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Screening preemergence herbicides for weed control in cassava

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Abstract

Weed competition severely constrains cassava root yield in sub-Saharan Africa; thus, good weed control measures, including the use of herbicides, are increasingly important. Herbicide trials were conducted at five locations across eastern, western, and north-central Nigeria over two cropping seasons (2014 and 2015). Nineteen premixed PRE herbicides applied at different rates were evaluated for efficacy on weeds and selectivity on cassava. Manual hoe-weeding at 4, 8, and 12 wk after planting (WAP) and two *S*-metolachlor + atrazine treatments commonly used by cassava growers were included for comparison. Six of the 19 PRE herbicide treatments (indaziflam + isoxaflutole, indaziflam + metribuzin, flumioxazin + pyroxasulfone, isoxaflutole, acetochlor + atrazine + terbuthylazine, and terbuthylazine + *S*-metolachlor) consistently provided 80% to 98% broadleaf and grass weed control up to 8 wk after treatment. Overall, PRE herbicide treatments and cassava yield were significantly positively correlated. Herbicide treatments terbuthylazine + *S*-metolachlor, flumioxazin + pyroxasulfone, diflufenican + flufenacet + flurtamone (respectively, 60 + 60 + 60, 120 + 120 + 120, 90 + 360 + 120, and 135 + 360 + 180 g ha^{-1}), acetochlor + atrazine + terbuthylazine (875 + 875 + 875 g ha^{-1}), *S*-metolachlor + atrazine (870 + 1,110 g ha^{-1}), oxyfluorfen (240 g ha^{-1}), indaziflam + isoxaflutole (75 + 225 g ha^{-1}), indaziflam + metribuzin (75 + 960 g ha^{-1}), and aclonifen + isoxaflutole (500 + 75 g ha^{-1}) contributed to yields exceeding twice the Nigerian national average of 8.76 tonnes ha^{-1}. These treatments had root yields of 1.4 to 2 times higher than plots that had been hoe-weeded three times. There were some adverse herbicide treatment effects such as delayed cassava sprouting and temporary leaf bleaching observed in indaziflam and diflufenican + flufenacet + flurtamone treatments, whereas sulfentrazone caused prolonged leaf crinkling. The PRE applications alone at rates safe for cassava did not provide adequate season-long weed control; supplemental POST weed control is needed about 10 WAP for satisfactory season-long control.

Introduction

Cassava is extensively cultivated in the humid and subhumid tropical regions of Africa (Lebot 2009), which produces more than 54% of the world's cassava output (FAOSTAT 2014). This crop is cultivated mainly by smallholders and medium-scale farmers in 37 countries (FAOSTAT 2011). Nigeria is a global leader in cassava production with an output of approximately 59.5 million tonnes from 6.79 million hectares under cassava cultivation (FAOSTAT 2017). This output accounts for approximately 62% of cassava production in West Africa (FAOSTAT 2011). Cassava is an important crop in sub-Saharan Africa (Nweke 2004), where it is a major staple food for more than 200 million people (Nweke and Emete 1999). It is the second most important staple food crop after maize in terms of calories consumed (Nweke 1994). Cassava plays a vital role in the food economy of many African countries, including Nigeria, where it remains a strategic crop for both food security and poverty alleviation (Donkor et al. 2017; FAO 2011). This crop is now also an essential source of industrial raw material for the production of starch, bioethanol, high-quality flour for pharmaceuticals, food, and beverages and has the potential to contribute to the economic growth of Nigeria and most cassava-producing countries in sub-Saharan Africa.

A major challenge to cassava production in Nigeria is the low root yield (8 to 12.6 tonnes ha^{-1}) obtained by smallholders and medium-scale farmers (Donkor et al. 2017; Ekeleme et al. 2016; FAOSTAT 2017) compared with yields ranging from 20 to >35 tonnes ha^{-1} from Asian and Caribbean countries (Donkor et al. 2017; Hauser and Ekeleme 2017). Yields higher than 25 tonnes ha^{-1} have been achieved in Nigeria on research plots with appropriate crop management (Ekeleme et al. 2016; Hauser and Ekeleme 2017).

Poor weed control has been identified as a major cause of low yields in farmers' fields (Chikoye et al. 2001; Ekeleme et al. 2016; Howeler 2007). Although competition from weeds occurs at all periods of growth, the most damaging effects of weeds on cassava occur during two specific periods: the first 3 to 12 wk after planting (WAP) when the crop is in its early canopy-formation stage and the third month after planting when the storage roots commence bulking (Akobundu 1980; Chikoye et al. 2001; Melifonwu 1994; Onochie 1975). Several studies have stressed the importance of early weed control in the first 1 to 3 mo after planting to achieve high yields (Aye 2011; Howeler 2007; Tongglum et al. 1992).

Manual weeding is the most common method of weed control in cassava cultivation in Nigeria. Farmers carry out two to three hoe-weedings in the first growth cycle of cassava, but in areas where rhizomatous perennial weeds such as cogon grass (*Imperata cylindrica* L.) or sedges are dominant, additional hoe-weeding may be required. Generally, manual hoe-weeding is labor-intensive and time-consuming, and in most cases, farmers do not follow the recommended weeding regimes of 3, 6, and 9; or 4, 8, and 12 WAP (Adigun and Lagoke 2003; Ekeleme et al. 2016; Joshua and Gworgwor 2000).

Smallholders and medium-scale farmers increasingly use herbicides to control weeds in cassava due to reduced manpower availability and high labor costs. Odoemenem and Otanwa (2011) reported that 68.9% of smallholder farmers used herbicides to control weeds in cassava in north central Nigeria. Of those farmers, 9.5% used a variety of PRE herbicide formulations, whereas 69.0% used POST herbicides such as glyphosate (52.6%) and paraquat (16.4%). Currently, a limited number of herbicides are registered for use in cassava production in Nigeria.

The most common PRE herbicides currently used by cassava farmers are formulations containing atrazine, diuron, and *S*-metolachlor. These herbicides are usually applied at high doses that are prohibitively expensive for smallholder farmers. It is therefore essential to provide farmers with efficient and sustainable weed management to enhance cassava yields. This could be achieved with PRE herbicides that are effective against weeds and environmentally safe. The objective of this research was to identify additional PRE herbicide options for weed control in cassava production ecosystems in Nigeria.

Materials and Methods

Site Description and Treatment Application

Trials were conducted in two cropping seasons (first season, April to December 2014; second season, August 2014 to April 2015) at five locations representing three agroecologies in Nigeria: Humid Forest, Humid Forest Transition (Derived Savanna), and Southern Guinea Savanna (Figure 1). The Humid Forest and Humid Forest Transition agroecologies have a growing season rainfall of >1,300 mm with a growing period of 211 to 270 d and a window for two planting periods (referred to here as "seasons"). The Southern Guinea Savanna has a growing season rainfall of 1,200 to 1,500 mm with a shorter growing period of 181 to 210 d and a single planting window (Ekeleme et al. 2003). The first season trials were established in April 2014 at three locations and the second season in August 2014 at two locations (Table 1).

Nineteen PRE herbicides (Table 2) and manual hoe-weeding at 4, 8, and 12 WAP were evaluated for weed control efficacy. A weedy check was included for determination of weed control (%) values. Except for isoxaflutole and metribuzin, which had only one recommended application rate, the other herbicides were evaluated at two or three rates. Application rates were selected to represent lower label-recommended rates and 1.5 times the recommended application rate except for herbicides supplied by Bayer Crop Science, which provided application rates for its products. In total, 49 PRE herbicide treatments were evaluated. At each site, trials were established in a randomized complete block design with three replications. All herbicide treatments were commercial formulations and *S*-metolachlor + atrazine, which is commonly used by farmers, was included for comparison.

The treated plot size at each location was a 4.0 × 4.0 m square. An erect cassava variety, TME 419, was used in the trial. The planting material consisted of cassava stem cuttings measuring 25 cm—known as cassava stakes. The first season trial was on a scale of 10,000 plants ha^{-1} and 20,000 plants ha^{-1} were used in the second season trial. The increase in cassava plant numbers for the second planting season was aimed at achieving early canopy closure before the dry season commenced. Every site was treated with glyphosate to control perennial grasses and broadleaf weeds at 2 to 3 wk before field plowing. The experimental site was plowed and then harrowed 2 wk after plowing. The PRE herbicide treatments were applied 1 or 2 d after planting (DAP) with a hand-pumped CP 15 (COOPER PEGLER®) knapsack sprayer calibrated to deliver 250 L ha^{-1} of water at 240 kPa through a Cooper Pegler Hypro Polijet nozzle AN1.2 Green (EXEL GSA, ZI NORS ARNAS – BP 30 424, 69653 Villefranche Cedex). The overall herbicide efficacy in each plot was visually assessed at 8 wk after treatment (WAT) using a 0 to 100 scale, where 0 = no weed control, 10 to 49 = poor control, 50 to 69 = moderate control, 70 to 79 = fair/acceptable control, 80 to 89 = good control, and 90 to 100 = excellent control. Weed species in each plot were identified and counted in two 1-m^2 quadrants placed along a diagonal transect in each plot at each herbicide efficacy rating period. Weed species density data were used to estimate herbicide efficacy on major species as follows:

$$\frac{WSP_{untreated} - WSP_{treated}}{WSP_{untreated}} \times 100$$

Where $WSP_{untreated}$ and $WSP_{treated}$ is the weed species population in untreated plots and treated plots, respectively. To evaluate crop selectivity, phytotoxicity was assessed by visually rating crop damage on a scale of 0 (no phytotoxicity) to 10 (total plant death) at 2 and 4 WAT. All plots treated with herbicides were hoe-weeded at 10 wk after PRE herbicide treatment. Cassava stand establishment was assessed at 8 WAP and calculated as a percentage of planted stakes that sprouted. Cassava stakes that failed to sprout after the application of herbicides were not replaced. Fresh roots were harvested at 9 mo after planting at each site.

