Received: 9 June 2020 | Accepted: 1 September 2020

DOI: 10.1111/wre.12450

ORIGINAL ARTICLE

WEED RESEARCH
An International Journal of Weed Biology, Ecology and Vegetation Management

WILEY

Comparison of crop and weed height, for potential differentiation of weed patches at harvest

Nooshin Shahbazi[1,2] | Ken C. Flower[1,3] | J. Nikolaus Callow[1] | Ajmal Mian[4] | Michael B. Ashworth[1,2] | Hugh J. Beckie[1,2]

[1]UWA School of Agriculture and Environment, The University of Western Australia, Crawley, WA, Australia

[2]Australian Herbicide Resistance Initiative, The University of Western Australia, Crawley, WA, Australia

[3]UWA Institute of Agriculture, The University of Western Australia, Crawley, WA, Australia

[4]UWA School of Computer Science and Software Engineering, The University of Western Australia, Crawley, WA, Australia

Correspondence
Nooshin Shahbazi, The University of Western Australia, Crawley, Stirling Highway, WA 6009, Australia.
Email: nooshin.shahbazi@research.uwa.edu.au

Funding information
Australian Government Training Program (RTP) Fees Offset Scholarship; The Australian Herbicide Resistance Initiative (AHRI); The Calenup Postgraduate Research Fund 2019.

Subject Editor: Graeme Bourdôt AgResearch, Lincoln, New Zealand

Abstract

Weeds and weed control are major production costs in global agriculture, with increasing challenges associated with herbicide-based management because of concerns with chemical residue and herbicide resistance. Non-chemical weed management may address these challenges but requires the ability to differentiate weeds from crops. Harvest is an ideal opportunity for the differentiation of weeds that grow taller than the crop, however, the ability to differentiate late-season weeds from the crop is unknown. Weed mapping enables farmers to locate weed patches, evaluate the success of previous weed management strategies, and assist with planning for future herbicide applications. The aim of this study was to determine whether weed patches could be differentiated from the crop plants, based on height differences. Field surveys were carried out before crop harvest in 2018 and 2019, where a total of 86 and 105 weedy patches were manually assessed respectively. The results of this study demonstrated that across the 191 assessed weedy patches, in 97% of patches with *Avena fatua* (wild oat) plants, 86% with *Raphanus raphanistrum* (wild radish) plants and 92% with *Sonchus oleraceus* L. (sow thistles) plants it was possible to distinguish the weeds taller than the 95% of the crop plants. Future work should be dedicated to the assessment of the ability of remote sensing methods such as Light Detection and Ranging to detect and map late-season weed species based on the results from this study on crop and weed height differences.

KEYWORDS

height, late-season weed control, site-specific weed management, weed-crop differentiation

1 | INTRODUCTION

Weeds have a negative impact on agricultural production and despite the gains in crop productivity achieved from recent advances in agriculture, weeds still significantly affect crop yield (Llewellyn *et al*., 2004). Herbicides have been the primary tool for weed control, but there are concerns about rising input costs (Llewellyn *et al*., 2004) and fears about chemical use on human health. Reliance on herbicides can result in weed resistance to herbicides like glyphosate, which is now widespread (Owen and Powles, 2010).

The increasing levels of herbicide resistance have resulted in a greater focus on cultural methods and reducing herbicide use, with practices such as site-specific weed management method (SSWM) and harvest weed seed control (HWSC) systems (Pena *et al*., 2015; Walsh *et al*., 2018). HWSC systems target weed seeds during the grain harvest and prevent them from entering the soil seed bank (Walsh *et al*., 2018). HWSC is now an established weed control method in Australia and accepted by 82% of growers (Walsh *et al*., 2017a). However, some weed species, such as *Bromus* spp. (brome grass) and *Avena fatua* (wild oat) shed some of their seeds before harvest and are not well suited to HWSC (Ashworth *et al*., 2016;

 © 2020 European Weed Research Society

Condon and Condon, 2018). SSWM is used to target weed patches based on detecting weed species and mapping their locations (Shaw, 2005). Therefore, weeds that shed their seeds and escape HWSC could be mapped for future control. The most critical factors for acceptance and adoption of SSWM are weed monitoring and having a management plan for the execution of an economical SSWM (Lopez-Granados, 2011). SSWM can be designed based on maps of mature weeds, to apply targeted weed control to where the largest weed seedbank will be located in subsequent years (Koger *et al*., 2003).

Remote sensing is a useful method for mapping crops and both early and late-season (when crops mature) weeds that are not well controlled by HWSC. Andujar *et al*. (2013) used ultrasonic and Terrestrial LiDAR (Light Detection and Ranging) based systems to differentiate germinated maize (*Zea mays*) from the soil. Lopez-Granados *et al*. (2016) used multispectral images collected by unmanned aerial vehicle (UAV) for mapping early weed infestation in sunflower (*Helianthus*). Lopez-Granados *et al*. (2006) used hyperspectral and multispectral imagery for locating late-season grass weed patches in wheat (*Triticum aestivum* L.). Castillejo-Gonzalez *et al*. (2014) mapped late-season *A. fatua* patches in wheat fields using Quickbird images. Rasmussen *et al*. (2019) mapped creeping thistle (*Cirsium arvense*) before harvest in cereals using a UAV mounted with RGB cameras.

Many persistent weed species that are present in the crop until harvest have a discernible height difference to commonly grown field crops and there is a potential for differentiating and detecting late-season weed patches from the surrounding crop plants. The aim of this study was to determine whether weed species that are present until late in the season may be differentiated based on their height above various crop canopies. The study had two objectives: (a) measure the height of common crops and weeds near maturity and (b) determine what combinations of weed and at what height thresholds the weed species could potentially be detected in the crops near to harvest time. For this purpose, late-season weed species were investigated in various crops in the Central Wheat-belt region of Western Australia just before harvest time in 2018 and 2019.

