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Integrating mechanical and cultural methods for weed control in organic chickpea

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Abstract

The Northern Great Plains of the United States is a major production region for organic pulse crops that are prone to yield losses due to weeds. Weed management in organic systems relies on the integration of several tactics to stack additive effects and for redundancy to deal with variable efficacy of individual weed management practices. To address the need for effective, integrated weed management, we conducted a 2-yr trial that evaluated the effects of planting date, seeding rate, and preemergent weed control practices (shallow tillage and flame weeding) on weed biomass, crop density, and yield in organically managed chickpea (*Cicer arietinum* L.) in Montana. Stacking weed management practices increased yields. Early planting had the largest effects on yields, increasing them by 1.8- to 3.6-fold compared with planting 10 to 14 d later. Increasing the seeding rate from the standard rate (43 viable seeds m^{-2}) by 50% increased yields by 47% from 889 to 1,304 kg ha^{-1}. Both preemergent weed control practices increased yields by 40% to 50 % relative to the non-weeded controls. By integrating all three practices, yields of organic chickpea increased greater than 6-fold from 318 kg ha^{-1} in the controls to 2,006 kg ha^{-1}. The effects of weed control treatments on midseason weed biomass were complex and variable. Although efficacy of the cultural (seeding rate and planting date) and physical (preemergent) treatments on weed biomass varied between years and when combined with other treatments, their full integration, that is, early planted, at higher seeding rate, and preemergent weed control, produced consistently lower weed biomass (84% reduction on average) compared with the standard grower practice (later planting, standard seeding rate, no preemergent weed control). The results lend support to the concept of integrating multiple weed management practices to achieve weed control and high yields in organically managed crops.

Introduction

Interest in non-herbicide weed control practices to improve sustainability in both conventional and organic cropping systems is growing. Throughout the world, herbicides are the most widely used method of weed control (Liebman and Davis 2009). However, they have been increasingly linked to negative environmental impacts (Annett et al. 2014; Davis et al. 2013). Additionally, many weed species are developing resistance, making herbicide-based weed management less effective and requiring the integration of alternative weed management practices to control weeds (Liebman and Gallandt 1997; Weiner et al. 2001). Moreover, consumer demand for organically produced foods is increasing. As a result, the production of organic crops has increased (USDA-NASS 2018). Organic production prohibits the use of most synthetic herbicides and further supports the need to develop organic and sustainable weed control strategies.

Weed management in organic systems relies on the integration of multiple tactics (Álvarez-Iglesias et al. 2018; Eslami and Davis 2018; Liebman and Gallandt 1997; Silva and Delate 2017) commonly known as integrated weed management (IWM). IWM combines several methods to control weeds, including mechanical (shallow tillage, flaming, mowing, etc.), preventive (residue management, clean machinery, management of field margins, etc.), cultural (varietal choice, seeding rate and date, etc.), and biological controls (Tautges et al. 2016). Many of these tactics are aimed at giving crops a competitive advantage by allowing the crop to emerge at sufficiently high densities into an environment with reduced weed competition. These practices are integrated because only their combined, additive, or synergistic effects can deliver adequate weed management (i.e., many little hammers) and efficacy of individual practices can be variable (Anderson 1997; Malik et al. 1993; Mertens and Jansen 2002). Many of these weed management strategies are both environment and crop specific (Bastiaans et al. 2008; Macé et al. 2007); thus strategies proven to be effective in one crop may have neutral or negative effects in another crop and/or region. IWM of chickpea (*Cicer arietinum* L.) is of particular interest for organic farmers in the Northern Great Plains region of the United States.

Chickpea is well-adapted to the Northern Great Plains and can be profitable as an organic crop if yields are high. In 2017, Montana, Washington, Idaho, and North Dakota produced 93% of the chickpea grown in the United States, and chickpea grown in Montana alone accounted for 35% (for 2017 specifically) to 40% of U.S. production (USDA-NASS 2018). While the exact number of chickpea hectares being produced organically has not yet been recorded, Montana has the second-largest certified organic acreage among U.S. states (USDA-NASS 2018). Increasing demand in domestic consumption and rising growth in volume exports, coupled with relatively high prices in the organic chickpea market (US\$1.32 to US\$1.54 kg^{-1}, three times greater than conventionally produced chickpea), suggests that farmers will continue to invest in organic chickpea acreage into the future.