Statistical Analysis

Analysis of variance was used to examine the differences in treatment effects of two key yield variables: cassava stand count at

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Table 1. Description of experiment sites in Nigeria in the first and second cropping seasons.

Location	Longitude/Latitude	Agroecological zone	Planting date	Date of PRE application	Soil texture	Soil chemical properties
First cropping season						
FUNAAB[a]	07°23.200′N, 03°43.730′E	Forest Transition	June 8, 2014	June 10, 2014	66% sand, 19% silt, 15% clay	Organic C (1.17%), total N (0.107%), available P (16.13 ppm); pH (7.2)
NRCRI	05°29.122′N, 07°31.908′E	Humid Forest	June 18, 2014	June 19, 2014	84% sand, 5% silt, 11% clay	Organic C (2.71%), total N (0.272%), available P (1.97 ppm); pH (4.1)
UAM	07°47.270′N, 08°37.667′E	Southern Guinea Savanna	June 30, 2014	July 1, 2014	81% sand, 7% silt, 12% clay	Organic C (0.68%), total N (0.058%), available P (2.23 ppm); pH (5.3)
Second cropping season						
IITA	07°29.390′N, 03°53.032′E	Forest Transition	August 29, 2014	August 31, 2014	84% sand, 3% silt, 13% clay	Organic C (1.04%), total N (0.130%), available P (2.02 ppm); pH (5.2)
NRCRI	05°29.189′N, 07°31.975′E	Humid Forest	September 11, 2014	September 12, 2014	68% sand, 4% silt, 28% clay	Organic C (1.27%), total N (0.088%), available P (4.93 ppm); pH (5.6)

[a]Abbreviations: FUNAAB, Federal University of Agriculture Abeokuta; IITA, International Institute of Tropical Agriculture; NRCRI, National Root Crops Research Institute; UAM, University of Agriculture Makurdi.

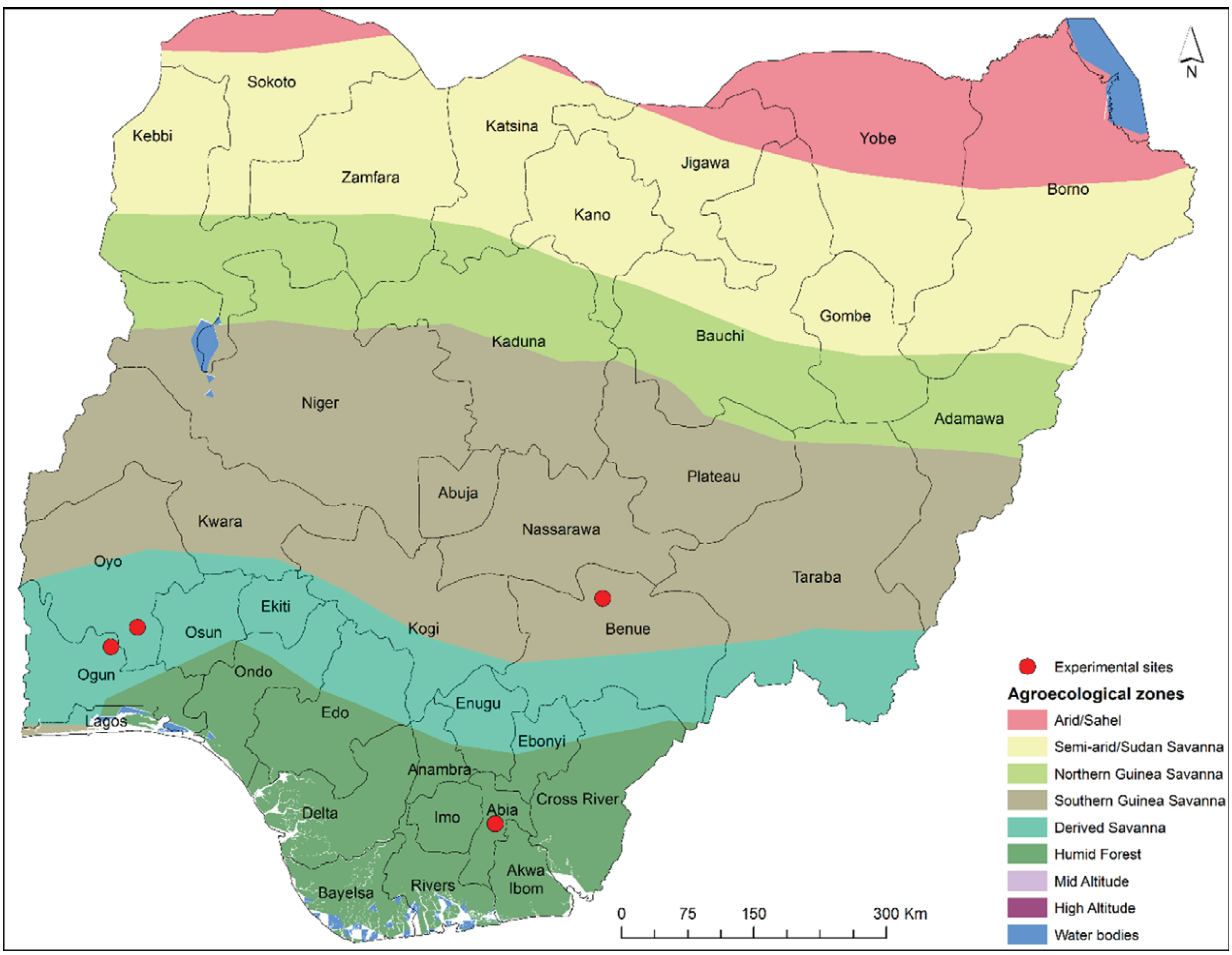

Figure 1. The study sites in Abia, Benue, Ogun, and Oyo states in Nigeria.

8 WAP and cassava fresh root yield at crop harvest. Significant treatment means were separated using the LSD at 5% probability. Where a location-by-treatment interaction effect was significant ($P < 0.05$), simple effect differences were evaluated among treatments to understand the nature of the interactions. Also, evaluated were Pearson linear correlation coefficients of cassava fresh root yield with herbicide control efficacy on various weed types (broadleaf weeds, grassy weeds, and all weeds) to discern the level of association between cassava root yield and weed control measures. Heat map presentation of the estimates of herbicide efficacy on all weeds, dominant weed species, cassava stand establishment, and root yield was used to strengthen the understanding and interpretation of the data matrix. Data on cassava stand establishment (%) was $\log_{10}(x + 1)$ transformed before analysis to stabilize the

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Table 2. Herbicide treatments and rates used in cassava experiments.

Herbicide	Active ingredient concentration	Unit	Commercial product
Aclonifen	600	g/L	Challenge 600 SC[a]
Aclonifen + isoxaflutole	500 + 75	g/L	Lagon 575 SC[a]
Acetochlor + atrazine + terbuthylazine	250 + 225 + 225	g/L	Bullet 700 SC
Clomazone + metribuzin	60 + 233	g/L	Metric 293 ZC[b]
Clomazone + pendimethalin	30 + 333	g/L	Stallion CS[b]
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	g/L	Vigon 420 SC[a]
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	g/L	Movon 450 SC[a]
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	g/L	Liberator forte 360 SC[a]
Dimethenamid-P + pendimethalin	212.5 + 250	g/L	Wing-P 462.5 EC[c]
Flumioxazin + pyroxasulfone	33.5 + 42.5	%	Fierce 75 WG
Indaziflam + metribuzin	37.5 + 480	g/L	Sencor Plus 517.5 SC[a]
Indaziflam + isoxaflutole	150 + 450	g/L	Merlin Total 600 SC[a]
Isoxaflutole	75	%	Merlin 75 WG[a]
Isoxaflutole + cyprosulfamide	240 + 240	g/L	Merlin Flexx 480 SC[a]
Metribuzin	480	g/L	Sencor 480 SC[a]
Mesotrione	480	g/L	Callisto 480 SC[e]
Oxyfluorfen	480	g/L	Goal 4F[d]
Prometryn + *S*-metolachlor	250 + 162.5	g/L	Codal Gold 412.5 DC[e]
S-metolachlor + atrazine	290 + 370	g/L	Primextra Gold 660SC[e]
Sulfentrazone	480	g/L	Authority 480 SC[b]
Terbuthylazine + *S*-metolachlor	187.5 + 312.5	g/L	Gardoprim Plus Gold 500 SC[e]

[a]Provided by Bayer Crop Science, Alfred-Nobel-Str. 50, Monheim, Germany https://www.cropscience.bayer.com/en.
[b]Provided by FMC Corporation, Market Street, PA, USA https://www.fmctechnologies.com.
[c]Provided by BASF Corporation, Research Triangle Park, NC, USA http://agrproducts.basf.us.
[d]Provided by SaroAgroscience, Amuwo-Odofin, Lagos, Nigeria http://saroafrica.com.ng.
[e]Provided by Syngenta Crop Protection AG, Basel, Switzerland https://www4.syngenta.com.

variance. All data analyses were performed using SAS software (version 9.4; SAS Institute Inc., Cary, NC).