2 | MATERIALS AND METHODS

2.1 | Study area selection

Field surveys were conducted near the end of the growing season, after anthesis when crops were beginning to mature (November) in 2018 and 2019 across the Central Wheat-belt region of Western Australia. The region has a Mediterranean-type climate, with hot dry summers and a cool, wet, winter growing season between May and November. About 50% of the annual rainfall occurs between June and August. Droughts are common, and rainfall is relatively low, with a 20 year mean of 313 mm (BOM, 2020).

Fields with known weed species that were present until the harvest were selected based on the information from agronomists and farmers in the area, the GPS coordinates of every field recorded and the locations are shown in Figure 1.

2.2 | Sampling methodology

We visited 65 fields over 2 years (30 fields in 2018 and 35 in 2019). The area of the field with weed patches was selected and the survey conducted by walking a 'Z' pattern until three separate weed patches had been assessed and the survey was then completed for that field. If an area of a field contained <3 patches, then another area was surveyed nearby. Weed species were identified and the height of up to 10 plants per weed species and 30 crop plants was measured within 1 m^2. Plant height was measured from the soil surface to the highest position of the plant (Figure 2).

A total of 86 weedy patches was assessed in 2018 and another 105 weedy patches were assessed in 2019. The crop types included wheat, barley (*Hordeum vulgare* L.), lupin (*Lupinus angustifolius* L.) and chickpea (*Cicer arietinum* L.). The same fields identified in 2018 were also visited in 2019 and the majority of fields were cultivated with the same crop in both years, except for seven fields, which were out of production or had different crops in 2019, so the nearest field with the same crop was visited. Of these seven fields, four were wheat and three were barley fields. The weed species investigated in this study included *Lolium Rigidum* (ryegrass), *A. fatua*, *Bromus* spp., *Raphanus raphanistrum* (wild radish), *Sonchus oleraceus* L. (sow thistles), volunteer wheat (2018 and 2019) and volunteer oilseed rape (2019).

2.3 | Data analysis

Data were checked for normality of residuals and then crop height data were analysed using a linear mixed model with restricted maximum likelihood (REML) over the 2 years. For this analysis, crop type and year were considered as fixed effects and patches as a random effect (Genstat 18th edition, VSN International Ltd, http://www.vsni.co.uk/).

We analysed crop height separately for the 2 years, due to between-year differences; we compared differences between mean crop and weed species height using REML, where crop/weed type was considered as a fixed effect. The variances of the crops and associated weeds were unequal, so patches were defined as a random effect in a diagonal covariance model. Height was considered to differ at $p \leq 0.05$. Crop mean height was compared to each weed in the field based on the approximate least significant difference of REML means.

A sensitivity analysis was carried out using three different thresholds of crop height in each field to assess the number of weeds that grew above the crop height thresholds. The thresholds were mean crop height (50% of the crop had a height less than this value), one standard deviation (SD) above the mean crop height (68% of the crop had a height less than this value) and 2 × SD above mean crop height

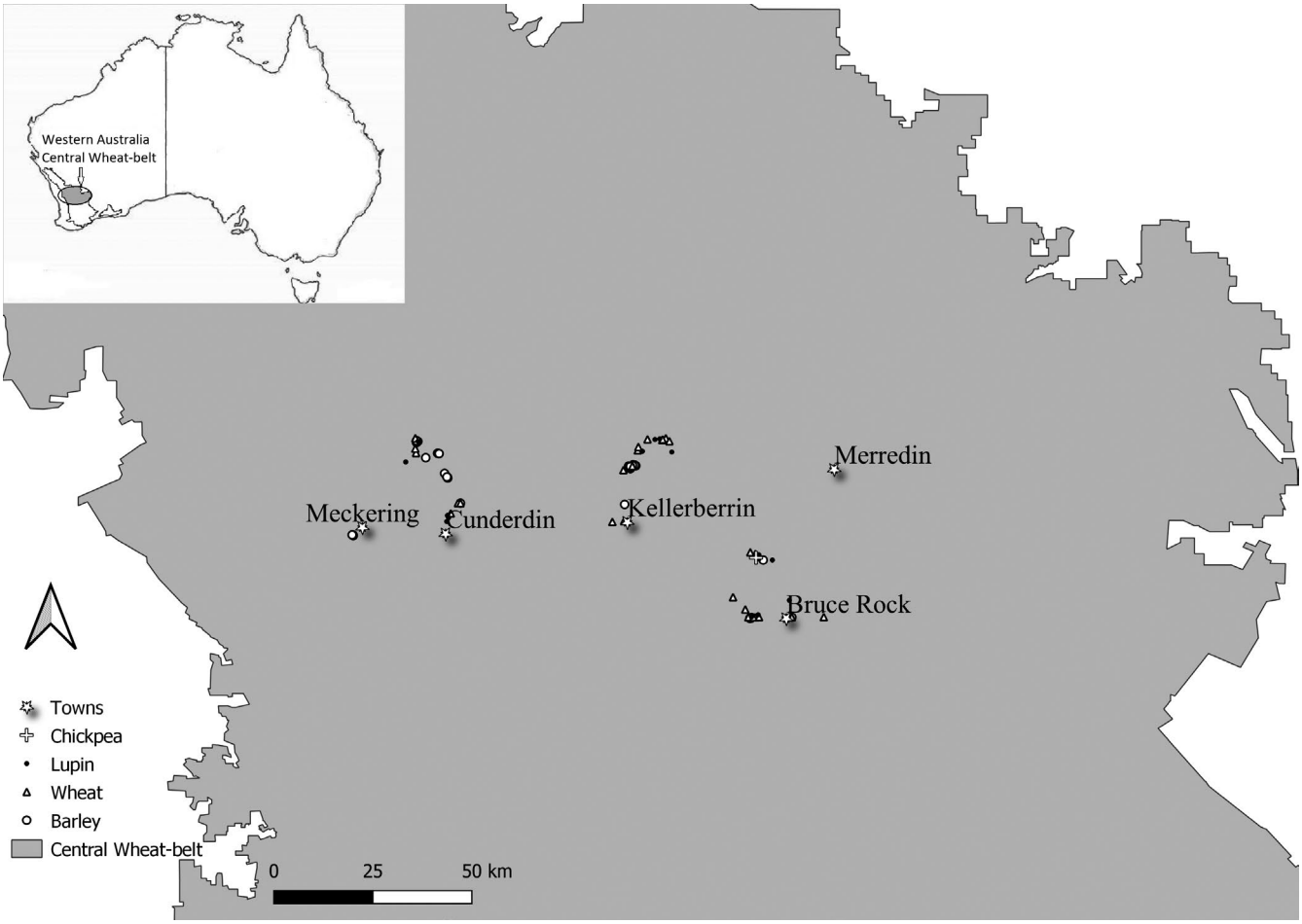

FIGURE 1 Location of studied crop fields in the Central Wheat-belt region of Western Australia

(95% of the crop had a height less than this value). These thresholds were used to quantify the differentiation percentage of each weed species, and the number of weedy patches with at least one weed above the defined thresholds was calculated in each field.

