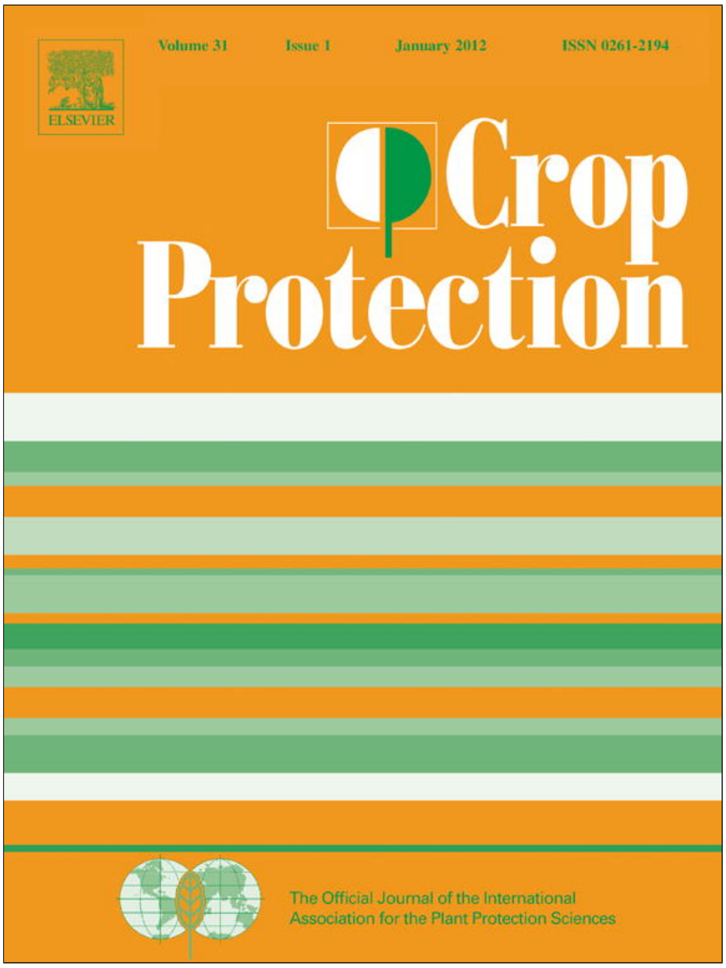
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Control of broadleaf weeds with post-emergence herbicides in four barley (*Hordeum* spp.) cultivars

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Limited information is available on control of broadleaf weeds in barley and response of barley cultivars to herbicides. Field experiments were conducted from 2007 to 2009 to evaluate post-emergence herbicides for control of broadleaf weeds in four barley cultivars. Herbicide treatments included 2,4-D sodium salt at 500 g ai ha^{-1}, carfentrazone-ethyl at three rates (15, 20 and 25 g ai ha^{-1}), and metsulfuron-methyl at 4 and 5 g ai ha^{-1}. The results suggested that density of broadleaf weeds was not affected by barley cultivars in 2007 and 2008, but it was influenced in 2009. Application of carfentrazone-ethyl or metsulfuron-methyl at all the rates was effective to reduce density and biomass of broadleaf weeds in all the years. A variable response was observed for yield attributes among barley cultivars. Barley grain yield was similar in all barley cultivars in 2007; however, higher yield was recorded in 'DWRUB 52' in 2008 and 2009 compared to other cultivars. All herbicide treatments were usually effective to secure higher barley yields in all the years and there was a significant interaction between barley cultivars and weed management treatments. Hand hoeing was not as effective as herbicide treatments to reduce density and biomass of broadleaf weeds; however, barley yield was usually comparable with herbicide treatments. Results also revealed that there was no significant herbicide injury on any barley cultivar during three year experiments. It is concluded that carfentrazone-ethyl and metsulfuron-methyl are additional tools for broadleaf weed control in barley. However, more research is required to evaluate efficacy of these herbicides as a tank mix partner that may increase weed control spectrum in barley.

1. Introduction

Barley (*Hordeum vulgare* L.) is one of the most highly adapted small grains with production ranging from sub-Arctic to subtropical climates. It is produced in a variety of climate and in both irrigated and dry land production areas. Barley is grown on about 57 million ha, of which 32 million ha are in the developing countries including those of central Asia and the Caucasus (Grando and Mcpherson, 2005). In 2010, Indian barley growers harvested 1.5 million tons of barley from 0.735 million ha (Anonymous, 2011) and exported ~0.5 million tons (USDA, 2011). Majority of barley cultivars traditionally grown in India are six-row cultivars primarily grown for animal feed. Despite a strong demand from India's growing malt-based beverage industry, barley production has remained stagnant (1.3–1.5 million tons annually) for several years because of poor yields and economic returns (USDA, 2011). However, in recent years, excellent malting-type- two-row cultivars of barley have been developed under the public–private breeding program partnership, that is replacing barley traditionally cultivated for animal feed. Availability of improved cultivars and their commercial use in malt industry are the major stimulus for increased barley cultivation in recent years.