Results and Discussion

There was a strong seasonal influence on herbicide efficacy, cassava stand establishment, and root yield. In the first cropping season, location-by-treatment interaction was significant ($P < 0.01$) for herbicide efficacy, cassava stand establishment, and root yield; therefore, data are presented separately by season and location. In the second cropping season, location by treatment was not significant ($P > 0.20$) for cassava stand establishment (%) or cassava stand population at crop harvest; therefore, data were pooled over location for these variables and combined data are presented. Data on herbicide efficacy against major weeds are presented by location.

Herbicide Efficacy: First Cropping Season

Herbicide Efficacy at the Abia State Site

At the National Root Crops Research Institute (NRCRI) site in Abia State, herbicide treatments varied considerably in broadleaf and grass weed control (Table 3). Overall, indaziflam + metribuzin provided superior (90%) broadleaf weed control at 8 WAT (Table 3, dark green). Similarly, grassy weeds were controlled more than 90% by indaziflam + metribuzin, indaziflam + isoxaflutole, and flumioxazin + pyroxasulfone (Table 3, dark green). Indaziflam + metribuzin, acetochlor + atrazine + terbuthylazine, sulfentrazone, isoxaflutole, isoxaflutole + cyprosulfamide, oxyfluorfen, and mesotrione (Table 3, dark green) showed excellent efficacy on hemorrhage plant [*Aspilia africana* (Pers.) C.D.]. Yellow tassel flower [*Emilia coccinea* (Sims) G. Don] was effectively controlled (>95%) by most of the herbicides. Diflufenican + flufenacet + flurtamone, clomazone + metribuzin, flumioxazin + pyroxasulfone, sulfentrazone, aclonifen + isoxaflutole, S-metolachlor + atrazine, mesotrione, and indaziflam + metribuzin (dark green in Table 3) provided excellent control of Siam weed [*Chromolaena odorata* (L.) R.M. King & Robinson]. Indaziflam + metribuzin, oxyfluorfen, and sulfentrazone (also coded dark green in Table 3) provided >90% control of giant potato (*Ipomoea mauritiana* Jacq.). The giant sensitive plant (*Mimosa diplotricha* C. Wright ex Sauuville) was controlled by acetochlor + atrazine + terbuthylazine, *S*-metolachlor + atrazine, diflufenican + flufenacet + flurtamone, and flumioxazin + pyroxasulfone (Table 3, dark green). The most efficient treatments on girdlepod [*Mitracarpus villosus* (Sw.) Cham. & Schltdl. ex DC.] were aclonifen, clomazone + pendimethalin, dimethenamid-P + pendimethalin, flumioxazin + pyroxasulfone, indaziflam + isoxaflutole, indaziflam + metribuzin, oxyfuorfen, and terbuthylazine + *S*-metolachlor (Table 3, dark green, Table 3). Hemorrhage plant, Siam weed, giant sensitive plant, and giant potato are prominent weeds in cassava fields (Alabi et al. 2001, 2004a; Nzegbule and Ogunremi 1995; Tarawali et al. 2013; Wakjira 2011). Siam weed and giant sensitive plant are reported as invasive species (Ikuenobe and Ayeni 1998; Uyi et al. 2014) that reduce cassava root yield in the Humid Forest and Derived Savanna agroecologies in Nigeria. Alabi et al. (2001) reported up to 85% root yield loss due to competition from giant sensitive plant and Nzegbule and Ogunremi (1995) reported significant cassava root yield reduction from competition with Siam weed. The most effective treatments on tropical carpet grass [*Axonopus compressus* (Sw.) P. Beauv.] and scrobic paspalum (*Paspalum scrobiculatum* L.) were indaziflam + metribuzin, indaziflam + isoxaflutole, and flumioxazin + pyroxasulfone (Table 3, dark green).

Although some herbicide treatments had generally poor to moderate control of broadleaf weeds and grasses, they were effective against specific weed species. For example, mesotrione generally showed poor control of most broadleaf weeds but excellent control of hemorrhage plant, Siam weed, and yellow tassel flower.

Table 3. Percentage of broadleaf and grass weeds controlled by different herbicide treatments at 8 wk after treatment in the first cropping season at the National Root Crops Research Institute site in Nigeria.

Herbicide	Rate	Broadleaf weeds[a]							Grassy weeds		
		APIAL	EMICO	EUPOD	IPOMT	MIMIN	MITCVI	Overall weed control	AXOCO	PASSC	Overall weed control
	g ai ha^{-1}										
Aclonifen	900	11	100	76	40	42	53	20	10	50	20
Aclonifen	1,500	29	100	81	24	27	97	30	74	59	30
Aclonifen + isoxaflutole	250 + 38	58	50	100	5	53	28	53	67	61	53
Aclonifen + isoxaflutole	375 + 56	59	50	94	17	22	12	30	76	67	23
Aclonifen + isoxaflutole	500 + 75	50	100	100	38	42	12	47	74	86	60
Acetochlor + atrazine + terbuthylazine	875 + 875 + 875	78	50	100	0	58	21	60	67	68	68
Acetochlor + atrazine + terbuthylazine	1,375 + 1,375 + 1,375	95	100	100	71	96	67	75	73	86	80
Clomazone + metribuzin	90 + 350	46	100	94	20	28	20	50	31	45	50
Clomazone + metribuzin	120 + 466	61	100	87	48	22	33	50	47	67	27
Clomazone + pendimethalin	90 + 999	40	100	46	51	17	67	20	30	67	20
Clomazone + pendimethalin	135 + 1,499	50	100	0	51	21	100	27	70	88	70
Diflufenican + flufenacet + flurtamone	30 + 120 + 60	49	100	64	30	59	54	43	67	72	47
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	25	100	64	44	55	78	47	68	89	53
Diflufenican + flufenacet + flurtamone	90 + 360 + 180	35	100	59	48	63	77	68	80	100	80
Diflufenican + flufenacet + flurtamone	45 + 120 + 60	44	100	44	38	23	48	33	57	60	43
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	28	50	64	74	25	50	33	21	86	53
Diflufenican + flufenacet + flurtamone	135 + 360 + 180	42	100	94	55	94	87	63	60	100	65
Diflufenican + flufenacet + flurtamone	60 + 60 + 60	41	100	13	55	39	52	23	38	67	30
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	57	100	62	84	58	75	43	67	76	40
Diflufenican + flufenacet + flurtamone	180 + 180 + 180	55	100	44	52	74	69	37	92	100	80
Dimethenamid-P + pendimethalin	850 + 1,000	34	100	46	54	55	92	33	60	88	50
Dimethenamid-P + pendimethalin	1,275 + 1,500	56	100	16	71	48	100	47	100	86	80
Flumioxazin + pyroxasulfone	110 + 140	65	100	89	79	61	79	78	76	100	78
Flumioxazin + pyroxasulfone	160 + 204	74	100	94	85	90	100	85	96	100	95
Indaziflam + isoxaflutole	49.5 + 148.5	71	100	67	70	53	77	77	76	87	80
Indaziflam + isoxaflutole	75 + 225	80	100	100	35	55	92	78	100	91	92
Indaziflam + metribuzin	38 + 480	67	100	100	70	63	87	73	86	67	70
Indaziflam + metribuzin	56 + 720	85	100	100	100	79	94	70	93	100	92
Indaziflam + metribuzin	75 + 960	98	100	100	81	85	93	90	92	98	90
Isoxaflutole + cyprosulfamide	72 + 72	62	100	89	10	57	12	33	77	52	40
Isoxaflutole + cyprosulfamide	120 + 120	98	100	86	0	59	14	50	71	61	60
Isoxaflutole	600	93	100	100	43	86	79	60	70	95	75
Mesotrione	96	60	100	100	52	29	29	30	17	10	30
Mesotrione	144	100	100	100	45	19	15	37	30	47	23
Metribuzin	317	51	50	100	54	62	6	23	80	33	23
Oxyfluorfen	240	41	100	21	29	61	60	57	46	100	63
Oxyfluorfen	360	100	100	100	100	58	100	77	90	100	80
Prometryn + *S*-metolachlor	750 + 488	31	100	33	15	48	56	37	25	46	53
Prometryn + *S*-metolachlor	1,125 + 731	71	100	68	40	42	74	43	68	70	43
S-metolachlor + atrazine	870 + 1,110	64	100	89	46	43	25	57	27	61	60
S-metolachlor + atrazine	1,305 + 1,665	70	100	100	67	93	64	78	96	76	80
Sulfentrazone	600	38	100	67	46	54	36	63	39	61	62
Sulfentrazone	912	91	100	95	94	63	65	73	92	69	73
Terbuthylazine + *S*-metolachlor	938 + 1,563	51	100	78	44	56	73	63	67	100	70
Terbuthylazine + *S*-metolachlor	1,875 + 3,125	43	100	85	75	63	97	83	67	95	83
Hoe-weeded three times[b]	NA	48	60	56	58	34	41	34	57	44	42

■ = Excellent weed control (90% to 100%), ■ = Good weed control (80% to 89%), ■ = Fair/acceptable weed control (70% to 79%), ■ = moderate weed control (50% to 69%), ■ = poor weed control (10% to 49%).