3 | RESULTS

3.1 | Climate

The monthly maximum temperature in the survey area during the 2018 growing season varied between 21 and 38°C and in 2019 between 21 and 44°C. There was higher annual rainfall in 2018 across the region, with 242–278 mm compared with 189–234 mm in 2019 (BOM, 2020). Figure 3 shows the monthly rainfall distribution of the area during the growing season in 2018 and 2019. The 2019 season was hotter and drier overall than in 2018.

3.2 | Crop height

Crop height differed ($p < 0.001$), with wheat being the tallest crop (mean over 66 cm both years), followed by barley (54 cm), lupin (48 cm) and chickpea (27 cm; Table 1). All crops were taller in 2018 than in 2019 ($p < 0.001$). Wheat and lupin were on average 14 cm taller in 2018 than 2019, while barley was 8 cm and chickpea only 3 cm taller in 2018.

3.3 | Late-season weed species present in the crops

Table 2 shows that *L. rigidum* and *A. fatua* were the most common weed species that were present until harvest in the studied crops. *L. rigidum* plants were observed in 89% of weed patches in wheat crops, 93% of patches in barley crops, 82% of patches in lupin crops and 100% of patches in chickpea crops. *A. fatua* plants were observed in 75, 58, 27 and 83% of weed patches in wheat, barley, lupin and chickpea fields, respectively.

3.4 | Weed species detection at different thresholds

After identifying the major weed species present in the study areas, the height of the crops and weed species were compared to the mean crop height, mean crop height + SD and mean crop height + 2 × SD in all of the studied fields.

FIGURE 2 The height of up to ten weeds of each species in a patch was measured from the ground to the tallest plant part

TABLE 1 Crop height range and mean height across the studied fields in the Central Wheat-belt region of Western Australia just before harvest time in 2018 and 2019

	2018		2019	
Crop	Range (cm)	Mean (cm)	Range (cm)	Mean (cm)
Wheat	43–98	74a	25–88	59a
Barley	27–101	59b	27–80	49b
Lupin	20–84	54c	14–70	40c
Chickpea	20–36	29d	17–33	26d

Note: Different letters indicate differences between crops within each year, based on LSD at $p \leq 0.05$. Crop height differed between years ($p < 0.001$).

Figures 4 and 5 show the average height distribution of wheat, barley, lupin and chickpea and different weed species across the studied fields in 2018 and 2019. The height of *A. fatua*, *R. raphanistrum* in both years and *S. oleraceus* in 2018 differed from wheat height (Figure 4a–b). *A. fatua* and *L. rigidum* in 2018 and *A. fatua* and *R. raphanistrum* in 2019 were taller than barley in 2018 and 2019 respectively (Figure 4c–d). *R. raphanistrum* was noticeably shorter than barley in 2018, ranging between 10 and 50 cm height (Figure 4c).

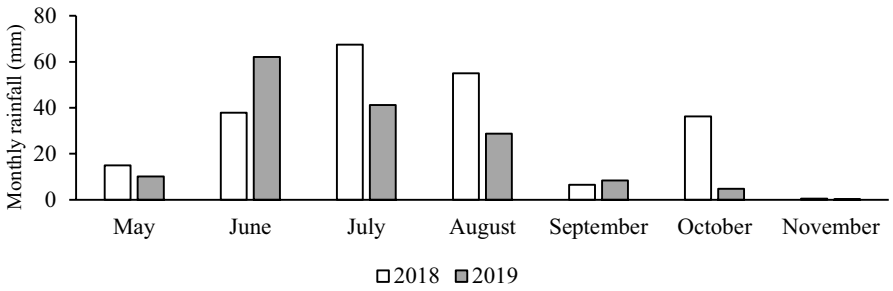

FIGURE 3 Monthly rainfall distribution from the Kellerberrin Bureau of Meteorology station (010073) (BOM, 2020) in the Central Wheat-belt region of Western Australia during the 2018 and 2019 growing season

TABLE 2 Number of weed plants and patches in the different crop fields in 2018 and 2019

	L. rigidum		*A. fatua*		*Bromus* spp.		*R. raphanistrum*		*S. oleraceus*		Volunteer (wheat and oilseed rape)	
Crop	Plants	Patches	Plants	Patches	Plants	Patches	Plants	Patches	Plants	Patches	Plants	Patches
2018												
Wheat	384	33	300	25	107	11	98	10	35	5	–	–
Barley	317	24	85	10	146	14	50	5	–	–	–	–
Lupin	227	19	102	9	30	3	102	10	52	8	21	1
Chickpea	40	3	30	3	–	–	–	–	–	–	30	3
2019												
Wheat	428	41	397	37	91	10	154	16	–	–	–	–
Barley	300	29	224	23	–	–	48	6	–	–	19	2
Lupin	180	18	31	3	–	–	142	14	–	–	50	5
Chickpea	31	3	12	2	–	–	–	–	–	–	–	–