Weed management is one of the main challenges in organic agriculture and is particularly an issue in chickpea (DeDecker et al. 2014; Rodriguez et al. 2009). Chickpea tends to mature slowly, with an open canopy and short height, thus limiting its competitive ability (Whish et al. 2002). Several studies have found that weed competition in chickpea reduces yields (AL-Thahabi et al. 1994; Rao and Nagamani 2010) with up to a 97% yield loss (Paolini et al. 2006). However, little information has been published regarding weed management in organic chickpea, especially in the Northern Great Plains.

We recently published the results of initial research that evaluated IWM strategies in organic chickpea (Mohammed et al. 2020). These trials incorporated two chickpea varieties (a Kabuli type, 'CDC Orion', and a Desi type, 'Black Butte'), two seeding rates (43 and 65 live seeds m^{-2}), and two preemergence weed control practices (shallow tillage and flame weeding) conducted at two sites over 2 yr in Montana. The Desi variety had greater weed suppression and yields that were driven by greater seedling survival and resulting stand densities than the Kabuli variety. Increasing seeding rate consistently increased stand densities and yields, but the magnitude of these effects varied by site and variety. The effects of weed control practices on weed biomass and crop yields varied by site and year. Some of the variation in the efficacy of weed control practices was associated with planting date, but this factor was not formally tested in the experimental design.

Effects of planting date in organic chickpea production have not been studied in this region, but earlier planting increases yield in conventionally managed chickpea (Auld et al. 1988; Machado et al. 2006). Yields increased up to 34% when crops were planted in April versus May in northern Idaho (Auld et al. 1988). Machado et al. (2006) reported increased yields by 112 to 224 kg ha^{-1} across multiple sites and years with earlier planting dates (late March/early April vs. late April) in Oregon. The authors of both studies hypothesized that planting at an earlier date allows chickpea seedlings to become established before annual weeds emerge in the spring, giving the crop a competitive advantage due to larger crop size relative to the emerging weeds (i.e., asymmetric competition; Connolly and Wayne 1996). Early planting may also increase yields by providing a longer flowering and seed development period and reducing the flowering period impacted by heat. High temperatures (>30 C) during flowering and pod development can severely reduce seed set and development and yields (Wang et al. 2006).

In trials conducted for 3 yr across six sites near Amsterdam, MT (45.758°N, 111.321°W), the effects of planting date on yields were evaluated across several conventionally produced chickpea cultivars. Planting dates ranged from late March to early June. On average, chickpea yields declined by 31% between the earliest and latest planting dates, with the most significant declines occurring after early May. Delaying seeding from mid-April to early May reduced yields in most but not all sites and by a smaller magnitude (by 5% to 15%) than in other studies done in the region (Miller and Holmes 2004, unpublished). Currently, no effective fungal or insecticidal seed treatments are approved for organic use on chickpea. Thus, the effects of planting date in organic chickpea may differ with climate conditions, as cool, wet spring soil conditions are conducive to seed rot, *Fusarium* sp., and *Pythium* sp. root rot (Machado et al. 2006).

The current study was conducted to build on this baseline knowledge about the integration of weed management practices in organic chickpea production in the Northern Great Plains of the United States. These IWM strategies include cultural (cultivar choice, seeding rate, and seeding date) and physical (shallow tillage and flaming) weed controls. The objective of this study was to determine the effects of these IWM strategies on chickpea plant stand density, grain yield, and weed biomass.

Materials and Methods

Site Description

This experiment was conducted in 2018 and 2019 at the Western Agricultural Research Center (WARC) in Corvallis, MT (46.3287 N, 114.0852 W), located at 1,096 m above sea level. The soil at WARC is Burnt Fork Loam, coarse-loamy, mixed, superactive, frigid Typic Haplustolls over coarse alluvium. Monthly average air temperatures and total rainfall for the growing seasons are presented in Table 1. Average air temperatures during these trials followed long-term trends. The precipitation for Corvallis was similar between the 2 yr but slightly above the long-term mean. As shown in Table 1, year-to-year seasonal variation in precipitation was substantial. In 2018, the site received 90% of the precipitation by the end of June. In 2019, most of the precipitation (58%) fell in the latter half of the growing season. However, the experiment received 142 mm of supplemental irrigation water. Irrigation was applied once per week until flowering (mid-July). Previous crops in these fields included winter wheat (*Triticum aestivum* L.) in 2017 and malt barley (*Hordeum vulgare* L.) 2018.