[a]Abbreviations: APIAL, hemorrhage plant; AXOCO, tropical carpet grass; EMICO, yellow tassel flower; EUPOD, Siam weed; IPOMT, giant potato; MIMIN, giant sensitive plant; MITCVI, girdlepod; PASSC, scrobic paspalum.

[b]Hoe-weeded once at the time of assessment.

Herbicide Efficacy at the Benue State Site

At this site, indaziflam + isoxaflutole and indaziflam + metribuzin (Table 4, dark green) provided superior (>90%) broadleaf weed control at 8 WAT compared with the other treatments. Indaziflam + isoxaflutole and indaziflam + metribuzin (Table 4, dark green) provided excellent control of coat buttons (*Tridax procumbens* L.), mint weed (*Hyptis suaveolens* Poit.), and ironweed (*Vernonia ambigua* Kotschy & Peyr). Similarly, acetochlor + atrazine + terbuthylazine, flumioxazin + pyroxasulfone, isoxaflutole + cyprosulfamide, and oxyfluorfen (Table 4, dark green) showed excellent control of coat buttons and ironweed. Flumioxazin + pyroxasulfone, indaziflam + isoxaflutole, indaziflam + metribuzin, isoxaflutole, isoxaflutole + cyprosulfamide, and terbuthylazine + *S*-metolachlor (Table 4, dark green) provided excellent control of crabgrass (*Digitaria horizontalis* Willd.), goosegrass [*Eleusine indica* (L.) Gaertn.], and itchgrass [*Rottboellia cochinchinensis* (Lour.) Clayton].

Coat buttons, mint weed, ironweed, crabgrass, goosegrass, and itchgrass are important competitive weed species that are difficult to control with the herbicides currently used by smallholder farmers in Nigeria (Olorunmaiye and Olorunmaiye 2008; Olorunmaiye et al. 2013). In north central Nigeria, which shares similar ecology with this

Table 4. Percentage of broadleaf and grass weeds controlled by different herbicide treatments at 8 wk after treatment in the first cropping season at the University of Agriculture Makurdi site in Nigeria.

		Broadleaf weeds[a]				Grassy weeds			
Herbicide	Rate	HYPSU	TRQPR	VENAM	Overall weed control	DIGHO	ELEIN	ROOEX	Overall weed control
	g ai ha^{-1}								
Aclonifen	900	51	50	59	43	32	78	64	57
Aclonifen	1,500	82	40	67	47	82	81	78	63
Aclonifen + isoxaflutole	250 + 38	52	33	69	30	22	77	73	47
Aclonifen + isoxaflutole	375 + 56	72	15	67	57	69	90	77	57
Aclonifen + isoxaflutole	500 + 75	78	52	93	60	83	87	87	87
Acetochlor + atrazine + terbuthylazine	875 + 875 + 875	67	58	87	70	15	82	78	43
Acetochlor + atrazine + terbuthylazine	1,375 + 1,375 + 1,375	79	92	91	85	89	85	83	85
Clomazone + metribuzin	90 + 350	30	47	40	23	80	82	62	73
Clomazone + metribuzin	120 + 466	74	53	76	57	83	89	78	77
Clomazone + pendimethalin	90 + 999	78	67	40	37	67	78	82	77
Clomazone + pendimethalin	135 + 1,499	75	78	99	82	100	87	81	83
Diflufenican + flufenacet + flurtamone	30 + 120 + 60	69	8	83	33	66	89	85	50
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	81	42	82	50	75	100	78	74
Diflufenican + flufenacet + flurtamone	90 + 360 + 180	92	67	90	80	80	100	87	82
Diflufenican + flufenacet + flurtamone	45 + 120 + 60	70	37	64	42	64	86	77	53
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	77	30	85	37	100	87	78	76
Diflufenican + flufenacet + flurtamone	135 + 360 + 180	78	33	95	53	100	90	88	80
Diflufenican + flufenacet + flurtamone	60 + 60 + 60	58	28	33	50	60	75	73	50
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	76	100	16	70	92	82	82	70
Diflufenican + flufenacet + flurtamone	180 + 180 + 180	78	100	88	80	58	85	75	60
Dimethenamid-P + pendimethalin	850 + 1,000	58	13	74	50	66	85	77	67
Dimethenamid-P + pendimethalin	1,275 + 1,500	84	42	74	60	55	100	92	73
Flumioxazin + pyroxasulfone	110 + 140	83	90	85	80	90	100	100	96
Flumioxazin + pyroxasulfone	160 + 204	89	100	94	86	100	100	94	96
Indaziflam + isoxaflutole	49.5 + 148.5	81	67	97	82	80	100	88	93
Indaziflam + isoxaflutole	75 + 225	85	100	96	95	100	100	88	95
Indaziflam + metribuzin	38 + 480	97	92	100	90	94	100	84	90
Indaziflam + metribuzin	56 + 720	99	97	89	93	92	100	84	95
Indaziflam + metribuzin	75 + 960	97	100	90	92	92	100	88	96
Isoxaflutole + cyprosulfamide	72 + 72	65	92	84	72	72	88	68	67
Isoxaflutole + cyprosulfamide	120 + 120	82	100	97	80	100	87	85	90
Isoxaflutole	600	69	83	100	63	100	100	85	96
Mesotrione	96	68	33	55	23	20	30	10	27
Mesotrione	144	73	37	33	63	46	46	20	19
Metribuzin	317	66	67	62	40	55	65	69	30
Oxyfluorfen	240	77	67	78	37	67	83	79	70
Oxyfluorfen	360	83	92	100	84	68	91	88	80
Prometryn + *S*-metolachlor	750 + 488	57	20	36	43	91	82	58	63
Prometryn + *S*-metolachlor	1,125 + 731	63	13	42	47	91	89	77	70
S-metolachlor + atrazine	870 + 1,110	73	50	55	62	62	82	76	67
S-metolachlor + atrazine	1,305 + 1,665	76	58	79	73	82	88	78	80
Sulfentrazone	600	50	78	65	43	97	84	80	80
Sulfentrazone	912	83	87	100	84	100	88	88	87
Terbuthylazine + *S*-metolachlor	938 + 1,563	75	20	77	40	66	89	82	63
Terbuthylazine + *S*-metolachlor	1,875 + 3,125	79	58	71	60	92	100	83	90
Hoe-weeded three times[b]	NA	40	34	52	48	38	42	35	40

■ = Excellent weed control (90% to 100%), ■ = Good weed control (80% to 89%), ■ = Fair/acceptable weed control (70 to 79%), ■ = moderate weed control (50% to 69%), ■ = poor weed control (10% to 49%).

[a]Abbreviations: DIGHO, crabgrass; ELEIN, goosegrass; HYPSU, mint weed; ROOEX, itchgrass; TRQPR, coat buttons; VENAM, ironweed.

[b]Hoe-weeded once at the time of assessment.

site (Southern Guinea Savanna), Olorunmaiye and Olorunmaiye (2008) observed that coat buttons, crabgrass, and itchgrass were not controlled by *S*-metolachlor + atrazine or by metolachlor + metobromuron when applied PRE alone or when followed by one or two manual hoe-weedings at 6 and 12 WAP in a cassava/maize intercrop. Several studies have identified resistance in some populations of itchgrass to some acetyl coenzyme-A carboxylase-inhibiting herbicides in Bolivia and Costa Rica (Avila et al. 2007; Castillo-Matamoros et al. 2016). At the International Center for Tropical Agriculture in Colombia, oxyfluorfen did not control goosegrass at the label rate of 0.5 kg ai ha^{-1} (Tonggulum and Leihner 2015). In the aforementioned study, goosegrass was controlled at a higher oxyfluorfen rate, but this caused unacceptable damage to cassava at 28 d after application. Flumioxazin + pyroxasulfone provided excellent control of coat buttons, mint weed, ironweed, crabgrass, goosegrass, and itchgrass.