There are many limiting factors in barley production in India including low yielding cultivars, poor growing conditions, and crop–weed competition. The average yield of barley in India is only 2172 kg ha^{-1} (Anonymous, 2011). The state of Punjab has the highest barley yield (3357 kg ha^{-1}) in India (Anonymous, 2011). Due to plant height, rapid canopy cover, and light interactions; barley is generally considered a competitive cereal crop (López-Castañeda et al., 1995). However, a significant yield reduction has been reported due to weed interference (Morishita and Thill, 1988;

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Watson et al., 2006). Several grass and broadleaf weeds infest the barley crop and may reduce yields depending on weed density and stage of the crop. Several studies reported that a season long weed competition reduced barely yields by 28.1% in India (Pandey et al., 1998) and 6–79% in Canada (Watson et al., 2006). The interference of 55–70 *Avena fatua* L. plants m^{-2} reduced barley yield by 14–22% in Canada (Dew, 1973), and 25% in Argentina (Scursoni and Satorre, 2005). A study in Germany reported that *Cirsium arvense* L. and *A. fatua* densities higher than 5 plants m^{-2} reduced the protein content and size of grain sufficient to result in a complete loss of valuable malting premiums (Gerhards et al., 2005).

Currently, 2,4-D is a widely used herbicide for control of broadleaf weeds in barley; however, 2,4-D use is stage specific and has use restrictions, especially if broadleaf crop is planted in nearby fields (Swan, 1975). Due to repeated use for several years, the efficacy of 2,4-D has been reduced especially against hard to control broadleaf weeds such as *Rumex dentatus* L., *Rumex spinosus* L., and *Malva neglecta* Wallr. In a long term study in rice–wheat cropping system, continuous use of 2,4-D for 13 years resulted in the buildup of *R. dentatus* and *Chenopodium album* L. weed seed bank (AICRPWC, 2010). Therefore, herbicides with alternate mode of action are required to control broadleaf weeds in small grains including barley.

Isoproturon [3-(4-isopropylphenyl)-1,1-dimethylurea or 3-*p*-cumenyl-1,1-dimethylurea] has been used traditionally for weed control in barley; however, due to evolution of isoproturon-resistant littleseed canarygrass, the use of this herbicide is very limited in Punjab (Singh, 2007). Some alternate herbicides such as metsulfuron-methyl and carfentrazone-ethyl were introduced for control of broadleaf weeds in wheat in 2000 and 2007, respectively (PAU, 2011). Metsulfuron-methyl is a sulfonylurea herbicide that inhibits acetolactate synthase (ALS), a key enzyme needed in biosynthesis of the branched chain amino acids. It has both, pre- and post-emergence activity for control of broadleaf weeds and can suppress some annual grasses (Ackerson and Davis, 1987; Tewari et al., 1998). Carfentrazone-ethyl is a post-emergence herbicide for control of broadleaf weeds in a variety of agricultural crops, turf, industrial and utility sites (Ilango, 2003).

The growing season of wheat and barley is the same and the same weed species infest both crops. Application of metsulfuron-methyl and carfentrazone-ethyl have shown excellent efficacy for hard to control broadleaf weeds in wheat when applied alone or in tank mixes with other herbicides (Howatt, 2005; Tewari et al., 1998; Tiwari et al., 2005; Zand et al., 2010). Limited information is available on tolerance of selected barley cultivars to metsulfuron-methyl and carfentrazone-ethyl (Singh and Punia, 2007). In addition, these herbicides have different mode of action, hence the rotational use of these herbicides with 2,4-D may reduce the selection pressure for evolution of herbicide resistant weeds. The objective of this research was to evaluate the response of four barley cultivars (two row and six row cultivars) to optimize the rate requirement of these herbicides for effective control of broadleaf weeds and compare their responses to hand-hoeing and 2,4-D treatments.

2. Materials and methods

2.1. General information

Field experiments were conducted at the Agronomy Research Station, Punjab Agricultural University, Ludhiana (30° 56′N latitude and 75° 52′E longitude), Punjab, India during 2007–08, 2008–09 and 2009–10 growing seasons. The soil type was sandy loam with pH 7.8, organic carbon 0.27%, N 215 kg ha^{-1}, P 22.8 kg ha^{-1}, K 255 kg ha^{-1}, and EC 0.20 dS m^{-1}. The experimental design was a split plot with barley cultivars as main plots and weed control treatments as sub plots with four replications. The four barley cultivars selected for this study are commercial cultivars grown most commonly in Punjab and several other northern states of India. Two cultivars ('DWRUB 52' and 'VJM 201') are two row barley (*Hordeum distichon*), while 'PL 426' and 'PL 419' are six row barley (*H. vulgare*) cultivars. The DWRUB 52 was planted only in 2008 and 2009, while PL 419 was planted only in 2007.