Experimental Design, Treatments, and Trial Plot Management

The experiment was conducted using a randomized complete block design with a split-plot arrangement and four replicates in both 2018 and 2019 in different fields at the site. In both trials, the whole-plot treatments were a factorial combination of physical weed control methods (a non-weeded control, shallow tillage, and flaming) and planting date (early and late). The subplot factor was a factorial combination of two chickpea varieties and seeding rate (2018) or seeding rate with one variety (2019). Although a subset of subplot treatments differed between trials, both trials share subplot treatments of the Desi variety, Black Butte, and two seeding rates (described later). These treatments are the primary focus of the study. In 2019, weed control treatments were misapplied in one block, and that block was removed from the analysis.

The early-planting date was based on soil temperature, but was delayed due to wet field conditions. The early-planting target was when 10-d, average minimum soil temperatures at 5-cm depth were above 5 C. Once the initial soil temperature threshold was met, early seeding occurred when field conditions allowed. In both

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Table 1. Monthly mean air temperature and monthly total precipitation at Corvallis, MT, in 2018 and 2019 during the crop growing season (April to September) and long-term (30-yr) mean (LTM)

	Average air temperature			Total precipitation		
	2018	2019	LTM	2018	2019	LTM
Month		C			mm	
April	6.5	7.1	6.7	38.9	45.0	28.0
May	13.7	11.7	11.7	39.1	26.7	32.0
June	14.7	15.8	16.1	98.8	11.4	50.0
July	19.7	18.5	21.7	0.5	60.2	15.0
August	18.0	18.7	20.0	9.4	21.1	18.0
September	12.6	13.7	14.4	9.4	35.1	25.0
Mean/total	14.2	14.3	15.1	196.1	199.4	168.0

years, wet field conditions caused delayed planting. The late planting occurred 10 to 14 d after the early planting. In 2018, early-planted chickpeas were sown on April 20 (soil temperatures had reached the planting threshold 10 d prior), and late-planted chickpeas were sown on April 30. In 2019, early-planted chickpeas were sown on April 29 (soil temperatures had reached the planting threshold 19 d prior) and late-planted chickpeas were sown on May 14.

In 2018, the subplot treatment was the factorial combination of two chickpea varieties (Black Butte, Desi type; CDC Orion, Kabuli type obtained from Timeless Seeds (TM), Ulm, MT) and two seeding rates: 1× and 1.5× (1× = standard seeding rate of 43 live seeds m^{-2} [Gan et al. 2003]; 1.5× = 50% increased seeding rate). CDC Orion seeds are twice the mass of Black Butte chickpea, thus the 1× seed rate was 278 kg ha^{-1} for CDC Orion compared with 150 kg ha^{-1} for the Black Butte chickpea. The Black Butte and CDC Orion are commonly grown on organic farms in the region.

CDC Orion is a Kabuli type, released in 2010 by the University of Saskatchewan, and is well suited to the Canadian prairies, which are much like the Northern Great Plains (Taran et al. 2011). Black Butte chickpea is a Desi type with a black seed coat and is a landrace from Central Asia. Typically, Desi-type chickpeas are smaller in size and darker in color than Kabuli-type chickpeas (Khan et al. 1995). Desi-type seeds have been included in this study due to their potential for reduced pest issues in organic production, as research has shown that tannin-rich seed coats have the potential to act as a pest deterrent (Khan et al. 1995; Mohammed et al. 2020).

In 2019, we used one chickpea variety, Black Butte. In this year, rather than compare varieties, the subplot treatments were three seeding rates: 1×, 1.5×, and 2× (1× = standard seeding rate of 43 live seeds m^{-2}; 1.5× and 2× = 65 and 86 live seeds m^{-2}, respectively). An additional seeding rate was added to determine the point at which an increased seeding rate offers diminishing returns.