Herbicide Efficacy at the Ogun State Site

The most effective herbicide treatments with 90% efficacy on all broadleaf weeds at the Federal University of Agriculture Abeokuta (FUNAAB) site in Ogun State at 8 WAT were indaziflam + isoxaflutole, isoxaflutole, and sulfentrazone (Table 5, dark green). At this site, flumioxazin + pyroxasulfone, indaziflam + isoxaflutole, indaziflam + metribuzin, and isoxaflutole (Table 5, dark green) use resulted in excellent control of red fruit passionflower (*Passiflora*

Table 5. Percentage of broadleaf and grass weeds controlled by different herbicide treatments at 8 wk after treatment in the first cropping season at the Federal University of Agriculture Abeokuta site in Nigeria.

Herbicide	Rate	Broadleaf weeds[a]					Grassy weeds		
		EPHHL	APIAL	PAQFO	TRQPR	Overall weed control	DIGHO	PASSC	Overall weed control
	g ai ha^{-1}								
Aclonifen	900	93	63	60	74	67	83	67	68
Aclonifen	1,500	92	70	67	51	62	81	71	62
Aclonifen + isoxaflutole	250 + 38	88	50	47	77	37	88	53	50
Aclonifen + isoxaflutole	375 + 56	79	53	0	63	43	90	37	63
Aclonifen + isoxaflutole	500 + 75	90	93	33	50	57	91	95	90
Acetochlor + atrazine + terbuthylazine	875 + 875 + 875	88	70	42	33	60	95	60	40
Acetochlor + atrazine + terbuthylazine	1,375 + 1,375 + 1,375	100	83	42	80	72	90	40	50
Clomazone + metribuzin	90 + 350	70	68	33	68	30	74	67	53
Clomazone + metribuzin	120 + 466	92	77	40	93	72	80	58	54
Clomazone + pendimethalin	90 + 999	100	53	0	46	16	76	65	60
Clomazone + pendimethalin	135 + 1,499	93	83	0	17	15	92	47	52
Diflufenican + flufenacet + flurtamone	30 + 120 + 60	87	83	33	32	47	92	67	67
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	90	90	33	45	40	85	81	80
Diflufenican + flufenacet + flurtamone	90 + 360 + 180	93	90	33	33	50	100	90	91
Diflufenican + flufenacet + flurtamone	45 + 120 + 60	83	80	0	22	15	78	67	55
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	93	80	33	52	18	90	55	60
Diflufenican + flufenacet + flurtamone	135 + 360 + 180	100	97	0	40	30	92	76	74
Diflufenican + flufenacet + flurtamone	60 + 60 + 60	87	87	0	12	23	87	57	60
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	88	87	0	31	7	86	38	55
Diflufenican + flufenacet + flurtamone	180 + 180 + 180	90	87	50	63	70	100	100	92
Dimethenamid-P + pendimethalin	850 + 1,000	89	87	0	37	33	90	63	67
Dimethenamid-P + pendimethalin	1,275 + 1,500	90	93	75	63	71	91	95	90
Flumioxazin + pyroxasulfone	110 + 140	100	93	67	85	83	100	90	90
Flumioxazin + pyroxasulfone	160 + 204	100	97	92	97	83	90	100	92
Indaziflam + isoxaflutole	49.5 + 148.5	100	100	97	81	90	96	67	60
Indaziflam + isoxaflutole	75 + 225	100	100	97	94	90	100	90	92
Indaziflam + metribuzin	38 + 480	100	100	83	80	80	93	80	81
Indaziflam + metribuzin	56 + 720	100	90	100	85	85	99	95	92
Indaziflam + metribuzin	75 + 960	100	100	93	90	83	100	95	92
Isoxaflutole + cyprosulfamide	72 + 72	100	97	33	33	53	87	43	53
Isoxaflutole + cyprosulfamide	120 + 120	100	97	8	71	63	89	67	60
Isoxaflutole	600	90	100	90	100	92	100	95	95
Mesotrione	96	79	67	0	15	8	30	10	8
Mesotrione	144	90	90	33	49	50	40	15	18
Metribuzin	317	83	83	0	67	28	80	67	55
Oxyfluorfen	240	100	67	0	59	20	83	26	50
Oxyfluorfen	360	100	93	25	72	63	97	67	57
Prometryn + S-metolachlor	750 + 488	79	77	42	40	15	75	100	80
Prometryn + S-metolachlor	1,125 + 731	87	78	67	42	53	93	100	92
S-metolachlor + atrazine	870 + 1,110	90	77	42	53	17	78	67	52
S-metolachlor + atrazine	1,305 + 1,665	93	93	33	37	37	100	53	60
Sulfentrazone	600	80	97	33	31	70	77	67	68
Sulfentrazone	912	89	100	87	36	90	97	67	80
Terbuthylazine + *S*-metolachlor	938 + 1,563	83	85	10	57	52	70	57	32
Terbuthylazine + *S*-metolachlor	1,875 + 3,125	88	90	67	63	68	82	87	80
Hoe-weeded three times[b]	NA	50	45	24	38	44	56	50	46

■ = Excellent weed control (90% to 100%), ■ = Good weed control (80% to 89%), ■ = Fair/acceptable weed control (70% to 79%), ■ = moderate weed control (50% to 69%), ■ = poor weed control (10% to 49%).
[a]Abbreviations: APIAL, hemorrhage plant; DIGHO, crabgrass; EPHHL, milkweed; PAQFO, red fruit passionflower; PASSC, scrobic paspalum; TRQPR, coat buttons.
[b]Hoe-weeded once at the time of assessment.

foetida L.) and coat buttons compared with the other treatments. The majority of these treatments controlled hemorrhage plant and milkweed (*Euphorbia heterophylla* L.) effectively. Aclonifen + isoxaflutole, diflufenican + flufenacet + flurtamone, dimethenamid-P + pendimethalin, flumioxazin + pyroxasulfone, indaziflam + isoxaflutole, isoxaflutole, and prometryn + *S*-metolachlor provided excellent control of crabgrass and scrobic paspalum (Table 5, dark green).

Weed Control Efficacy: Second Cropping Season

Herbicide Efficacy at the Abia State Site

At the NRCRI site, the most effective herbicide treatments were mesotrione, indaziflam + metribuzin, indaziflam + isoxaflutole, isoxaflutole, flumioxazin + pyroxasulfone, and diflufenican + flufenacet + flurtamone (Table 6, coded yellow), which controlled broadleaf weeds 70% to 77% at 8 WAT. At this location, sulfentrazone controlled grasses by 82% at 8 WAT (Table 6, light green).

Herbicide Efficacy at the Oyo State Site

At the International Institute of Tropical Agriculture (IITA) site in Oyo State, indaziflam + metribuzin, terbuthylazine + *S*-metolachlor, sulfentrazone, *S*-metolachlor + atrazine, and acetochlor + atrazine + terbuthylazine provided excellent (90% to 97%) control of grasses up to 8 WAT (Table 6, dark green).

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Table 6. Percentage of broadleaf and grass weeds controlled by different herbicide treatments at 8 wk after treatment in the second cropping season at two sites in Nigeria.

Herbicide	Rate	Broadleaf weeds[a]		Grass weeds	
		NRCRI	IITA	NRCRI	IITA
	g ai ha^{-1}				
Aclonifen	900	43	33	22	40
Aclonifen	1,500	50	20	33	37
Aclonifen + isoxaflutole	250 + 38	30	30	22	58
Aclonifen + isoxaflutole	375 + 56	57	43	33	65
Aclonifen + isoxaflutole	500 + 75	50	47	48	58
Acetochlor + atrazine + terbuthylazine	875 + 875 + 875	62	77	47	83
Acetochlor + atrazine + terbuthylazine	1,375 + 1,375 + 1,375	52	80	30	97
Clomazone + metribuzin	90 + 350	63	40	50	57
Clomazone + metribuzin	120 + 466	57	58	42	65
Clomazone + pendimethalin	90 + 999	42	37	28	80
Clomazone + pendimethalin	135 + 1,499	57	62	50	80
Diflufenican + flufenacet + flurtamone	30 + 120 + 60	65	32	55	62
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	53	32	30	67
Diflufenican + flufenacet + flurtamone	90 + 360 + 180	73	62	60	78
Diflufenican + flufenacet + flurtamone	45 + 120 + 60	43	50	22	63
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	67	42	63	60
Diflufenican + flufenacet + flurtamone	135 + 360 + 180	60	60	65	65
Diflufenican + flufenacet + flurtamone	60 + 60 + 60	57	37	35	63
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	47	37	33	47
Diflufenican + flufenacet + flurtamone	180 + 180 + 180	62	42	57	40
Dimethenamid-P + pendimethalin	850 + 1,000	50	45	58	68
Dimethenamid-P + pendimethalin	1,275 + 1,500	68	45	65	77
Flumioxazin + pyroxasulfone	110 + 140	65	67	60	63
Flumioxazin + pyroxasulfone	160 + 204	72	77	53	83
Indaziflam + isoxaflutole	49.5 + 148.5	67	82	50	85
Indaziflam + isoxaflutole	75 + 225	75	85	65	85
Indaziflam + metribuzin	38 + 480	45	75	52	95
Indaziflam + metribuzin	56 + 720	77	75	50	92
Indaziflam + metribuzin	75 + 960	70	83	58	93
Isoxaflutole	600	75	78	77	85
Isoxaflutole + cyprosulfamide	72 + 72	47	25	37	33
Isoxaflutole + cyprosulfamide	120 + 120	55	35	42	45
Mesotrione	96	57	20	19	28
Mesotrione	144	70	30	17	30
Metribuzin	317	52	43	40	55
Oxyfluorfen	240	52	63	42	70
Oxyfluorfen	360	57	70	33	85
Prometryn + *S*-metolachlor	750 + 488	50	43	40	62
Prometryn + *S*-metolachlor	1,125 + 731	42	47	33	65
S-metolachlor + atrazine	870 + 1,110	40	63	38	78
S-metolachlor + atrazine	1,305 + 1,665	62	77	65	90
Sulfentrazone	600	60	77	70	83
Sulfentrazone	912	62	87	82	92
Terbuthylazine + *S*-metolachlor	938 + 1,563	50	72	30	80
Terbuthylazine + *S*-metolachlor	1,875 + 3,125	65	83	43	92
Hoe-weeded three times[b]	NA	35	44	42	50

