purse	*Capsella bursa-pastoris* (L.) Medicus	CAPBP	WA	M	5.9	0.9	13.3	0.1	0.4	3.3
19	garden pea	*Pisum sativum* L.	PIBSX	SA	M	8.8	0.5	7.6	0.1	0.2	3
20	dandelion	*Taraxacum officinale* (L.) Weber	TAROF	P	M	5.9	0.5	9.8	0.1	0.6	2.7
21	barnyardgrass	*Echinochloa crus-gali* (L.) P. Beauv.	ECHCG	SA	M	5.9	0.5	7.6	0.1	0.3	2.5
22	common cocklebur	*Xanthium strumarium* L.	XANST	SA	A, M	5.9	0.5	6.7	0.1	0.1	2.2
23	horseweed	*Erigeron canadensis* L.	ERICA	SA, WA	A, M	2.9	0.5	13.3	0.1	1.1	2.1
24	nightshade species	*Solanum* spp.	SOLSPP	SA, WA	A, M	5.9	0.2	3.3	0.1	0.1	1.9
25	wild mustard	*Sinapis arvensis* L.	SINAR	WA	M	2.9	0.2	16.7	0.1	2.3	1.7
26	henbit	*Lamium amplexicaule* L.	LAMAM	WA	A, M	2.9	0.5	13.3	0.1	0.5	1.7
27	quackgrass	*Elymus repens* (L.) Gould	AGRRE	P	M	2.9	0.1	8.3	0.1	2	1.4
28	yellow nutsedge	*Cyperus esculentes* L.	CYPES	P	A, M	2.9	0.1	3.3	0.1	0.8	1.4
29	Marestail	*Hippuris vulgaris* L.	HPPVU	P	M	2.9	0.1	3.3	0.1	0.1	1
30	volunteer soybean	*Glycine max* (L.) Merr.	GLXMA	SA	M	2.9	0.1	3.3	0.1	0.1	0.9
31	witchgrass	*Panicum capillare* L.	PANCA	SA	M	2.9	0.1	3.3	0.1	0.1	0.9
	Palmer amaranth	*Amaranthus palmeri* S.Wats.	AMAPA	SA	A, M	5.9	0.2	3.8	0.1	0.1	.
	waterhemp	*Amaranthus tuberculatus* (Moq.) Sauer	AMATU	SA	M	41.2	7.3	17.9	0.3	0.6	.
	common ragweed	*Ambrosia artemisiifolia* L.	AMBEL	SA	A, M	8.8	0.5	4.4	0.1	0.1	.
	giant ragweed	*Ambrosia trifida* L.	AMBTR	SA	A, M	5.9	0.2	4.8	0.1	0.6	.
	ivyleaf morningglory	*Ipomoea hederacea* Jacq.	IPOHE	SA	A, M	8.8	1.7	16.7	0.1	0.5	.
	Pennsylvania smartweed	*Persicaria pensylvanica* (L.) M.Gómez	POLPY	SA	M	2.9	0.2	8.7	0.1	0.4	.
	giant foxtail	*Setaria faberi* Herrm.	SETFA	SA	M	2.9	2.3	70	1.5	43.6	.

[i] Ranked by relative abundance.
[ii] EPPO = European and Mediterranean Plant Protection Organization code, formerly known as a Bayer code.
[iii] P = perennial; SA = summer annual; WA = winter annual.
[iv] A = Mid-Atlantic; M = Midwest.
[v] Frequency was the percentage of fields with a species present based on within-quadrat observations.
[vi] Uniformity was determined by dividing the number of quadrats in which the species was observed by the total number of quadrats of all surveyed fields (all fields) or total number of quadrats of fields where the species was observed (occurrence fields); both were expressed as a percentage.
[vii] Density was the number of plants per square meter in all fields (all fields) or fields where the species was observed (occurrence fields).
[viii] Relative abundance ranks of the contribution of individual species in the overall weed community based on equal importance of unadjusted frequency, uniformity in all fields, and density in all fields. The total value for relative abundance of all species is 300.

Table 4. Reported field and management details of lima bean fields surveyed in the US Mid-Atlantic region from 2019 to 2022.