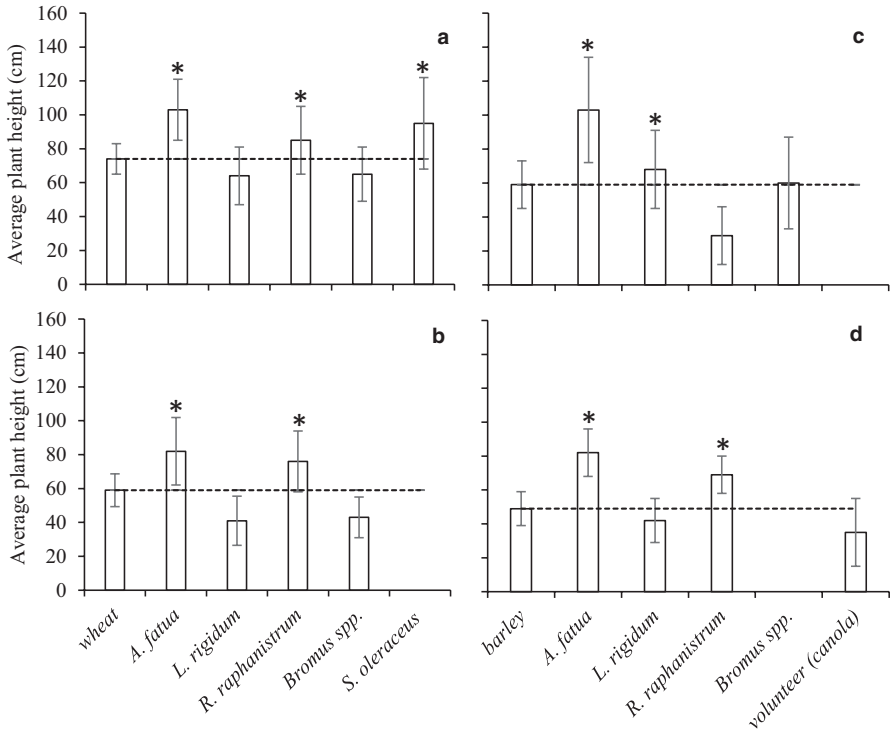

FIGURE 4 Plant height distribution of wheat (a and b) and barley (c and d) and different weed species across the studied fields in 2018 (a and c) and 2019 (b and d) (dash line shows mean crop height). Asterisks indicate that weed species was taller than the crop ($p \leq 0.05$). A maximum of five of the most abundant weeds is shown. Error bars represent ± *SD*

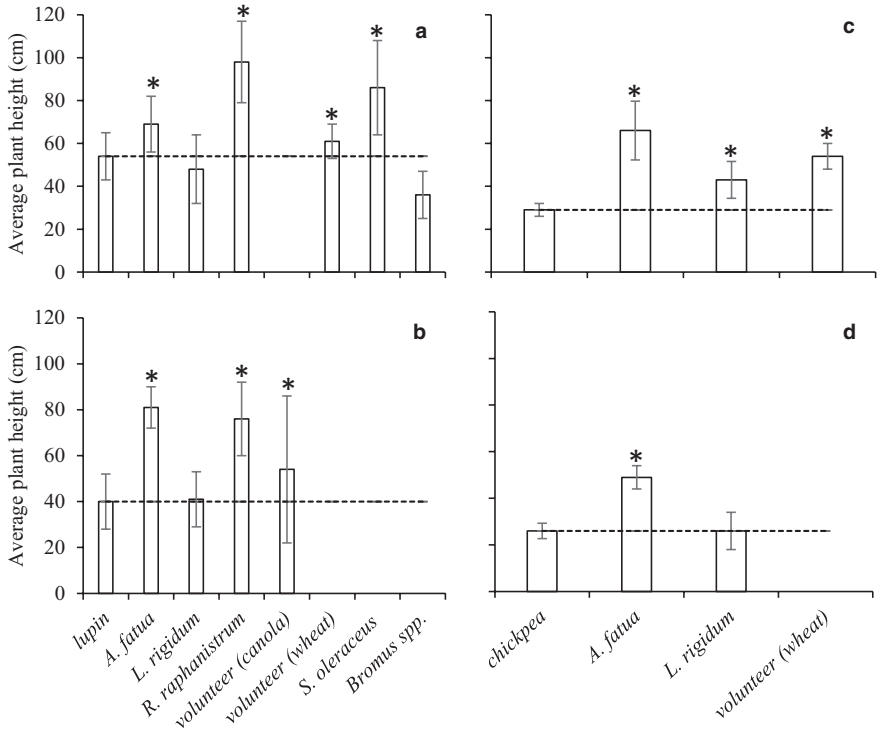

FIGURE 5 Plant height distribution of lupin (a and b) and chickpea (c and d) and different weed species across the studied fields in 2018 (a and c) and 2019 (b and d; dash line shows mean crop height). Asterisks indicate that weed species was taller than the crop ($p \leq 0.05$). A maximum of five of the most abundant weeds is shown. Error bars represent ± *SD*

L. rigidum and *Bromus* spp. were similar or shorter than the height of lupin, while *A. fatua*, *R. raphanistrum* and *S. oleraceus* were taller (Figure 5a–b). Weeds were taller than chickpea in both years, except *L. rigidum* in 2019 that was of a similar height (Figure 5c–d).

Table 3 shows weeds with ≥50% detectability in at least one of the 2 years at all crop height thresholds (where 50, 68 and 95% of the crop plants were below the threshold).

The comparison of the mean height of crop and weed plants in the 2018 and 2019 survey showed that ≥90% of *A. fatua* plants, ≥76% of *R. raphanistrum* plants and 91% of *S. oleraceus* plants were taller than the average height of wheat. Whereas, ≥75% of *A. fatua* plants, 59% of *R. raphanistrum* plants and 62% of *S. oleraceus* plants were taller than 2 × *SD* the mean wheat height. In barley fields, ≥98% of *A. fatua* plants were taller than the average crop height.