2.2. Treatment details

Weed control treatments included carfentrazone-ethyl at three rates (15, 20 and 25 g ai ha^{-1}), 2,4-D sodium salt at 500 g ae ha^{-1}, and metsulfuron-methyl at 4 and 5 g ai ha^{-1}. An untreated control and one hand hoeing treatments were included for comparison. The main plot size was 7 m × 21.6 m and sub plot was 7 m × 2.7 m. The seedbed was prepared by one ploughing with disc harrow followed by two ploughing with cultivators and each ploughing was followed by planking. The barley was seeded at 4–5 cm depth in moist soil in rows spaced at 22.5 cm on flat beds at the seed rate of 75 kg ha^{-1}. Before seeding, the barley seeds were treated with vitavax and thiram at 3 g kg^{-1} to prevent stripe disease and loose smut in barley. The trials were seeded on 11 November, 2007, 18 November, 2008, and 01 December, 2009.

The crop was fertilized with 62.5 kg N, 30 kg P_2O_5 and 15 kg K_2O ha^{-1}. The nitrogen was applied in the form of urea (46% N), P_2O_5 in form of single super phosphate (16% P_2O_5) and K_2O in form of muriate of potash (60% K_2O). Total quantity of all the fertilizers was drilled at the time of seeding. The crop was supplied with two irrigations (2.5 cm), one at crown root initiation and the second at panicle emergence stage. The herbicides were sprayed at 30 days after seeding barley using a knap sack sprayer fitted with flat fan nozzles in a spray volume of 375 L ha^{-1}. Grassy weeds were controlled with an application of clodinafop at 0.06 kg ha^{-1} at 35 days after seeding.

2.3. Data collection

The broadleaf weed densities were assessed during the growing season within 0.5 m^2 quadrats (two quadrats per plot), at 21 days after herbicide treatments. Biomass of broadleaf weeds was taken at 28–30 days after herbicide treatments. The broadleaf weeds within a randomly selected 0.5 m^2 quadrats (two quadrats per plot) were cut at the stem base close to the soil surface, placed in paper bags, dried in an oven for 72 h at 60 °C and biomass was recorded. The data on herbicide injury on barley cultivars were recorded at 7, 14 and 28 days after herbicide treatments based on 0–100% scale where 0% being no injury and 100% being complete death of plant. The data on barley plant height was determined by measuring the height to the terminal node of 10 randomly selected plants per plot. The effective tillers were counted from 1 m row length from four randomly selected spots per plot; spike length, seeds per spike and seed weight per spike were recorded from 10 randomly selected spikes per plot three to four days before crop harvest. The crop was harvested manually on 17 April 2008, 17 April 2009 and 13 April 2010 and grain yield was recorded. The net plot harvested was 6 m × 2.25 m.

2.4. Statistical analysis

All data were subjected to ANOVA using statistical analysis software version 9.2 (SAS, 2009) to test for treatment effects and possible interactions. Normality, homogeneity of variance, and interactions of treatments and years were tested. Interactions among years were significant; therefore, data were presented separately for each year. The data of weed density and biomass were square root transformed, while data of herbicide injury were arc-sine transformed prior to analysis; however, non-transformed means are presented with mean separation based on transformed values. Where the ANOVA indicated that treatment effects were significant, means were separated at $P \leq 0.05$ with Fisher's Protected Least Significant Difference (LSD) test.

3. Results and discussion

3.1. Crop injury

No significant barley injury was observed in any herbicide treatment in any year (data not shown), which indicated that all herbicides were safe for use in all barley cultivars. Some minor injury was observed at 7 DAT with application of carfentrazone-ethyl at 20 and 25 g ha^{-1}; however, injury was no longer visible at 14 DAT (data not shown), and barley yield was not affected by carfentrazone-ethyl injury. All herbicides were applied as per the labeled guidelines; therefore, the absence of sustained injury was expected. Howatt (2005) reported that application of carfentrazone-ethyl at 18 g ha^{-1}caused 21% wheat injury 3 DAT, but it was no longer visible 3 weeks after treatment and there was no yield loss.