■ = Excellent weed control (90 to 100%), ■ = Good weed control (80 to 89%), ■ = Fair/acceptable weed control (70 to 79%), ■ = moderate weed control (50 to 69%), ■ = poor weed control (10 to 49%).

[a]Abbreviations: IITA, International Institute of Tropical Agriculture; NRCRI, National Root Crops Research Institute.

[b]Hoe-weeded once at the time of assessment.

Indaziflam + isoxaflutole and indaziflam + metribuzin consistently had the highest efficacy against broadleaf and grass weeds relative to other tested herbicides at most locations. This trend may be attributed to indaziflam, which has been reported to provide season-long residual control of annual grasses and broadleaf weeds in many crops when applied PRE (Sebastian et al. 2017; Singh et al. 2011). In Florida, Singh et al. (2011) reported that indaziflam applied as a PRE herbicide provided 3 to 4 mo of residual weed control in citrus groves.

In general, flumioxazin + pyroxasulfone consistently provided very good to excellent control of broadleaf and grass weeds at all sites (Table 6, dark green). Flumioxazin + pyroxasulfone has been reported to provide excellent weed control at rates similar to those evaluated in this study. This herbicide has been shown to be effective in soybean fields against broadleaf weeds such as velvetleaf (*Abutilon theophrasti* Medik), redroot pigweed (*Amaranthus retroflexus* L.), smooth pigweed (*Amaranthus hybridus* L.), and lambsquarter (*Chenopodium album* L.; Mahoney et al. 2014). Curtis et al. (2011) reported its effectiveness against grasses such as annual bluegrass (*Poa annua* L.), perennial ryegrass (*Lolium perenne* L.), and tall fescue [*Lolium arundinaceum* (Schreb.)]. Long soil residual activity has been reported for flumioxazin + pyroxasulfone (Bernards et al. 2010).

Cassava Stand Establishment and Selectivity

First Cropping Season

In the first cropping season, a significant treatment effect on cassava stand establishment was observed at the NRCRI (P = 0.0246),

Table 7. Effect of herbicide treatment on cassava stand establishment at 8 wk after planting in the first and second cropping seasons.

		Cassava stand establishment[a,b]				
		First cropping season			Second cropping season	
Herbicide	Rate	NRCRI	UAM	FUNAAB	NRCRI	IITA
	g ai ha^{-1}	%				
Aclonifen	900	92 abcd	81 cdefg	50 cdefg	99 ab	100 a
Aclonifen	1,500	88 abcde	94 abc	60 bcdef	99 ab	99 ab
Aclonifen + isoxaflutole	250 + 38	88 abcde	92 abcd	65 abcd	97 ab	99 ab
Aclonifen + isoxaflutole	375 + 56	83 abcdef	94 abc	67 abcd	93 abc	99 ab
Aclonifen + isoxaflutole	500 + 75	88 abcde	94 abc	69 abc	94 abc	97 abcd
Acetochlor + atrazine + terbuthylazine	875 + 875 + 875	94 abc	98 a	58 bcdefg	86 abcd	99 ab
Acetochlor + atrazine + terbuthylazine	1,375 + 1,375 + 1,375	92 abcd	92 abcd	67 abcd	96 ab	99 ab
Clomazone + metribuzin	90 + 350	94 abc	90 abcde	65 abcd	94 abc	100 a
Clomazone + metribuzin	120 + 466	92 abcd	88 abcde	63 abdcef	93 abc	100 a
Clomazone + pendimethalin	90 + 999	92 abcd	90 abcde	46 fgh	91 abcd	98 abc
Clomazone + pendimethalin	135 + 1,499	81 abcdef	94 abc	56 bcdefg	99 ab	100 a
Diflufenican + flufenacet + flurtamone	30 + 120 + 60	96 ab	90 abcde	65 abcd	96 ab	99 ab
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	85 abcdef	92 abcd	79 a	95 abc	99 ab
Diflufenican + flufenacet + flurtamone	90 + 360 + 180	90 abcde	92 abcd	63 abcdef	91 abcd	100 a
Diflufenican + flufenacet + flurtamone	45 + 120 + 60	85 abcdef	94 abc	58 bcdefg	93 abc	100 a
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	83 abcdef	83 abcdefg	46 fgh	96 ab	100 a
Diflufenican + flufenacet + flurtamone	135 + 360 + 180	94 abc	92 abcd	50 cdefg	91 abcd	94 def
Diflufenican + flufenacet + flurtamone	60 + 60 + 60	88 abcde	90 abcde	54 bcdefg	96 ab	99 ab
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	77 cdefg	94 abc	56 bcdefg	91 abcd	98 abc
Diflufenican + flufenacet + flurtamone	180 + 180 + 180	92 abcd	98 a	65 abcd	98 ab	100 a
Dimethenamid-P + pendimethalin	850 + 1,000	69 fg	79 defg	48 efgh	92 abcd	99 ab
Dimethenamid-P + pendimethalin	1,275 + 1,500	81 abcdef	88 abcde	58 bcdefg	95 abc	99 ab
Flumioxazin + pyroxasulfone	110 + 140	79 bcdef	88 abcde	56 bcdefg	91 abcd	98 abc
Flumioxazin + pyroxasulfone	160 + 204	75 defg	92 abcd	48 efgh	90 abcd	99 ab
Indaziflam + isoxaflutole	49.5 + 148.5	90 abcde	73 fg	48 efgh	76 ef	96 bcd
Indaziflam + isoxaflutole	75 + 225	73 efg	71 g	46 fgh	79 def	91 f
Indaziflam + metribuzin	38 + 480	75 defg	92 abcd	31 g	82 cdef	100 a
Indaziflam + metribuzin	56 + 720	73 efg	88 abcde	46 fgh	73 f	99 ab
Indaziflam + metribuzin	75 + 960	73 efg	77 efg	42 hg	74 ef	92 ef
Isoxaflutole + cyprosulfamide	72 + 72	79 bcdef	96 ab	65 abcd	93 abc	99 ab
Isoxaflutole + cyprosulfamide	120 + 120	77 cdefg	88 abcde	63 abcdef	97 ab	95 cde
Isoxaflutole	600	94 abc	92 abcd	65 abcd	92 abcd	97 abcd
Metribuzin	317	81 abcdef	85 abcdef	71 ab	95 abc	99 ab
Mesotrione	96	83 abcdef	96 ab	67 abcd	92 abcd	99 ab
Mesotrione	144	88 abcde	88 abcde	52 cdeg	100 a	100 a
Oxyfluorfen	240	90 abcde	85 abcdef	60 bcdef	97 ab	99 ab
Oxyfluorfen	360	60 g	96 ab	60 bcdef	99 ab	99 ab
Prometryn + *S*-metolachlor	750 + 488	85 abcdef	94 abc	71 ab	90 abcd	97 abcd
Prometryn + *S*-metolachlor	1,125 + 731	92 abcd	96 ab	71 ab	98 ab	100 a
S-metolachlor + atrazine	870 + 1,110	85 abcdef	90 abcde	69 abc	93 abc	100 a
S-metolachlor + atrazine	1,305 + 1,665	88 abcde	92 abcd	60 bcdef	95 abc	100 a
Sulfentrazone	600	88 abcde	83 abcdefg	50 cdefg	92 abcd	99 ab
Sulfentrazone	912	83 abcdef	92 abcd	52 cdefg	82 cdef	100 a
Terbuthylazine + *S*-metolachlor	938 + 1,563	98 a	92 abcd	54 cdefg	96 ab	99 ab
Terbuthylazine + *S*-metolachlor	1,875 + 3,125	90 abcde	92 abcd	58 bcdefg	94 abc	98 abc
Hoe-weeded times[c]	NA	85 abcdef	96 ab	56 bcdefg	97 ab	100 a
Untreated control	NA	80 abcdef	94 abc	48 efgh	100 a	96 bcd

[a]Abbreviations: FUNAAB, Federal University of Agriculture Abeokuta; IITA, International Institute of Tropical Agriculture; NRCRI, National Root Crops Research Institute; UAM, University of Agriculture Makurdi.
[b]Values followed by the same letter within a column are not significantly different at $\alpha = 0.05$.
[c]Hoe-weeded at 4, 8, and 12 wk after planting.