Detail	Fields with reported information, no.	Variables	Fields, no.	Fields, %
Soil texture	58	Sandy loam	25	43.1
		Loamy sand	27	46.6
		Sand	5	8.6
		Loam	1	1.7
Cultivar	59	Cypress	38	64.4
		Meadow	10	16.9
		Emperor	5	8.5
		C-Elite	6	10.2
Row spacing (cm)	36	76.2	36	100
Mechanical	49	Spring tillage	41	83.7
		Fall tillage	0	0
	59	Interrow cultivation	15	25.4
Planting date	59	140 to 159	16	27.1
		160 to 179	12	20.3
		180 to 199	15	25.4
		200 to 220	16	27.1

On the contrary, all fields in the Midwest region reported spring tillage, and almost half of them received fall tillage the previous year (Table 5). For both regions, interrow cultivation was the exception rather than the norm, with 25% and 11% of the fields receiving interrow cultivation in the Mid-Atlantic and Midwest regions, respectively.

A slight majority of growers used herbicides in sequence (PRE followed by POST herbicides) to control weeds in lima bean. Nonetheless, approximately 36% and 24% of fields relied exclusively on a single-pass application of either PRE or POST herbicide only in the Mid-Atlantic (Table 6) and Midwest (Table 7) regions, respectively. The most common PRE herbicides across both regions were *S*-metolachlor and halosulfuron-methyl used on 78% and 69% of fields, respectively. Pendimethalin was also commonly used in the Midwest region as a PRE application. Bentazon was the most widely used (applied to 58% of fields) POST herbicide across all regions. Additional POST herbicides included imazamox or a graminicide (i.e., clethodim and sethoxydim). Applied to 82% of fields, ALS-inhibiting herbicides were the most popular herbicide mode action. In contrast, only 6% of fields received protoporphyrinogen oxidase (PPO)-inhibiting herbicides.

Some fields were sprayed with use rates below the labeled rate for SLN 24c-labeled herbicides, such as carfentrazone and sulfentrazone, in Delaware (Spartan Charge; FMC Corporation, Philadelphia, PA, USA). The rate applied was approximately one-half of the labeled rate for weed control. Fields in the Midwest received higher rates of chemical application than those for many other herbicides in the Mid-Atlantic, such as *S*-metolachlor, bentazon, and pendimethalin (Tables 6 and 7), presumably because of the differences in soil textures between regions.

The most parsimonious CART model for weed ground coverage used three nodes with two predictor variables, specifically, planting date and crop cultivar. The model explained 48% of the variability in weed ground coverage. Fields with the highest weed ground coverage (average, 27%) were in fields planted before 7 Jun (Fig. 1). Fields with the lowest weed ground coverage (average, 5%) occurred in fields planted after 7 Jun with the cultivars Cypress, Emperor, or Meadow.

The Mann-Whitney-Wilcoxon test was used to determine whether fields that received a two-pass herbicide application system had significantly lower weed ground coverage than single-pass application systems. Weed ground coverage was lower with a PRE herbicide program followed by POST herbicide program.

Discussion

Despite ongoing management efforts, amaranth species remain a major challenge in US bean production. Yield reductions in dry bean have been observed at densities as low as 1 Palmer amaranth per 100 m^2 (Miranda et al. 2021). Surveyed field densities reached 1.4 plants/m^2 in the Mid-Atlantic and 0.62 plants/m^2 in the Midwest, exceeding thresholds known to reduce yield in related species. Furthermore, both producers and researchers widely regard various amaranth species as problematic within lima bean production (Van Wychen 2022). Species from this genus are highly competitive and adaptative to weed management practices in many crops. Notably, some populations have evolved resistance to multiple herbicide modes of action (Aguyoh and Masiunas 2003; Carvalho and Christoffoleti 2008; Miranda et al. 2021; Steckel and Sprague 2004).

Other significant residual weeds included common chickweed, common purslane, and several grasses, including foxtail species and fall panicum. Many of these weeds cause significant yield loss from competition with dry bean (Mesbah et al. 2004; Vengris and Stacewicz-Sapuncakis 1971). The Midwest region also had high frequencies of common lambsquarters, which is also considered a troublesome weed by producers (Van Wychen 2022). However, winter annuals such as common chickweed and henbit are not likely to cause significant yield loss because they emerge late in the growing season and are

Table 5. Reported field and management details of lima bean fields surveyed in the US Midwest region from 2019 to 2022.