3.2. Weed density and biomass

Common broadleaf weeds present at experimental sites during the 3-year period included *R. dentatus*, *Medicago polymorpha* L., *C. album*, and *Anagallis arvensis* L. A significant treatment by year interaction ($P < 0.05$) was observed for weed density and biomass; therefore, data of all three years were presented separately. There was no difference in broadleaf weed density among barley cultivars in 2007 and 2008 (Table 1), but variable result was observed in 2009 (Fig. 1). The exact reason for this variable response is unknown, but it might be because of the fact that barley cultivars can vary in their competitiveness with weeds. For example, density of *A. arvensis* was significantly higher (6.7 plants m^{-2}) in DWRUB 52 compared to other two cultivars with the lowest density (3.0 plants m^{-2}) in VJM 426 in 2009 (Fig. 2). A similar response was observed for *C. album* in 2009 (Fig. 2). Didon (2002) suggested that the barley cultivars with strong to medium competitive ability against weeds shortened the time of emergence in the presence of white mustard (*Sinapsis alba* L.) in contrast to least competitive cultivar. Several factors affecting competitiveness of a crop including quick emergence, abundant tillering, high leaf area index, and canopy height (Didon and Hansson, 2002; Huel and Hucl, 1996).

Broadleaf weed density was affected by weed management treatments. All weed management treatments reduced density of broadleaf weeds compared to untreated control at 21 DAT (Table 1). Hand hoeing was usually not effective compared to herbicide treatments and resulted in higher density of *M. polymorpha*, *C. album*, and *A. arvensis*. The density of *R. dentatus* was reduced as low as <3 plants m^{-2} with application of carfentrazone-ethyl at 20 or 25 g ha^{-1}or metsulfuron-methyl usually at all the rates compared to 2,4-D sodium salt in 2008 and 2009 (Table 1; Fig. 1). While, density of *M. polymorpha*, *C. album*, and *A. arvensis* was almost similar in treatments including 2,4-D sodium salt, carfentrazone-ethyl, and metsulfuron-methyl. Kelly and Coats (2000) reported that application of metsulfuron at 32 g ha^{-1} or more was effective for control of *Diodia virginiana*. A recent study in Tennessee and Texas reported that metsulfuron applied alone at 21 g ha^{-1} controlled >77% broadleaf weeds at 56 DAT, similar to a tank mix with carfentrazone (Brosnan et al., 2012).

Interaction effects of barley cultivars and weed management treatments were significant for broadleaf weed densities (Figs. 1 and 2). For majority of treatment combinations, there was no significant difference for broadleaf weed density (Figs. 1 and 2). Lyon et al. (2007) reported that carfentrazone at 18 g ha^{-1} tank mixed with 2,4-D amine or dicamba improved *Salsola iberica* Sennen & Pau, *Kochia scoparia* L., and *Helianthus annuus* control without injury on proso millet (*Panicum miliaceum* L.) and foxtail millet (*Setaria italica* L.) in Nebraska.

Biomass of broadleaf weeds was not affected by barley cultivars. Compared to untreated control, all weed management treatments were effective to reduce broadleaf weed biomass (Table 1). In 2007, there was no difference among herbicide treatments on broadleaf weed biomass and all the treatments resulted in <20 g m^{-2} weed

Table 1
Effects of weed management treatments on broadleaf weed density and biomass in four barley cultivars in 2007, 2008 and 2009.

Treatment	Rate (g ai or ae ha^{-1})	Broadleaf weed density m^{-2} at 21 DAT[a,b,c]				Weed biomass (g m^{-2})
		R. dentatus	*M. polymorpha*		*A. arvensis*	
		2008	2007	2008	2008	2007
Barley cultivars[d]						
DWRUB 52	–	4.6 a	–	4.5 a	4.1 a	–
VJM 201	–	2.5 a	9.0 a	4.5 a	4.6 a	28.1 a
PL 426	–	3.0 a	9.7 a	3.7 a	3.7 a	29.6 a
PL 419	–	–	9.9 a	–	–	32.3 a
Weed management treatments						
Untreated control	–	6.9 a	26.0 a	6.7 a	7.6 a	111.3 a
Hand hoeing	–	5.3 ab	8.2 bc	4.9 ab	6.2 ab	25.7 b
2,4-D sodium salt	500	5.3 ab	6.0 d	2.9 c	4.0 bc	16.5 bc
Carfentrazone-ethyl	15	4.7 ab	7.5 bcd	4.2 bc	3.6 c	19.4 bc
Carfentrazone-ethyl	20	1.8 c	8.6 b	3.8 bc	3.3 c	18.1 bc
Carfentrazone-ethyl	25	0.4 c	6.3 cd	4.7 bc	1.6 c	17.1 bc
Metsulfuron-methyl	4	1.6 c	7.3 bcd	3.6 bc	4.0 bc	15.8 c
Metsulfuron-methyl	5	0.9 c	6.5 cd	3.1 bc	2.9 c	16.5 bc
Interaction effects[e]	–	NS	NS	NS	NS	NS

[a] DAT, days after treatment.
[b] The data were arc-sine transformed for homogenous variance prior to analysis; however, data presented are the means of actual values for comparison.
[c] Least square means within columns with no common letters are significantly different according to Fisher's protected least significant difference (LSD) test where $P < 0.05$.
[d] Barley cultivar 'DWRUB 52' was planted only in 2008 and 2009, while cultivar 'PL 419' was planted only in 2007.
[e] Interaction effects denoted by NS is non-significant at $P < 0.05$; significant interactions are presented in figures.