TABLE 3 Percentage of weeds taller than 50, 68 and 95% of crop plants, which represent the mean, mean + 1 x SD and mean + 2 x SD of crop plant height, respectively

Crop	Year	50%	68%	95%	Weed species
Wheat	2018	94	90	84	*A. fatua*
	2019	90	86	75	
	2018	76	65	60	*R. raphanistrum*
	2019	83	68	59	
	2018	91	74	62	*S. oleraceus*
	2019	–	–	–	
Barley	2018	99	97	94	*A. fatua*
	2019	98	97	81	
	2018	4	3	3	*R. raphanistrum*
	2019	92	89	57	
Lupin	2018	87	69	66	*A. fatua*
	2019	100	100	97	
	2018	96	93	91	*R. raphanistrum*
	2019	100	99	94	
	2018	88	67	65	*S. oleraceus*
	2019	–	–	–	
	2018	94	90	75	Volunteer wheat
	2019	72	60	50	Volunteer oilseed rape
Chickpea	2018	100	100	97	*A. fatua*
	2019	100	100	100	
	2018	100	100	80	*L. rigidum*
	2019	–	–	–	
	2018	100	100	100	Volunteer wheat
	2019	–	–	–	

Note: Only weeds taller than the mean crop height in at least one of the 2 years (2018 and 2019) are shown.

For *R. raphanistrum* in barley, there was only 4% detectability in 2018, but this increased to 92% in 2019. At 2 × *SD*, ≥81% of *A. fatua* plants and only 3% of *R. raphanistrum* plants in 2018 were taller than the mean barley height, although this increased to 57% the following year. In lupin fields, ≥87% of *A. fatua* plants, ≥96% of *R. raphanistrum* plants, 88% of *S.oleraceus*, ≥94% of volunteer wheat plants and ≥72% volunteer oilseed rape plants, were taller than the average crop height. Whereas, ≥66% of *A. fatua* plants, ≥91% of *R. raphanistrum* plants, ≥65% of *S. oleraceus* plants and ≥50% of volunteer oilseed rape plants and ≥75% volunteer wheat plants were taller than 2 × *SD* the mean lupin height. In chickpea fields, 100% of *A. fatua* plants were taller than the average crop height. Whereas, ≥97% *A. fatua* plants, 80% of *L. rigidum* plants and 100% of volunteer wheat plants (which were wheat plants) were taller than 2 × *SD* the mean chickpea height.

The results showed that in the 2 years of study, in 109 patches out of 112 (97%) studied weedy patches with *A. fatua*, in 50 out of the 58 (86%) studied weedy patches with *R. raphanistrum* plants and in 12 out of 13 (92%) studied weedy patches with *S. oleraceus* plants, at least one plant of each of these weed species was taller than 2 × *SD* of the mean associated crop height. Overall, the main weed species that grew taller than the crop, across all thresholds at harvest time were *A. fatua*, *R. raphanistrum*, and *S. oleraceus*. Table 4 (wheat) shows that across the wheat fields in ≥96% of *A. fatua* patches, in ≥84% of *R. raphanistrum* patches and 80% of *S. oleraceus* patches at least one plant of these weed species was differentiated above the defined thresholds. Across the barley fields in ≥96% of *A. fatua* patches and ≥84% of *R. raphanistrum* patches in 2019, at least one plant of these weed species was differentiated above the defined thresholds. In 2018, only 20% of patches were potentially differentiated for the latter weed in barley (Table 4 [barley]). Across the lupin fields in 100% of weed patches of *A. fatua*, *R. raphanistrum* and *S. oleraceus* at least one plant of these weed species was differentiated above the defined thresholds (Table 4 [lupin]). Across the chickpea fields, 100% of *A. fatua* patches had at least one plant growing above the defined crop thresholds (Table 4 [chickpea]).

4 | DISCUSSION

4.1 | Comparison of 2 years of crop and weed height

This study aimed to determine the weed species that grow taller than the crop and their differentiation compared to the crop height at harvest time. Two surveys were performed during the harvest season in 2018 and 2019. The varieties of the studied crops (wheat, barley, lupin, and chickpea) were the same in both years, however, the rainfall amount was different. The amount of moisture for crop and weed seeds for immediate germination in 2019 was less than 2018, and as expected plants were shorter in 2019 because of delayed germination and development during the growing season. The development of crop morphological characteristics such as plant height, leaf area, flowering, and pod settings can be impacted by the amount and distribution of rainfall during spring and summer (Podlesny and Podlensa, 2011). Shortage of rain during the growing season can have a negative effect on chickpea (Rathore *et al*., 1998), barley (Shakhatreh *et al*., 2001), lupin (Podlesny and Podlensa, 2011) and wheat (Dehghani *et al*., 2014) height.

4.2 | Weed differentiation and potential control using site-specific weed management

In this study, the main weed species that grew taller than the crop height thresholds (50%, 68% and 95%) at harvest time were *A. fatua*, *R. raphanistrum*, and *S. oleraceus*. In 97% of the weed patches with *A. fatua* plants, 86% of weed patches with *R. raphanistrum* plants and 92% of weed patches with *S. oleraceus* plants, at least one weed plant could be differentiated above the 95% of the studied crop height. However, there was an exception, as *R. raphanistrum* plants/patches in barley in 2018 were exceptionally short. This weed was

TABLE 4 The percentage of weed patches with at least one weed taller than 50%, 68% and 95% of crop plants, which represent the mean, mean + 1 x SD and mean + 2 x SD of crop plant height respectively

		Crop height					
		50%		68%		95%	
Crop	Weed species	2018	2019	2018	2019	2018	2019
Wheat	*L. rigidum*	82	36	33	2	27	0
	A. fatua	96	100	96	97	96	97
	R. raphanistrum	100	100	100	85	100	84
	Bromus spp.	73	40	64	10	54	0
	S. oleraceus	80	–	80	–	80	–
Barley	*Lolium rigidum*	87	62	87	38	87	25
	A. fatua	100	100	100	96	100	96
	R. raphanistrum	20	100	20	100	20	84
	Bromus spp.	78	–	78	–	71	–
	Volunteer oilseed rape	–	50	–	–	–	50
Lupin	*L. rigidum*	68	78	53	61	31	45
	R. raphanistrum	100	100	100	100	100	100
	A. fatua	100	100	100	100	100	100
	Volunteer oilseed rape and wheat	100	60	100	60	100	60
	S. oleraceus	100	–	100	–	100	–
	Bromus spp.	67	–	33	–	33	–
Chickpea	*L. rigidum*	100	67	100	67	100	67
	Volunteer wheat	100	–	100	–	100	–
	A. fatua	100	100	100	100	100	100

only found in two surveyed barley fields in 2018 and the farmer had applied herbicide under good moisture conditions, which was likely to affect *R. raphanistrum* growth. In addition, barley is a competitive crop (Cousens *et al*., 1987) and the earlier rains in 2018 would have enabled good barley growth that may have helped reduce *R. raphanistrum* growth.