Detail	Fields with reported information, no.	Variables	Fields, no.	Fields, %
Soil texture	34	Sandy loam	6	17.6
		Silt loam	6	17.6
		Sand	5	14.7
		Loamy sand	5	14.7
		Clay loam	4	11.8
		Loam	4	11.8
		Silty clay loam	2	5.9
		Sandy clay loam	2	5.9
Previous crop	34	Field pea	17	50
		Field Corn	8	23.5
		Sweet Corn	4	11.8
		Soybean	3	8.8
		Potatoes	1	2.9
		Silage Corn	1	2.9
Cultivar	30	Cypress	11	36.7
		1639	6	20
		1621	6	20
		Meadow	4	13.3
		Kingston	3	10
Row spacing (cm)	34	38.1	18	52.9
		76.2	11	32.4
		55.9	5	14.7
Mechanical	34	Spring tillage	34	100
		Fall tillage	15	44.1
	34	Interrow cultivation	4	11.8
Planting date (Julian day)	34	140 to 159	17	50
		160 to 179	6	17.6
		180 to 199	11	32.4
Harvest date (Julian day)	31	220 to 239	3	9.7
		240 to 259	11	35.5
		260 to 279	14	45.2
		280 to 299	3	9.7

Table 6. Herbicides used on lima bean fields surveyed in the US Mid-Atlantic region from 2019 to 2022.

Application type	Application time	Herbicide	Herbicide mode of action[i]	Labeled minimum use rate g a.i./ha	Avg use rate g a.i./ha	Fields, no.	Fields, %
PRE only		—			—	21	35.6
	PRE	*S*-metolachlor	15	1067.6	1094.9	21	35.6
		Halosulfuron-methyl	2	26.3	34.6	21	35.6
		Clomazone	13	105.1	92	9	15.3
		Pendimethalin	3	1064.1	958.3	5	8.5
		Imazethapyr	2	35	39.4	2	3.4
		Sulfentrazone	14	103.4	55.2	2	3.4
		Carfentrazone	14	11.5	6.1	2	3.4
PRE + POST		—			—	38	64.4
	PRE	*S*-metolachlor	15	1067.6	1102.4	37	62.7
		Halosulfuron-methyl	2	26.3	29.7	35	59.3
		Clomazone	13	105.1	105.2	12	20.3
		Imazethapyr	2	35	37.5	9	15.3
		Sulfentrazone[ii]	6	103.4	69	4	6.8
		Carfentrazone[ii]	6	11.5	7.7	4	6.8
		Pendimethalin	3	1064.1	1064.8	2	3.4
	POST	Bentazon	2	560 210.2 with Imazamox	355.7	26	44.1
		Clethodim	1	105.1	145.9	22	37.3
		Imazamox	2	35	34.9	19	32.2
		Sethoxydim	1	105.1	210.6	2	3.4

[i] Following the Weed Science Society of America Herbicide Modes of Action.
[ii] Sulfentrazone and carfentrazone were sprayed together in a pre-mixed formulation (Spartan Charge®).
a.i. = active ingredient; POST = postemergence herbicide; PRE = preemergence herbicide.

outcompeted by the lima bean crop (personal observation).

Morningglories can be particularly disruptive to lima bean production because of their highly competitive nature, which reduces yield, and their capacity to contaminate harvest loads with seed capsules (Blessing et al. 2003; Glaze and Mullinix 1984; Sankula et al. 2024). They had high frequency in the Mid-Atlantic region, yet they were missing from most Midwestern fields. Morningglories can further cause harvest complications by vining over the lima bean plant and obstructing the harvester. Loads of lima bean contaminated with morningglory seed can be rejected by the processer (Kee et al. 1997).