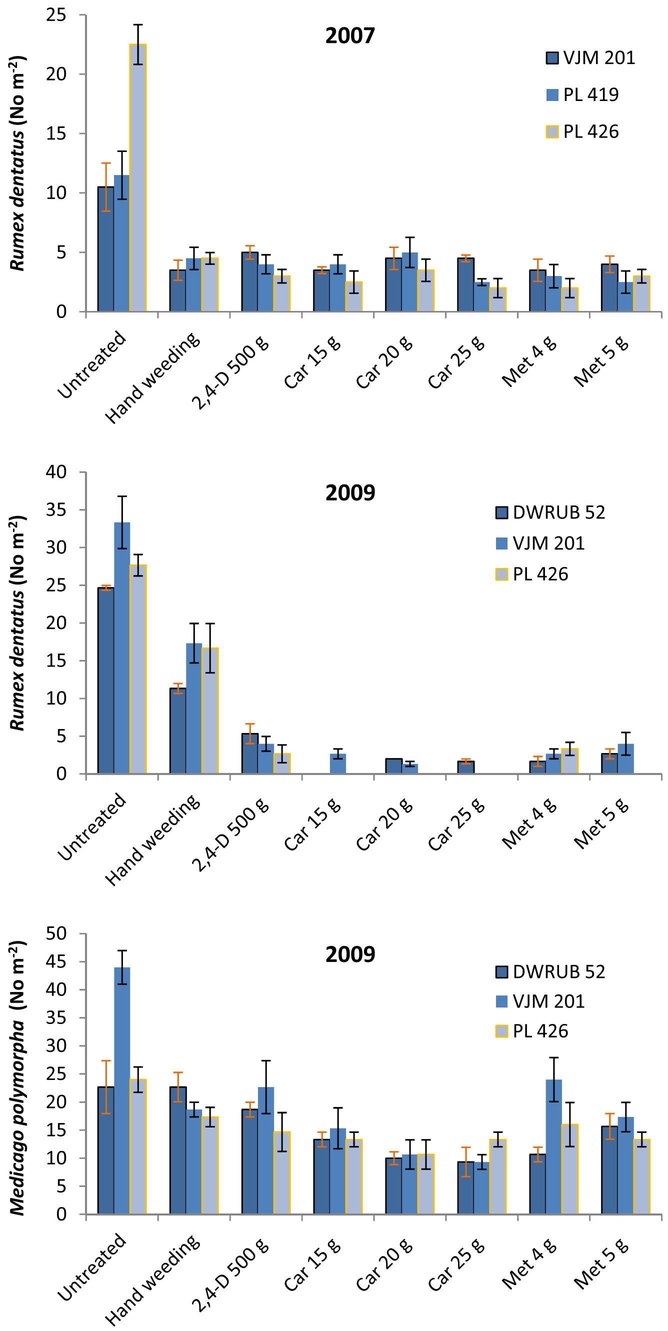

Fig. 1. Interaction effects of herbicide treatments and barley cultivars on density of *Rumex dentatus* in 2007 and 2009 and *Medicago polymorpha* in 2009. Abbreviations: Car, carfentrazone-ethyl; Met, metsulfuron-methyl. All herbicide rates are in g ai ha^{-1}. Error bars represent 95% confidence interval.