University of Agriculture Makurdi (UAM; $P < 0.0001$), and FUNAAB ($P < 0.0001$) sites (Table 7). Cassava establishment among herbicide treatments at the three sites (NRCRI, UAM, and FUNAAB; coded yellow in Table 7) was below 80%. At the NRCRI and UAM sites, cassava establishment in the other herbicide treatments ranged from 80% to 98% except for dimethenamid-P + pendimethalin treatment at the NRCRI site (Table 7, light brown). Cassava stakes in plots treated with all herbicides that contained indaziflam exhibited delayed sprouting at all sites. Delay in cassava sprouting was consistent in plots treated with indaziflam + isoxaflutole and indaziflam + isoxaflutole (Table 7, coded yellow). These two herbicide treatments contain a higher concentration of indaziflam. In the majority of the plots treated with indaziflam-containing herbicides, we noted that buds on the exposed part of unsprouted cassava stakes were still fresh and green in color when they were scratched. Still, when the stakes were inspected at 3 WAP, we observed cassava shoots emerging from the buried portion of the stake. A possible explanation is that cassava shoots sprouting from the buried buds on the stake required more time to emerge, and in clay soil, emergence may be prolonged or hindered. Indaziflam has been shown to inhibit cellulose biosynthesis in plants (Brabham et al. 2014), and this may be responsible for

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the delayed sprouting. At the FUNAAB site, cassava establishment was generally poor due to poor soil drainage.

Second Cropping Season

In the second cropping season, cassava establishment was >80% at the NRCRI and IITA sites except in plots treated with indaziflam + isoxaflutole and indaziflam + metribuzin, which had 73% to 79% of the expected cassava population of 20,000 plants ha^{-1} (Table 7, yellow). In both cropping seasons, diflufenican + flufenacet + flurtamone caused temporary leaf bleaching for 2 to 3 wk. Sulfentrazone caused prolonged leaf crinkling at the tip of the cassava shoot. Legleiter and Johnson (2013) reported similar symptoms on soybean leaves in fields treated with sulfentrazone as a PRE herbicide. Crop injury from sulfentrazone has often been attributed to such conditions as wet soil or heavy rainfall (Legleiter and Johnson 2013; Swantek et al. 1998). Swantek et al. (1998) noted that several heavy rainfall events totaling 170 mm in 16 DAP caused significant injury to soybean in Keiser, Florida. Our study was conducted in areas that received a total annual rainfall of 1,100 to 1,500 mm.

Cassava Fresh Root Yield

Cassava fresh root yield in the first cropping season varied with location (P = 0.0047). The location-by-treatment effect was significant only in the first cropping season (P = 0.0084).

First Cropping Season

A significant 7.72 to 12.3 tonnes ha^{-1} increase in fresh root yield was observed in herbicide-treated plots compared with hoe-weeded plots at the NRCRI site. This result occurred in plots treated with terbuthylazine + atrazine (Table 8, dark and light codes), and acetochlor + atrazine + terbuthylazine, diflufenican + flufenacet + flurtamone, oxyfluorfen, and indaziflam + isoxaflutole (Table 8, light green). Indaziflam + metribuzin, isoxaflutole, *S*-metolachlor + atrazine, flumioxazin + pyroxasulfone, aclonifen + isoxaflutole, clomazone + pendimethalin, dimethenamid-P + pendimethalin, and diflufenican + flufenacet + flurtamone had a 4 to 7.3 tonnes ha^{-1} yield advantage over the hoe-weeded treatment (Table 8, light green). Overall, uncontrolled weed growth in the untreated plots led to a reduction in root yield of 28.5% to 66.4%. Cassava fresh root yield at the NRCRI site in 23 out of 45 herbicide treatments was 1.5 to more than 2 times the Nigerian national root yield average. FAOSTAT (2017) reports a national yield average of 8.76 tonnes ha^{-1} for Nigeria, which is lower than the 22 tonnes ha^{-1} average yields currently obtained in Asia.

Cassava root yield at the UAM site was generally lower than yields obtained from the other locations, mainly due to poor soil drainage at the site after rain (Table 8). Cassava root yield from plots treated with isoxaflutole + cyprosulfamide, indaziflam + isoxaflutole, prometryn + *S*-metolachlor, and diflufenican + flufenacet + flurtamone (Table 8, yellow) more than doubled the yield from the hoe-weeded plot.

At the FUNAAB site, plots treated with dimethenamid-P + pendimethalin, indaziflam + metribuzin, and acetochlor + atrazine + terbuthylazine (Table 8, light green) produced yields that were significantly increased by 13.1 to 16.7 tonnes ha^{-1} over the hoe-weeded plot. Plots treated with flumioxazin + pyroxasulfone, diflufenican + flufenacet + flurtamone, dimethenamid-P + pendimethalin, and aclonifen + isoxaflutole (Table 8, yellow) yielded 8 to 10.7 tonnes ha^{-1} more than the hoe-weeded treatment.

Second Cropping Season

Cassava root yield in the second cropping season was not affected by location (P = 0.2671). Location-by-treatment interaction did not affect root yield (P = 0.7145). A significant treatment effect was observed when treatments were averaged across location (P = 0.0011) mainly due to root yield from plots treated with aclonifen (Table 8, yellow) and the weedy treatment. Aclonifen was not effective in controlling weeds at this site, resulting in severe weed competition with cassava. Cassava root yields in 24 out of 45 herbicide treatments in the second cropping season were comparable to those in hoe-weeded treatments. Cassava root yield in plots treated with isoxaflutole, indaziflam + isoxaflutole, sulfentrazone, and terbuthylazine + *S*-metolachlor (Table 8, dark green) was significantly higher by 8.7 to 13.7 tonnes ha^{-1} than for plots treated with *S*-metolachlor + atrazine at both rates. Cassava root yield in both seasons correlated positively with herbicide efficacy against broadleaf and grass weeds (Table 9). Generally, cassava root yield from the second cropping season was higher than the yield from the first cropping season. The cassava population was modeled after farmers' practice especially in the Humid Forest and Humid Forest Transition Savanna where small-hold farmers intercrop cassava with maize and vegetables in the first planting period (April to June), which usually receives more rainfall. In the planting period (August to October) with less rainfall, farmers tend to increase cassava population to compensate for the absence of a second crop in the season. Ekeleme et al. (2016) reported a similar season-dependent trend in the same agroecology in southwestern Nigeria where our study was conducted. Cassava yield from the second cropping season exceeded the national yield average by 1.8 to 3 times.

Cassava root yield in the hoe-weeded plots exceeded the average national yield of 8.76 tonnes ha^{-1} (FAOSTAT 2017) except at Benue and Ogun states. There, root yields from most herbicide-treated plots remained below the average national yield, suggesting that selection of an appropriate herbicide and dose rate for weed control in cassava may require the consideration of site-specific conditions. Manual weeding with appropriate timing, especially in the first cropping season, resulted in root yields that were equivalent to those from most herbicide treatments. In this study, hoe-weeding was conducted at 4, 8, and 12 WAP. Several weeding regime recommendations (Alabi et al. 2004b; NACWC 1994) exist for smallholder cassava production systems, however, farmers often do not follow them because of scarcity and the high cost of labor, or lack of awareness of the scale of yield damage caused by weed competition with crops. Farmers often perform their first weeding via hoe after the period when cassava should be free of weeds (critical period); this can result in severe yield loss due to competition from weeds. A critical period of 2 to 6 and 8 to 12 WAP is when cassava should be free of weed competition in Nigeria (Akobundu 1980; Melifonwu 1994). These periods correspond to early canopy formation and initiation of the storage roots.

In conclusion, our work identified several PRE herbicides (indaziflam + isoxaflutole, indaziflam + metribuzin, flumioxazin + pyroxasulfone, isoxaflutole, acetochlor + atrazine + terbuthylazine, terbuthylazine + *S*-metolachlor, and aclonifen + isoxaflutole) with excellent efficacy against broadleaf weeds and grasses for up to 8 WAT. These treatments plus one hoe-weeding at 10 WAP resulted in root yields that more than doubled the national root yield average in Nigeria. Because cassava is a long-duration crop, PRE herbicides at use rates that are safe on cassava do not provide season-long control through harvest at 12 mo after planting. Cassava requires POST weed control to supplement PRE

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Table 8. Cassava fresh root yield as influenced by herbicide treatment and manual hoe-weeding in first and second cropping seasons 9 mo after planting.