The differentiation of individual weed species improves with shorter crops and taller weeds. In this study chickpea was the shortest measured crop and *L. rigidum* patches were 100% differentiated above 95% of the crop height, while *L. rigidum* patch differentiation for this threshold in taller crops, wheat, barley, and lupin was 0%, 24% and 30% respectively. *Bromus* spp. patches were 70% differentiated above 95% of barley height, whereas no *Bromus* spp. patches were differentiated in wheat above this threshold.

The majority of the studied weed species grow in the form of patches, which only expand slowly, however, some factors such as natural seed distribution, tillage, and machinery can impact patch stability. For example, natural seed distribution and tillage can move patches by 1 m and machinery can produce new weed patches from the original patch (Beckie *et al*., 2005; Rew and Cussans, 1995). Most of *R. raphanistrum* and *A. fatua* seeds are large and fall in the vicinity of the parent plant and a small proportion can spread in chaff and hay (Owen and Powles, 2016). However, Shirtliffe and Entz (2005) reported that combine harvesters can cause high weed infestation, that is the dispersal rate of *A. fatua* seeds by using combine without chaff collection can be more than 10 seeds m^{-2} up to 145 m. Weed patches can be identified and managed through precision agriculture using remote sensing and mapping (Castillejo-Gonzalez *et al*., 2014; Rasmussen *et al*., 2019).

The study shows that *L. rigidum* and *A. fatua* were the most frequent weed species in the studied crops. *L. rigidum* and *A. fatua* plants were measured in ≥87 and ≥55% of the studied weed patches respectively. In addition, Llewellyn *et al*. (2016) reported Australia's major crop-damaging weed species that can compete aggressively for water, nutrients, and sunlight and reduce the crop quality and quantity as *A. fatua* (Owen and Powles, 2016), *L. rigidum* (Walsh *et al*., 2017b), *Bromus* spp. (Davies *et al*., 2019) and *R. raphanistrum* (Lu *et al*., 2020). *L. rigidum* is one of the major crop weeds with resistance to both selective and non-selective herbicides. *L. rigidum* is a highly competitive, wind-pollinated plant that can grow up to 90 cm, with the ability to produce ~45,000 seeds per square metre (Peltzer and Douglas, 2019). In this study, the maximum height of *L. rigidum* in wheat, barley, lupin, and chickpea were 100, 85, 76 and 60 cm respectively. However, *L. rigidum* patch differentiation varied from 0–100%, depending on the crop type and year. The nature of *R. raphanistrum* is competitive with widespread resistance to four herbicide groups. Mature *R. raphanistrum* plants can reach 150 cm in height (Nugent, 1999). In this study, the maximum height of *R. raphanistrum* in wheat, barley and lupin was 140, 93 and 120 cm respectively. *A. fatua* is a widespread weed commonly found in cereal

crops in Western Australia with high resistance to herbicide (Owen and Powles, 2016). *A. fatua* can grow up to 170 cm and can reduce yield up to 66% by competing for resources throughout their life cycle (Cudney *et al*., 1991; HerbiGuide, 2018). In this study, the maximum height of *A. fatua* in wheat, barley, lupin, and chickpea was 158, 120, 110 and 92 cm respectively. *S. oleraceus* is a weed species with an annual life cycle that can grow between 30 and 200 cm tall (HerbiGuide, 2018). In this study, the maximum height of *S. oleraceus* in wheat and lupin was 120 and 110 cm respectively. *S. oleraceus* is a widespread weed species with high herbicide resistance and ranks in the top five most difficult to control weed species (Widderick and Walker, 2009). Therefore, it is essential to find practical methods with a high level of success to control these weed species.

Although HWSC systems can be used to capture seeds of problematic weed species and prevent them from entering seed banks, the efficacy of weed control is reduced when weeds shed their seeds before harvest, therefore more weed seeds enter the seed bank and the efficiency of HWSC may decrease (Walsh *et al*., 2018). White *et al*. (2018) reported that 11% of annual *L. rigidum* seeds and 21% of *A. fatua* seeds have already been shed 2 weeks before crop maturation. Many of the weeds which shed their seeds early, thereby avoiding HWSC, also grow taller than crops. Therefore, they could, potentially, be mapped, based on their greater height, and then the weed patches targeted for control in the following season with SSWM practices (Lopez-Granados, 2011). Many persistent weed patches that are multiple-herbicide resistant could be managed in the long term by implementing SSWM and minimising herbicide use (Pena *et al*., 2015). For example, farmers could use variable seed rates for their crops, greatly increasing the rate in the areas with weed patches, to enhance crop competition. Choosing the method to differentiate and locate the weeds in crops requires knowledge of the crop and weed size at their different stages of growth (Lopez-Granados, 2011).

4.3 | Limitations of data set

Although the surveys measured all present weed species in wheat, barley, lupin and chickpea crops in the study area, other important weeds like *Bromus* spp. (Walsh and Powles, 2014) were absent in chickpea and lupin fields. *Bromus* spp. could be potentially differentiated in chickpea and lupin because of these pulse crop height. Also, more detail is required to determine the effect of weather conditions and farmer practices on weed height in relation to the crop, as shown by the relatively short *R. raphanistrum* plants in two barley fields in 2018.