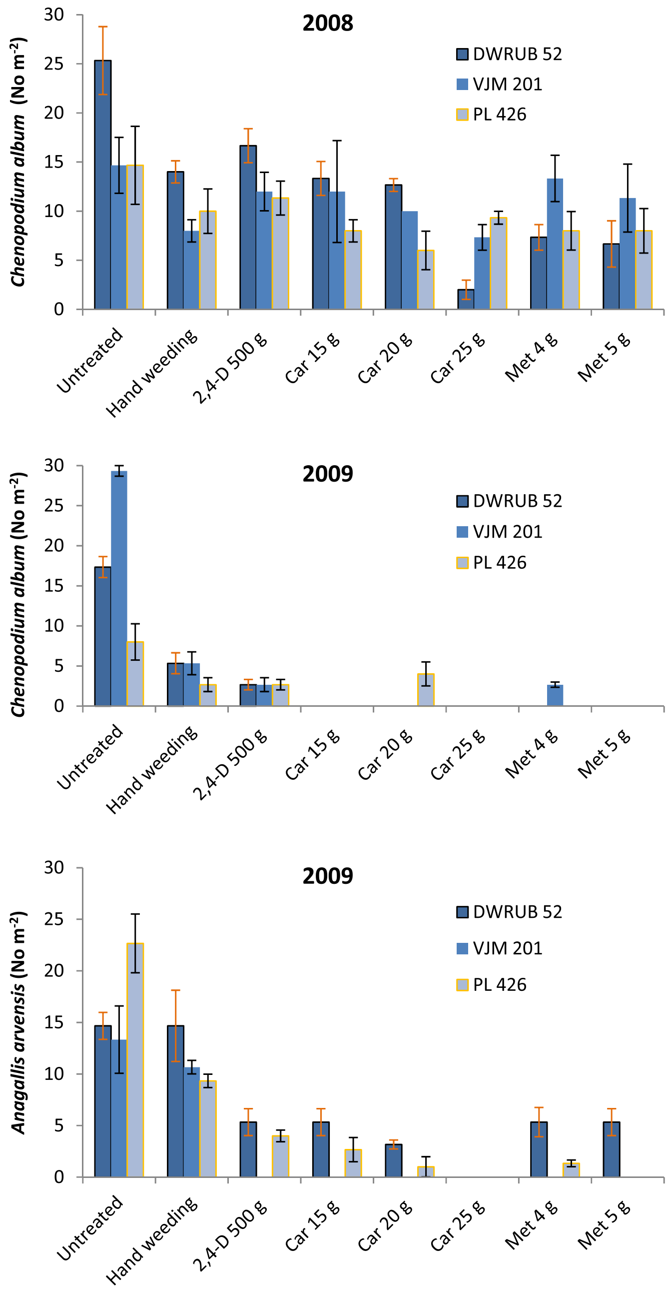

Fig. 2. Interaction effects of herbicide treatments and barley cultivars on density of *Chenopodium album* in 2008 and 2009 and *Anagallis arvensis* in 2009. Abbreviations: Car, carfentrazone-ethyl; Met, metsulfuron-methyl. All herbicide rates are in g ai ha^{-1}. Error bars represent 95% confidence interval.

biomass (Table 1). The interaction effect of barley cultivars and weed management treatments was significant for weed biomass in 2008 and 2009 (data not shown). Although significant difference was not observed among interaction treatments, carfentrazone and metsulfuron were effective to reduce broadleaf weed biomass in all barley cultivars (data not shown). For control of volunteer *Solanum tuberosum* L. in maize (*Zea mays* L.), Boydston (2004) reported that two applications of carfentrazone-ethyl at early post-emergence and late post-emergence reduced weight of tubers produced by 76–96% compared with untreated control and prevented maize yield loss.

3.3. Crop yield attributes

Crop yield attributes are important characters to determine the competitive ability of cultivars in presence and absence of weed competition (O'Donovan et al., 2000). Barley cultivars had variable yield attributes. For example, plant height of VJM 201 was significantly higher compared to other cultivars in all three years and there was no significant interaction between barley cultivars and weed control treatments for plant height (Table 2). Compared to weed management treatments, untreated control resulted in poor yield attributes. This result suggested that herbicide treatments were effective for weed control that reduced crop–weed

Table 2
Effects of weed management treatments on yield attributes of barley cultivars in 2007, 2008, and 2009.

Treatment	Rate (g ai or ae ha^{-1})	Plant height[a](cm)			Effective tillers[a](No. m^{-1})	Grains per spike[a]	Spike length[a] (cm)		
		2007	2008	2009	2009	2009	2007	2008	2009
Barley cultivars[b]									
DWRUB 52	–	–	76.7 b	79.7 b	116.7 a	26.7 b	–	8.41 a	7.74 b
VJM 201	–	69.7 a	90.2 a	89.6 a	116.5 a	24.0 b	5.48 a	9.19 a	9.28 a
PL 426	–	54.8 b	72.6 b	66.5 c	75.5 b	46.9 a	5.34 a	8.80 a	7.50 b
PL 419	–	52.6 b	–	–	–	–	5.22 a	–	–
Weed management treatments									
Untreated Control	–	59.0 abc	68.3 b	65.4 b	90.2 b	28.5 b	3.74 b	6.4 b	7.58 b
Hand hoeing	–	57.8 bc	82.5 a	75.6 a	103.1 a	32.7 a	5.69 a	8.80 a	8.37 a
2,4-D sodium salt	500	60.4 a	78.4 a	77.9 a	105.8 a	33.9 a	5.54 a	8.93 a	8.26 a
Carfentrazone-ethyl	15	60.3 ab	78.8 a	80.1 a	104.4 a	34.3 a	5.67 a	8.65 a	8.26 a
Carfentrazone-ethyl	20	60.2 ab	80.1 a	78.8 a	99.4 a	31.8 a	5.67 a	8.71 a	8.22 a
Carfentrazone-ethyl	25	57.1 c	78.0 a	78.9 a	100.1 a	33.3 a	5.43 a	9.01 a	8.25 a
Metsulfuron-methyl	4	59.8 ab	80.2 a	79.9 a	102.2 a	33.7 a	5.47 a	8.80 a	8.20 a
Metsulfuron-methyl	5	57.8 bc	82.2 a	79.4 a	101.3 a	30.7 b	5.55 a	9.04 a	8.44 a
Interaction effects[c]	–	NS	NS	NS	NS	NS	NS	NS	NS