Herbicide	Rate	Fresh cassava root yield[ab]			
		First cropping season			Second cropping season
		NRCRI	UAM	FUNAAB	Mean[c]
	g ai ha^{-1}	t ha^{-1}			
Aclonifen	900	19.30 bcdefgh	5.37 efg	8.12 efghij	12.33 hi
Aclonifen	1,500	16.18 defghij	12.56 abcde	3.79 ij	23.13 abcdefg
Aclonifen + isoxaflutole	250 + 38	20.00 abcdefgh	7.53 efg	8.95 defghij	17.49 cdefgh
Aclonifen + isoxaflutole	375 + 56	14.39 ghij	9.75 cdefg	9.22 cdefghij	19.47 cdefgh
Aclonifen + isoxaflutole	500 + 75	20.89 abcdefg	10.60 bcdefg	18.69 abcde	22.65 abcdefg
Acetochlor + atrazine + terbuthylazine	875 + 875 + 875	23.82 abc	10.76 abcdefg	11.50 bcdefghij	18.62 cdefgh
Acetochlor + atrazine + terbuthylazine	1,375 + 1,375 + 1,375	18.34 bcdefgh	9.53 cdefg	21.09 abcd	20.05 cdefgh
Clomazone + metribuzin	90 + 350	12.83 hij	4.57 g	8.51 dcefghij	19.94 cdefgh
Clomazone + metribuzin	120 + 466	16.84 cdefghij	12.54 abcde	8.76 dcdefghij	21.67 abcdefg
Clomazone + pendimethalin	90 + 999	16.83 cdefghij	6.11 efg	NV	22.07 abcdefg
Clomazone + pendimethalin	135 + 1,499	20.84 abcdefg	12.07 abcdef	3.42 ij	19.43 cdefgh
Diflufenican + flufenacet + flurtamone	30 + 120 + 60	16.06 efghij	12.58 abcde	5.70 fghij	17.00 defgh
Diflufenican + flufenacet + flurtamone	60 + 240 + 120	15.01 fghij	8.48 defg	17.99 abcdefg	15.43 gh
Diflufenican + flufenacet + flurtamone	90 + 360 + 180	23.48 abcd	10.94 abcdefg	17.83 abcdefgh	20.87 bcdefg
Diflufenican + flufenacet + flurtamone	45 + 120 + 60	17.85 bcdefghi	6.64 efg	6.35 efghij	18.90 cdefgh
Diflufenican + flufenacet + flurtamone	90 + 240 + 120	14.18 ghij	10.53 bcdefg	4.23 ij	20.74 bcdefg
Diflufenican + flufenacet + flurtamone	135 + 360 + 180	22.91 abcde	11.10 abcdefg	11.01 bcdefghij	20.42 bcdefg
Diflufenican + flufenacet + flurtamone	60 + 60 + 60	24.59 ab	6.51 efg	13.63 abcefghij	24.32 abcde
Diflufenican + flufenacet + flurtamone	120 + 120 + 120	20.87 abcdefg	5.85 efg	4.08 ij	20.19 bcdefgh
Diflufenican + flufenacet + flurtamone	180 + 180 + 180	18.68 bcdefgh	15.16 abcd	8.56 dcdefghij	20.68 bcdefg
Dimethenamid-P + pendimethalin	850 + 1,000	13.82 ghij	5.64 efg	18.28 abcdef	18.17 cdefh
Dimethenamid-P + pendimethalin	1,275 + 1,500	19.10 bcdefgh	9.19 defg	24.76 a	24.20 abcdef
Flumioxazin + pyroxasulfone	110 + 140	20.99 abcdefg	11.81 abcdef	9.42 cdefghij	24.91 abcd
Flumioxazin + pyroxasulfone	160 + 204	20.35 abcdefg	7.43 efg	11.97 bcdefghij	18.00 cdefgh
Indaziflam + isoxaflutole	49.5 + 148.5	17.81 bcdefghi	7.01 efg	21.86 abc	24.50 abcde
Indaziflam + isoxaflutole	75 + 225	22.73 abcde	16.80 ab	10.39 bcdefghij	27.99 ab
Indaziflam + metribuzin	38 + 480	18.67 bcdefgh	10.35 bcdefg	9.40 cdefghij	22.99 abcdefg
Indaziflam + metribuzin	56 + 720	22.05 abcdef	9.24 cdefg	22.48 ab	23.94 abcdef
Indaziflam + metribuzin	75 + 960	18.97 bcdefgh	4.57 g	13.05 abcdefghij	18.43 cdefgh
Isoxaflutole + cyprosulfamide	72 + 72	17.70 bcdefghi	6.82 efg	8.59 dcefhij	20.90 bcdefg
Isoxaflutole + cyprosulfamide	120 + 120	13.98 ghij	17.64 a	8.85 dcdefghij	16.80 efgh
Isoxaflutole	600	21.84 abcdef	10.02 bcdefg	12.13 abcdefghij	28.97 a
Metribuzin	317	12.72 hij	4.59 g	5.37 ghij	18.34 cdefgh
Mesotrione	96	17.36 bcdefghi	7.17 efg	16.11 abcdefghi	18.77 cdefgh
Mesotrione	144	10.95 ij	7.34 efg	5.24 hij	18.40 cdefgh
Oxyfluorfen	240	23.06 abcde	8.92 defg	12.55 abdcefghij	23.66 abcdef
Oxyfluorfen	360	16.64 cdefghij	8.00 efg	8.94 defghij	20.75 abcdefg
Prometryn + *S*-metolachlor	750 + 488	18.35 bcdefgh	6.81 efg	14.39 abcdefghi	23.06 abcdefg
Prometryn + *S*-metolachlor	1,125 + 731	16.92 cdefghij	16.21 abc	10.93 bcdefghij	16.30 fgh
S-metolachlor + atrazine	870 + 1,110	17.53 bcdefghi	7.84 efg	10.59 bcdefghij	15.32 gh
S-metolachlor + atrazine	1,305 + 1,665	21.08 abcdefg	8.89 defg	10.79 bcdefghij	19.31 cdefgh
Sulfentrazone	600	17.38 bcdefghi	10.32 bcdefg	8.99 defghij	25.16 abc
Sulfentrazone	912	16.66 cdefghi	11.98 abcdef	6.26 efghij	25.22 abc
Terbuthylazine + *S*-metolachlor	938 + 1,563	22.48 abcde	6.53 efg	14.98 abcdeghij	25.10 abc
Terbuthylazine + *S*-metolachlor	1,875 + 3,125	27.07 a	4.48 g	8.45 defghij	21.55 abcdefg
Hoe-weeded three times[d]	NA	14.76 fghij	7.01 efg	8.03 efghij	22.82 abcdefg
Untreated	NA	9.09 ij	5.15 efg	1.67 j	6.49 i

[a]Values followed by the same letter within a column are not significantly different at α = 0.05.
[b]Abbreviations: FUNAAB, Federal University of Agriculture Abeokuta; IITA, International Institute of Tropical Agriculture; NRCRI, National Root Crops Research Institute; NA, data not available; UAM, University of Agriculture Makurdi.
[c]Average cassava fresh root yield from the International Institute of Tropical Agriculture, Research Farm and National Root Crops Research Institute Research Farm site.
[d]Hoe-weeded at 4, 8, and 12 wk after planting.

herbicide treatments. In this experiment, plots treated with herbicides received one hoe-weeding at 10 wk after the PRE herbicide treatment. This suggests the need to screen potential POST herbicides for use together with the PRE herbicides identified here for weed control in cassava. Several PRE herbicide treatments plus one hoe-weeding at 10 WAP gave superior cassava root yield compared with hoe-weeding at 4, 8, and 12 WAP. We attributed this trend to early weed emergence in the hoe-weeded treatment. Although hoe-weeding at 4, 8, and 12 WAP is usually recommended to smallholder farmers as the appropriate weeding regime in cassava, field observation at all sites showed that the first hoe weeding at 4 WAP was too late for effective weed control. At 4 WAP, perennial and fast-growing weed species such as Mexican sunflower [*Tithonia diversifolia* (Hemsl.) A. Gray], cogon grass, giant potato, passionflower, guineagrass (*Panicum maximum* Jacq.), and woodrose [*Merremia cissoides* (Lam.) Hallier f.] had infested the field, resulting in intense competition with cassava. Cassava is susceptible to weed competition, especially at 2 to 3 WAP when the

Table 9. Correlation of cassava root yield with herbicide efficacy against broadleaf and grass weeds.

Variables	N[a]	Pearson correlation coefficient	P value
First season			
Cassava root yield vs herbicide efficacy on all weed types	414	0.20	<0.0001
Cassava root yield vs herbicide efficacy on broadleaf weeds	414	0.13	0.0068
Cassava root yield vs herbicide efficacy on grass weeds	414	0.14	0.0032
Second season			
Cassava root yield vs herbicide efficacy on all weed types	141	0.22	0.0078
Cassava root yield vs herbicide efficacy on broadleaf weeds	141	0.20	0.0188
Cassava root yield vs herbicide efficacy on grass weeds	141	0.25	0.0025

[a]Number of observations.

growth rate is slow and at the root formation stage. A first hoe-weeding at 3 WAP in the plowed and ridged field and at 2 WAP in the plowed but unridged field may result in better weed control and root yield than a first hoe-weeding at 4 WAP. The need for early and timely weed control in cassava makes the use of PRE herbicide a better option than manual hoe-weeding.

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