5 | CONCLUSION

Removing weed seeds at harvest can prevent them from entering the soil seed bank, however, weeds which shed their seeds before harvest can reduce the efficacy of HWSC. Many of these weed species grow above the crop and present an opportunity to map the location these taller weeds, before or at harvest. Therefore, it is essential to identify and locate these weed species in the crop and manage them using SSWM in the following season. Identifying, locating and mapping the problematic weed species that survive early weed control methods and develop late in the season is the first step in developing a long-term approach to the management of persistent weed species. Precise weed patch mapping also helps farmers to evaluate the success of previous weed management strategies, to, assist with planning for future herbicide applications. Once these weeds are controlled, the weed seed bank can be reduced using a range of methods such as crop competition and reducing or avoiding tillage which stimulates weeds during critical periods.

Studying weed species at harvest, when weeds are mature, is a suitable time to use methods based on plant height for differentiating and locating weed species. For an instance, *Silybum marianum* (milk thistle), which grows up to 150–200 cm, was successfully mapped using UAV multispectral images by Zisi *et al*. (2018), based on its estimated height and spatial texture in wheat crops. The findings of this paper confirm that *A. fatua*, *R. raphanistrum*, and *S. oleraceus* may be suitable candidates in wheat, barley, lupin and chickpea to be differentiated based on their height at harvest time. Future studies will be conducted to assess the detectability of these weed species in crops using remote sensing methods such as LiDAR.

ACKNOWLEDGEMENTS

This work was partly funded by the Australian Government Research Training Program (RTP) Fees Offset Scholarship, the Australian Herbicide Resistance Initiative and the Calenup Postgraduate Research Fund 2019. The authors would like to thank Roberto Lujan Rocha (Research Officer, Australian Herbicide Initiative), Ci Sun (Research Assistant, The University of Western Australia) and Cheryl Rimmer (Communication Officer, The University of Western Australia) for helping in the field surveys and compilation of this study.

CONFLICT OF INTEREST

No conflicts of interest have been declared by the authors.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/wre.12450.

ORCID

Nooshin Shahbazi https://orcid.org/0000-0001-6348-2164
Ken C. Flower https://orcid.org/0000-0002-7477-9921
J. Nikolaus Callow https://orcid.org/0000-0001-6525-953X
Ajmal Mian https://orcid.org/0000-0002-5206-3842
Michael B. Ashworth https://orcid.org/0000-0002-8267-8231
Hugh J. Beckie https://orcid.org/0000-0002-2659-2265

REFERENCES

Andujar, D., Moreno, H., Valero, C., Gerhards, R. and Griepentrog, H.W. (2013) Weed-crop discrimination using LiDAR measurements. *Precision agriculture*, 13, 541–545.

Ashworth, M.B., Walsh, M.J., Flower, K.C., Vila-Aiub, M.M. and Powles, S.B. (2016) Directional selection for flowering time leads to adaptive evolution in *Raphanus raphanistrum* (Wild radish). *Evolutionary Applications*, 9, 619–629. https://doi.org/10.1111/eva.12350

Beckie, H.J., Hall, L.M. and Schuba, B. (2005) Patch management of herbicide-resistant wild oat (*Avena fatua*). *Weed Technology*, 19, 697–705. https://doi.org/10.1614/WT-04-222R.1

BOM. (2020). *Australian Government Bureau Meteorology (BOM) [Online]*. Australia: BOM. Available at: http://www.bom.gov.au/ [Accessed 2 February 2020]

Castillejo-Gonzalez, I.L., Pena-Barragan, J.M., Jurado-Exposito, M., Mesas-Carrascosa, F.J. and Lopez-Granados, F. (2014) Evaluation of pixel- and object-based approaches for mapping wild oat (*Avena sterilis*) weed patches in wheat fields using Quick Bird imagery for site-specific management. *European Journal of Agronomy*, 59, 57–66. https://doi.org/10.1016/j.eja.2014.05.009

Condon, G. and Condon, K. (2018) *Harvest weed seed control – beyond windrow burning [Online]*. GRDC. Available at: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2018/07/harvest-weed-seed-control-beyond-windrow-burning [Accessed 8 August 2019]

Cousens, R., Brain, P., Odonovan, J.T. and Osullivan, P.A. (1987) The use of biologically realistic equations to describe the effects of weed density and relative-time of emergence on crop yield. *Weed Science*, 35, 720–725. https://doi.org/10.1017/s0043174500060872

Cudney, D.W., Jordan, L.S., Bendixen, W.E., Holt, J., Hall, A.E., Corbett, C.J. *et al.* (1991) Wild oat competition in short-statured wheat. *California Agriculture*, 45, 22–23.

Davies, L.R., Hull, R., Moss, S. and Neve, P. (2019) The first cases of glyphosate resistance in UK poverty brome (*Bromus sterilis*) population. *Weed Science*, 67, 41–47. https://doi.org/10.1017/wsc.2018.61

Dehghani, R., Joniyas, A. and Latip, S. (2014) Rainfall distribution and temperature effects on wheat yield in torbate heydarie. *International Journal of Science Research in Knowledge*, 2. (Special Issue), 121–126.

HerbiGuide. (2018) *Weeds Description [Online]*. Australia. Available at http://www.herbiguide.com.au/ [Accessed 20 March 2019].

Koger, C.H., Shaw, D.R., Watson, C.E. and Reddy, K.N. (2003) Detecting late-season weed infestations in soybean (*Glycine max*). *Weed Technology*, 17, 696–704. https://doi.org/10.1614/wt02-122

Llewellyn, R.S., Lindner, R.K., Pannell, D.J. and Powles, S.B. (2004) Grain grower perceptions and use of integrated weed management. *Australian Journal of Experimental Agriculture*, 44, 993–1001. https://doi.org/10.1071/ea03115

Llewellyn, R.S., Ronning, D., Clarke, M., Mayfield, A., Walker, S. and Ouzman, J. (2016) *Impact of weeds in Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices*. Australia: Report for Grains Research and Development Corporation, CSIRO.