Mechanical weed control was expected to be an important weed management practice in lima bean production because of the limited number of registered herbicides. However, contrary to expectations, interrow cultivation was observed infrequently in the surveyed fields. In addition, fall tillage practices were absent in the Mid-Atlantic region. Lack of interrow cultivation could be attributed to concerns about disrupting the zone of herbicide-treated soil surface, allowing for weed emergence. Interrow cultivation could also create uneven terrain, increasing the potential for crop loss when harvesting (Johnson 2014; Kee et al. 1997). Furthermore, lima bean has narrower row spacings in the Midwest region than in the Mid-Atlantic region. However, previous research found that decreasing row spacing from 56 cm to 38 cm did not reduce weed density or impact lima bean yield (Sankula et al. 2001). Finally, some fields in the Midwest and the Mid-Atlantic had field pea as an early season crop preceding lima bean, which is a relatively common practice because of the short growing season of both crops (Kee et al. 1997).

The PRE herbicides were applied in many fields and sometimes comprised the only herbicide application. No PRE herbicide registered for lima bean controls morningglory species, perhaps accounting for morningglory species observed in several fields. Cases of resistance to *S*-metolachlor in waterhemp and Palmer amaranth also exist in the Midwest, which could be a potential future concern (*Amaranthus palmeri* S. Wats) (Heap 2023).

Many growers also rely heavily on ALS-inhibiting herbicides; however, even when combined with other modes of action, ALS-inhibiting herbicides often fail to control important weeds. Almost all fields that received

Table 7. Herbicides used on lima bean fields surveyed in the US Midwest region from 2019 to 2022.

Application type	Application time	Herbicide	Herbicide mode of action[i]	Labeled minimum use rate g a.i./ha	Avg use rate g a.i./ha	Fields, no.	Fields, %
PRE only		—			—	4	11.8
	PRE	*S*-metolachlor	15	1067.6	1868.3	4	11.8
		Imazethapyr	2	35	52.5	2	5.9
POST only		—		—	—	4	11.8
	POST	Bentazon	6	560	952.7	4	11.8
		Sethoxydim	1	105.1	210.6	4	11.8
PRE + POST		—			—	26	76.5
	PRE	Pendimethalin	3	1064.1	1255.1	12	35.3
		S-metolachlor	15	1067.6	1678	11	32.4
		Halosulfuron-methyl	2	26.3	26.3	8	23.5
		Metolachlor	15	1092.8	588.7	4	11.8
		Imazethapyr	2	35	52.5	2	5.9
	POST	Bentazon	6	560 210.2 with Imazamox	660	24	70.6
		Imazamox	2	35	32.3	13	38.2
		Sethoxydim	1	105.1	210.6	10	29.4
		Fomesafen	14	280.2	175.1	2	5.9

[i] Following the Weed Science Society of America Herbicide Modes of Action.
a.i. = active ingredient; POST = postemergence herbicide; PRE = preemergence herbicide.

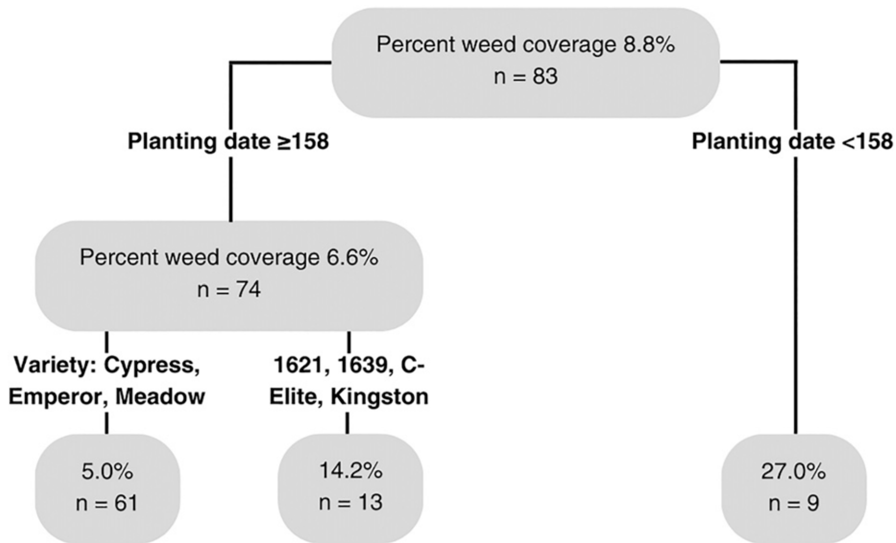

Fig. 1. Final classification and regression tree for percent weed coverage in lima bean fields. Mean field coverage and the number of observations are listed under each node. Eighty-three observations, one for each field, were used. The model explains 47.7% variability in percent weed coverage.

an application of imazamox also received a reduced rate of bentazon, which has been shown to reduce crop injury compared with that when bentazon is applied alone (Hekmat et al. 2008; Wall 1995). However, while the combination of imazamox plus bentazon may improve overall weed control, it does not provide acceptable control of ALS-resistant Palmer amaranth (Beiermann et al. 2022a).