The whole-plot dimensions in 2018 were 1.2 m by 24.4 m, and subplots measured 1.2 m by 6.1 m. In 2019, the whole-plot dimensions were 1.2 m by 36.6 m, and subplots measured 1.2 m by 12.2 m. To minimize edge effects, whole plots were planted next to each other (~30 cm separating the long edge of the whole plot), and buffer plots were planted on the outer edges of the trials. Each plot contained seven rows with a 16.5-cm space between rows. Chickpeas were seeded at a depth of 5 cm using a small plot drill (Hege 90, Hege Maschinen, Germany). The seeds were inoculated with peat-based commercial Rhizobium N-Charge® (Verdesian Life Sciences, Cary, NC).

Due to evidence of wireworm (*Lumonius* sp.) activity in the fields at this site, and their ability to affect crop emergence, 20 wireworm traps were built and set up via the solar bait trap method (Esser 2012). These traps were buried randomly, with five traps per replication, between early- and late-planting dates. Traps were unearthed 2 wk later, and wireworms in each trap were counted by hand.

Physical weed control treatments (flaming and shallow tillage) were applied between 9 and 10 d after seeding chickpea, and before chickpeas emerged from the soil surface (chickpea emergence is expected to occur at approximately 15 d after planting at this site). Shallow tillage was conducted with sweeps, triangular metal blades, mounted on a tool bar that attached to the rear of the tractor. Seven sweeps (35.6 cm wide) were mounted 15.2-cm apart on a custom toolbar in two rows (e.g. sweeps mounts alternate between the front and rear row to allow overlapping tillage). The total width of the area receiving shallow tillage was 127 cm, slightly larger than the plot width. Depth of tillage was set at 2 cm, below the soil surface. During tillage, the tractor was driven at ~6.4 kph. Flaming treatments were applied using a Red Dragon Vegetable Bed Flamer™ (Flame Engineering, Lacrosse, KS). The propane was applied at ~52 kg ha^{-1}. Propane was burned in eight burners (Liquid Torch-model LT11/2X8D) mounted 18.1 cm apart and 10 cm above the soil surface. The flame weeder applied parallel to the crop rows. The flame weeder was mounted at the rear of the tractor, driven at approximately 6.4 kph.

Chickpea plant density was counted approximately 3 wk after crop emergence. Native weed populations consisted of a mix of annual grasses (e.g., green foxtail [*Setaria viridis* (L.) P. Beauv.] and witchgrass [*Panicum capillare* L.]) and broadleaf weeds (predominately common stork's bill [*Erodium cicutarium* (L.) L'Hér. ex Aiton], redroot pigweed [*Amaranthus retroflexus* L.], and common lambsquarters [*Chenopodium album* L.]). Weed biomass samples were collected when ~50% of the chickpea plants were flowering in a plot. The weed biomass samples were taken in the second week of June for the early-planting date and third week of June for the late-planting date. Weed biomass was randomly sampled from a 1-m^2 area located over the middle three rows in each plot. Chickpea was harvested at maturity (seed moisture content <18%) with a plot combine harvester (Wintersteiger, Salt Lake City, UT). Early-planted plots were harvested on August 31, 2018, and August 26, 2019. Late-planted plots were harvested August 31, 2018, and September 4, 2019. Chickpea seeds were cleaned of weed seed and crop residues using a 5-mm sieve and an Air Blast Seed Cleaner (Almaco, Nevada, IA). Grain moisture content was measured with a grain moisture tester (GAC 2100-Agri Grain Analysis Computer, Dickey-John, Auburn, IL), and grain yield was adjusted to 13% before statistical analysis.

Statistical Analysis

Data were analyzed using split-plot ANOVA in R (R Core Team 2013). Response variables were transformed to meet assumptions of ANOVA when needed. Trials (or years) and blocks within trial were modeled as random effects. Weed control methods (WC), planting date (PD), seeding rates (SR), and interactions of these factors with each other and with trial (i.e., year and field) were considered to be fixed effects. When ANOVA showed significant effects ($P \leq 0.05$), least significant difference (LSD) values were calculated to differentiate the means of the treatment effects using the AGRICOLAE package in R (de Mendiburu 2013).