[a] Least square means within columns with no common letters are significantly different according to Fisher's protected least significant difference (LSD) test where $P < 0.05$.
[b] Barley cultivar 'DWRUB 52' was planted only in 2008 and 2009, while cultivar 'PL 419' was planted only in 2007.
[c] Interaction effects denoted by NS is non-significant at $P < 0.05$; significant interactions are presented in figures.

competition and resulted in better yield attributes. A significant interaction between barley cultivars and weed management treatments was observed for many variables of yield attributes. For example, grain weight per spike was highest in PL 426 in 2008 (Fig. 3), while effective number of tillers per meter row length was influenced by interacting between 2007 and 2008 (data not shown). Number of grains per spike was also affected by interaction among barley cultivars and weed management treatments (Fig. 3).

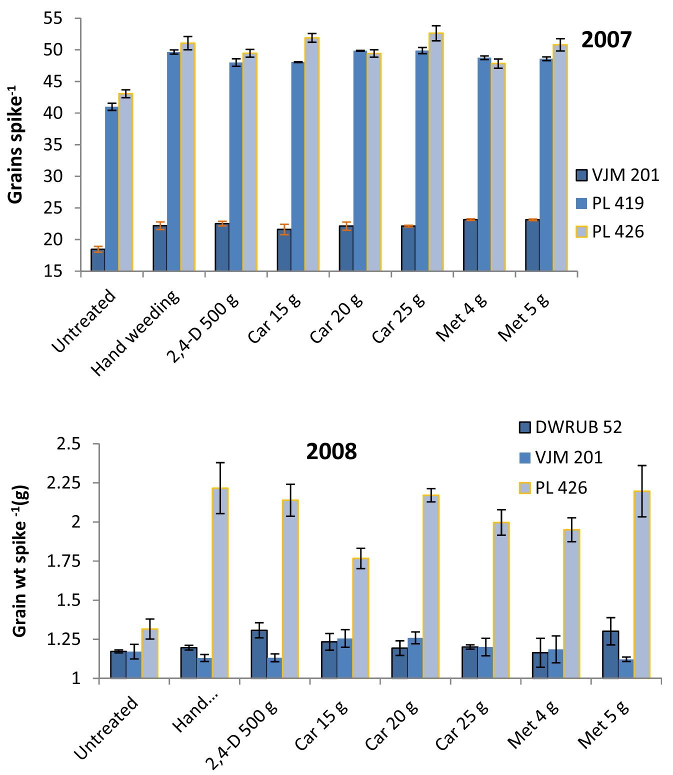

Fig. 3. Interaction effects of herbicide treatments and barley cultivars on grains per spike in 2007 and 2008. Abbreviations: Car, carfentrazone-ethyl; Met, metsulfuron-methyl. All herbicide rates are in g ai ha^{-1}. Error bars represent 95% confidence interval.

3.4. Barley yield

The interaction effect of barley cultivars and weed management treatments was significant (Fig. 4). Grain yield of barley was influenced by type of cultivar in 2008 and 2009. For example, DWRUB 52 resulted in the highest grain yield (4.8–6.1 t ha^{-1}) compared to other barley cultivars in 2008 and 2009 (Fig. 4). Barley yield was also influenced by weed management treatments. Compared to weed management treatments, untreated control usually resulted in poor yield (3.7–4.5 t ha^{-1}). The higher application rate of carfentrazone-ethyl or metsulfuron-methyl had not much additive effect on barley yield and usually lower rates also provided similar yields. Carfentrazone-ethyl and metsulfuron-methyl were usually effective at any rate for securing higher barley yields with generally little difference with 2,4-D. Overall results suggested that DWRUB 52 in combination with any herbicide treatment provided higher yields. This might be because application of 2,4-D, carfentrazone-ethyl, and metsulfuron-methyl reduced broadleaf weed density that resulted in reduced crop–weed competition and higher yields. A study in Australia reported that increasing the density of rigid ryegrass from 16 to 125 plants m^{-2} decreased barley grain yield by reducing tiller number and harvest index (Paynter and Hills, 2009).