Widespread resistance to ALS-inhibiting herbicides has been well-documented within the surveyed regions; 49 populations of weeds, including common lambsquarters and multiple amaranth species, have ALS resistance within the five surveyed states (Heap 2023; Powles and Yu 2010). Nonetheless, ALS-inhibiting herbicides appear to be an integral part of lima bean weed control, perhaps because of the range of weed species present as well as the limited number of registered herbicides.

Overreliance on ALS-inhibiting herbicides, bentazon, and *S*-metolachlor in lima bean production as well as rotation crops could further reduce herbicide efficacy (Powles and Yu 2010). Because producers have few chemical control options available for weeds, further resistance development to any of these herbicides would be highly detrimental to lima bean production.

PPO-inhibiting herbicides were rarely used, potentially because of a lack of registered products as well as a high risk of crop injury. Even at low use rates, sulfentrazone/carfentrazone (applied together) or fomesafen can result in unacceptable levels of crop injury (McNaughton et al. 2004; Soltani et al. 2022; VanGessel et al. 2015; VanGessel et al. 2000). Sulfentrazone/carfentrazone are labeled for use in Delaware only under a 24(c) special local needs label, while fomesafen is labeled only for dry lima bean production. When any PPO was applied, it was at a significantly lower rate than labeled.

The CART analysis showed that planting date and lima bean cultivar are important predictors of weed ground coverage. Growers have some degree of control over both variables. Earlier planting dates linked to higher weed ground coverage may be caused by difficulties controlling early cohorts of weeds. Fields with later planting dates may have less weeds emerging because a large percentage of weeds could have already germinated and been killed by spring tillage before planting. In general, later plantings have been found to reduce weed interference within dry bean (Beiermann et al. 2022a; Esmaeilzadeh and Aminpanah 2015; Nazer Kakhki et al. 2022). Days from planting to maturity are 77 to 79 d for 'Cypress', 'Meadow', and 'Emperor'. In comparison, the range of days to maturity for 'C-Elite' is 84 to 86 d (Ernest and Johnson 2021). Perhaps longer-maturing lima bean cultivars such as C-Elite are weedier because of additional time for soil-active herbicides to fail. A longer growing season could also allow for weeds to emerge further in the season. Cultivars are often selected according to when it would be appropriate to plant lima bean (personal observation). This may mean that planting date could be partially linked with cultivar selection.

Hypothesis testing determined that using a two-pass herbicide application made a significant difference in percentage weed ground coverage within a field when compared with fields with a one-pass herbicide application. This confirmed the hypothesis that two-pass herbicide applications could lead to less weed ground coverage, and perhaps reducing weed interference. A two-pass herbicide application system can improve weed control across both corn and soybean, lengthening the period of weed control (Craigmyle et al. 2013; Soltani et al. 2013). Lima bean production systems similarly appear to benefit from a two-pass herbicide application system.

Lima bean growers are facing many of the same weed challenges as those encountered 20 years ago (Blessing et al. 2003). Weeds persist until harvest for most fields, often at densities that can result in yield loss and contaminate harvested product. Amaranth species and morningglory species remain particularly problematic. Herbicides registered for lima bean remain limited, with few new prospects on the horizon. Several growers used a one-pass application; however, two-pass systems would reduce the risk of weed control failure. Additionally, low adoption of interrow cultivation because of potential risks of reducing herbicide efficacy and harvest efficiency only exacerbates reliance on a limited number of herbicides for weed control. Efficacy of weed control in preceding crops also influence the weed community; therefore, a multiyear strategy that also exploits more efficacious weed management systems in rotation crops is valuable for minor crops such as lima bean (Bhowmik 1997).

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