López-granados, F. (2011) Weed detection for site-specific weed management: mapping and real-time approaches. *Weed Research*, 51, 1–11. https://doi.org/10.1111/j.1365-3180.2010.00829.x

Lopez-Granados, F., Jurado-Exposito, M., Pena-Barragan, J.M. and Garcia-Torres, L. (2006) Using remote sensing for identification of late-season grass weed patches in wheat. *Weed Science*, 54, 346–353. https://doi.org/10.1614/WS-05-54.2.346

Lopez-Granados, F., Torres-Sanchez, J., Serrano-Perez, A., de Castro, A.I., Mesas-Carrascosa, F.J. and Pena, J.M. (2016) Early season weed mapping in sunflower using UAV technology: variability of herbicide treatment maps against weed thresholds. *Precision Agriculture*, 17, 183–199. https://doi.org/10.1007/s11119-015-9415-8

Lu, H., Yu, Q., Han, H.P., Owen, M.J. and Powles, S.B. (2020) Non-target-site resistance to PDS-inhibiting herbicides in a wild radish (*Raphanus raphanistrum*) population. *Pest Management Science*, 76, 2015–2020. https://doi.org/10.1002/ps.5733

Nugent, T. (1999) Managing wild radish (*Raphanus raphanistrum* L.). In *CRC for Weed Management Systems and the Grains Research and Development Corporation*, 20 pp.

Owen, M.J. and Powles, S.B. (2010) Glyphosate-resistant rigid ryegrass (*Lolium rigidum*) populations in the Western Australian grain belt. *Weed Technology*, 24, 44–49. https://doi.org/10.1614/wt-09-054.1

Owen, M.J. and Powles, S.B. (2016) The frequency of herbicide-resistant wild oat (*Avena* spp.) populations remains stable in Western Australian cropping fields. *Crop & Pasture Science*, 67, 520–527. https://doi.org/10.1071/cp15295

Peltzer, S.andDouglas, A. (2019) *Annual Ryegrass [Online]*. Western Australia: Department of Primary Industries and Regional Development. Available at: https://www.agric.wa.gov.au/grains-research-development/annual-ryegrass [Accessed 17 April 2019]

Pena, J.M., Torres-Sanchez, J., Serrano-Perez, A., de Castro, A.I. and Lopez-Granados, F. (2015) Quantifying efficacy and limits of unmanned aerial vehicle (UAV) technology for weed seedling detection as affected by sensor resolution. *Sensors*, 15, 5609–5626. https://doi.org/10.3390/s150305609

Podlesny, J. and Podlensa, A. (2011) Effect of rainfall amount and distribution on growth, development and yields of determinate and indeterminate cultivars of blue lupin. *Journal of Agronomy*, 4, 16–22.

Rasmussen, J., Nielsen, J., Streibig, J.C., Jensen, J.E., Pedersen, K.S. and Olsen, S.I. (2019) Pre-harvest weed mapping of Cirsium arvense in wheat and barley with off-the-shelf UAVs. *Precision Agriculture*, 20, 983–999. https://doi.org/10.1007/s11119-018-09625-7

Rathore, A.L., Pal, A.R. and Sahu, K.K. (1998) Tillage and mulching effects on water use, root growth and yield of rainfed mustard and chickpea grown after lowland rice. *Journal of the Science of Food and Agriculture*, 78, 149–161.

Rew, L.J. and Cussans, G.W. (1995) Patch ecology and dynamics - How much do we know? In *Brighton Crop Protection Conference-Weeds*, vol. 3, pp. 1059–1068. Farnham, Surrey, UK.

Shakhatreh, Y., Kafawin, O., Ceccarelli, S. and Saoub, H. (2001) Selection of barley lines for drought tolerance in low-rainfall areas. *Journal of Agronomy and Crop Science-Zeitschrift Fur Acker Und Pflanzenbau*, 186, 119–127. https://doi.org/10.1046/j.1439-037X.2001.00459.x

Shaw, D.R. (2005) Translation of remote sensing data into weed management decisions. *Weed Science*, 53, 264–273. https://doi.org/10.1614/ws-04-072r1

Shirtliffe, S.J. and Entz, M.H. (2005) Chaff collection reduces seed dispersal of wild oat (*Avena fatua*) by a combine harvester. *Weed Science*, 53, 465–470. https://doi.org/10.1614/ws-03-109r2

Walsh, M.J., Aves, C. and Powles, S.B. (2017b) Harvest weed seed control systems are similarly effective on rigid ryegrass. *Weed Technology*, 31, 178–183. https://doi.org/10.1017/wet.2017.6

Walsh, M.J., Broster, J.C., Schwartz-Lazaro, L.M., Norsworthy, J.K., Davis, A.S., Tidemann, B.D. *et al.* (2018) Opportunities and challenges for harvest weed seed control in global cropping systems. *Pest Management Science*, 74, 2235–2245. https://doi.org/10.1002/ps.4802

Walsh, M., Ouzman, J., Newman, P., Powles, S. and Llewellyn, R. (2017a) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. *Weed Technology*, 31, 341–347. https://doi.org/10.1017/wet.2017.9

Walsh, M.J. and Powles, S.B. (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. *Weed Technology*, 28, 486–493. https://doi.org/10.1614/wt-d-13-00183.1

White, B., Giumelli, J.andSaunders, M. (2018) *Harvest weed seed control for the southern high rainfall zone [Online]*. Weed Smart, 097. Available at: https://weedsmart.org.au/wp-content/uploads/2018/06/RR_1802_weedsmart.pdf [Accessed 12 December 2018]

Widderick, M.andWalker, S. (2009) *Management of common sowthistle [Online]*. Australia, Queensland: QPIF, Leslie Research Centre. Available at: https://www.daf.qld.gov.au/__data/assets/pdf_file/0004/75640/Management-of-common-sowthistle.pdf [Accessed 4 June 2019]

Zisi, T., Alexandridis, T.K., Kaplanis, S., Navrozidis, I., Tamouridou, A.A., Lagopodi, A. *et al*. (2018) Incorporating surface elevation information in UAV multispectral images for mapping weed patches. *Journal of Imaging*, 4, 132. https://doi.org/10.3390/jimaging4110132

How to cite this article: Shahbazi N, Flower KC, Callow JN, Mian A, Ashworth MB, Beckie HJ. Comparison of crop and weed height, for potential differentiation of weed patches at harvest. *Weed Res*. 2020;00:1–10. https://doi.org/10.1111/wre.12450