Results and Discussion

Chickpea Crop Densities

In the first year of this study, a comparison of two chickpea cultivars confirmed that the Desi chickpea (Black Butte) had superior survival and emergence compared with the Kabuli chickpea (CDC Orion). The densities of the Desi-type (Black Butte) chickpea averaged greater than 25 plants m^{-2}, much greater than Kabuli type (CDC Orion, mean =1 plant m^{-2}). The emergence of the Kabuli type was reduced by wireworm damage (personal observation) and was so low that plots were tilled under and not included in the analysis. In our previous trials, stand densities of CDC Orion were lower and more variable than those of Black Butte, ranging from 17% to 67% of seeded rate (Mohammed et al. 2020).

Wireworms were present in both trials, conducted in different fields each year. In 2018, there were on average 20.8 per trap. In 2019, we collected an average of 25.0 wireworms per trap. Although chickpea-specific thresholds for wireworm abundance and economic damage have not been established, the standard damage threshold is one wireworm per trap (Knodel and Shrestha 2018).

Often the objective of selecting crop cultivars for weed management is to gain greater competitive ability (Benaragama and Shirtliffe 2013). Previous research on differences in competitive ability among chickpea cultivars have focused on canopy characteristics, that is, rate of growth and branch and leaf characteristics (Paolini et al. 2006). Results from the trial presented here suggest that key traits for improved competitive ability of chickpea in organic systems are related to seed and seedling survival, specifically resistance to fungal disease and insect pests. Although we did not directly measure the causes of seed and seedling mortality, common issues in the region are damping-off and wireworm predation of crop seeds. Previous research has shown that Kabuli-type chickpeas (like CDC Orion) have thinner seed coats and are more susceptible to damping-off than their thicker-skinned counterparts, Desi-type chickpeas (Kumar et al. 1991). Wireworms are a damaging pest in pulses across the Northern Great Plains (Knodel and Shrestha 2018), as are soil-borne diseases (Navas-Cortés et al. 1998). More research is needed on breeding resistant varieties and developing effective seed treatments that can be used in certified organic systems (i.e., OMRI-approved).

Among the core IWM treatments investigated in the Black Butte variety, planting date and seeding rate were the only treatments that affected chickpea crop densities (Table 2). Physical weed control methods (flaming and tillage) did not impact chickpea crop densities (Table 2), indicating that these practices did not damage the chickpea stands. The effects of planting date on chickpea densities varied between years (Table 2), but early planting consistently increased crop densities relative to late planting (Table 3). In 2018, chickpea densities were lower than in 2019, and the effect of early planting was larger (1.48-fold increase) in 2018 than in 2019 (1.13-fold increase).

The effects of increasing the seeding rate on crop density were consistent between trials (Table 2). When planted at the 1.5× seeding rate (mean = 53 plants m^{-2}), densities were 32% greater than at the standard rate (mean = 41 plants m^{-2}). However, in 2019, when the 2× seeding rate was evaluated, further increases beyond the 1.5× rate did not provide significant increases in crop densities. Doubling the seeding rate resulted in an average of 74 plants m^{-2}, which was similar to densities at the 1.5× rate (mean = 65 plants m^{-2}).

Weed Biomass

Weed management in organic systems relies heavily on integration of several tactics to both stack additive effects and for redundancy to deal with variable efficacy of individual practices. The effects of the weed management treatments were variable and emphasize the importance of integration to create redundancies that increase the probability of better weed control. Weed biomass measured at chickpea flowering was impacted by preemergent weed control practices, planting date, and seeding rate, but effects of treatments varied by their integration and by year, that is, the interaction of all four treatments was significant (Table 2). The interaction among all treatments and trials may be a result of nonadditive effects of stacking treatments that varied between years or fields. Averaged between trials, each individual weed management tactic (i.e., earlier planting dates, increased seeding rates, flame weeding, and shallow tillage) reduced weed biomass, but no single tactic consistently decreased weed biomass in both trials. Only when weed management practices were integrated were consistent reductions in weed biomass achieved (Table 4).

The effects of planting date on weed biomass differed between trials (Table 2). In 2018, weed biomass was similar between planting dates in all treatment combinations, except when tillage was combined with the 1.5× seeding rate (Table 4). In this treatment combination, early planting reduced weed biomass by ~50% (Table 4). In 2019, early planting reduced weed biomass by 69% to 28.9 g m^{-2} from 87.5 g m^{-2} in the late-planting date. This study was not designed to isolate the causes of variation in the efficacy of weed management practices, but it may be associated with differences in the timing of precipitation between years (Table 1). In 2018, spring was wetter than average, followed by a drier than average summer. In 2019, a dry spring was followed by a wet summer. The drier conditions in the spring of 2019 may have increased crop–weed competition early in the growing season, resulting in greater reductions in weed biomass under the canopy of the earlier-seeded crop.