Barley cultivated in northern India has very limited herbicide options for weed control. Although growers are encouraged to use various agronomic and cultural practices such as selecting competitive cultivars, there are times when herbicides are better option. For example, for control of hard to control broadleaf weeds that are not easily controlled with 2,4-D, application of carfentrazone-ethyl or metsulfuron-methyl improves control. Overall results of this study suggested that use of both herbicides (carfentrazone-ethyl and metsulfuron-methyl) was effective to reduce broadleaf weed density and biomass. There was no significant injury on any of the barley cultivars tested suggesting excellent crop safety at the tested rates. There was no much difference on broadleaf weed control with higher application rates of both the herbicides; therefore, the lower rate was sufficient to secure competitive grain yields. More research is required to compare the efficacy of tank mix of carfentrazone-ethyl and metsulfuron-methyl with other herbicides such as 2,4-D, dicamba, fenoxaprop-p-ethyl, clodinafop, pinoxaden to attain broad-spectrum weed control in barley.

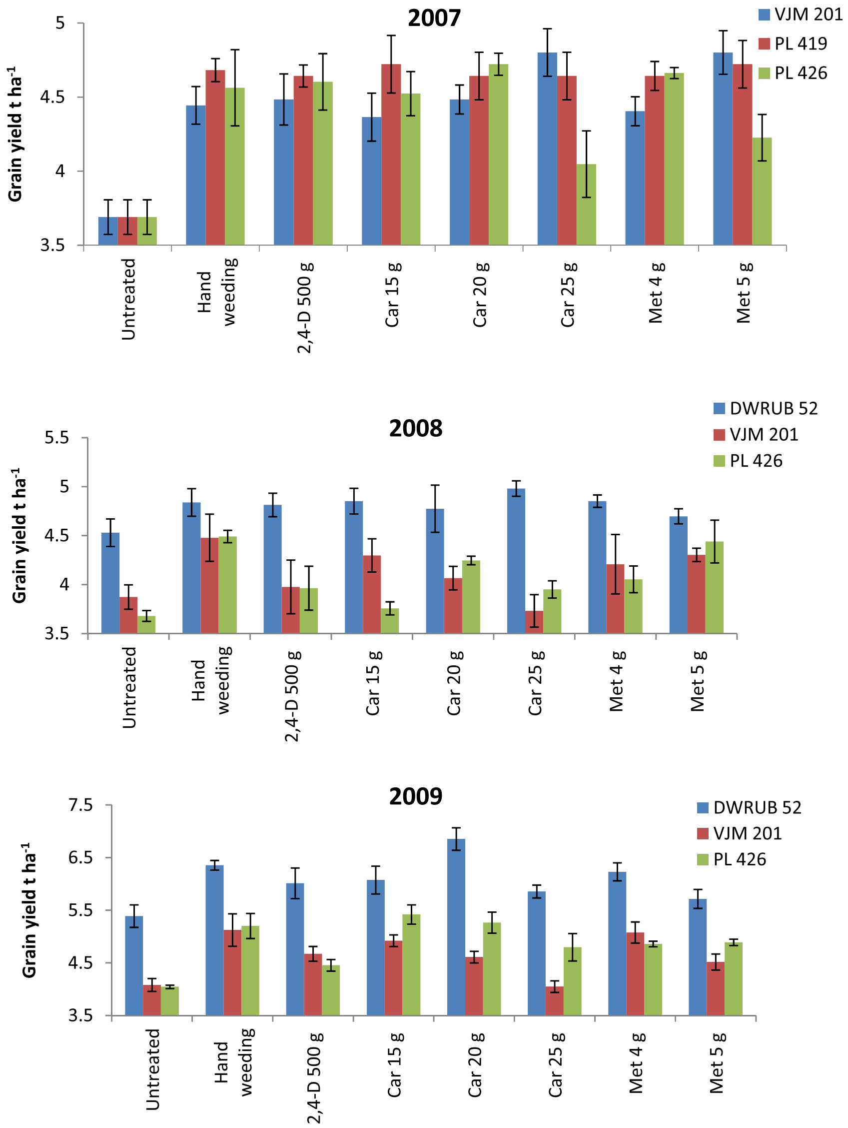

Fig. 4. Interaction effects of herbicide treatments and barley cultivars on grain yield in 2007, 2008 and 2009. Abbreviations: Car, carfentrazone-ethyl; Met, metsulfuron-methyl. All herbicide rates are in g ai ha^{-1}. Error bars represent 95% confidence interval.

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