Increasing the seeding rate reduced weed biomass on average by 25% but was only effective in limited combinations of other weed control practices that were not consistent between years. In 2018, the increasing seeding rate only reduced weed biomass when combined with tillage and the early-planting date (Table 4). In 2019, the only treatment combination where increasing the seeding rate showed a reduction in weed biomass was late planting plus tillage.

These variable effects of seeding rate on weed biomass are similar to results of our trials in 2016 to 2017 in Corvallis, where effects of increasing the seeding rate on weed biomass occurred only in some treatment combinations and were not consistent between years (Mohammed et al. 2020). These results differ from those of previous studies that have found that increasing crop density is more effective and reliable in managing weeds compared with other cultural practices (Benaragama and Shirtliffe 2013; Chen et al. 2008; Kolb et al. 2010; Mason et al. 2007; Scursoni and Satorre 2005). A recent study in Saskatchewan, Canada, found that doubling the seeding rate in organically managed lentils (*Lens culinaris* Medik.) consistently reduced weed biomass by 16% (Alba et al. 2020). Similar studies have found that increased seeding rates in pea (*Pisum sativum* L.) (2×) and lentil (4×) resulted in 60% to 70% reductions in weed biomass (Baird et al. 2009).

The efficacy of the preemergent weed control practices (flaming/tilling) to reduce weed biomass varied between trials and depended on the planting date and seeding rate treatments

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Table 2. Split-plot ANOVA table for the effects of integrated weed management treatments on chickpea grain crop density, weed biomass, and yield

Source of variation	df	Crop density		Weed biomass		Grain yield	
		F	P-value	*F*	P-value	*F*	P-value
Whole plot							
Weed control (WC)	2	3.2	NS	21.4	***	10	***
WC × year (YR)	1	0.7	NS	2.2	NS	0.3	NS
Planting date (PD)	1	43.8	***	17.9	***	141.5	***
PD × WC	2	2.4	NS	0.1	NS	3.1	NS
PD × YR	1	4.8	*	8.1	***	23	***
PD × WC × YR	2	1.3	NS	2.3	NS	1.2	NS
Error	25						
Split plot							
Seeding rate (SR)	1	22.9	***	7.1	**	45.8	***
PD × SR	1	1.8	NS	1.6	NS	1.2	NS
WC × SR	2	0.5	NS	1.0	NS	0.2	NS
SR × YR	1	0.9	NS	0.2	NS	3.3	NS
PD × WC × SR	2	0.2	NS	1.4	NS	0.8	NS
PD × SR × YR	1	0.01	NS	2.5	NS	0	NS
WC × SR × YR	2	0.02	NS	0.6	NS	1	NS
WC × PD × SR × YR	2	0.6	NS	3.4	*	0.3	NS
Error	30						

*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.
NS = not significant, $P > 0.1$.

Table 3. Effects of planting date and year on chickpea densities (plants m^{-2})

Planting date	Year[a]			
	2018		2019	
	plants m^{-2}			
Early	43	c	62	a
Late	29	d	55	b

[a]Treatments mean with different letters indicate a significant difference in post hoc tests.

(Tables 2 and 4). In 2018, flaming and shallow tillage always reduced weed biomass relative to the controls. But the relative efficacy of each method depended on planting date. For the early-planting date, weed biomass was similar between tillage and flaming, but for the late-planting date, flaming reduced weed biomass relative to tillage (Table 4). In 2019, when weed biomass was high for the late planting and low for the early planting, flaming and tillage did not consistently reduce weed biomass relative to the control. For the early-planting date treatment, weed biomass was low in the control treatment and flaming consistently reduced weed biomass relative to the control. Tillage only reduced weed biomass when combined with early planting. A late-planting date increased weed biomass relative to early planting, and preemergent weed control practices were less effective. Weed biomass was reduced relative to the controls only when tillage was combined with the increased seeding rate (Table 4).

In this study, preemergent weed control practices reduced weed biomass in most but not all conditions. Previous studies have found variable efficacy of preemergent mechanical weed control (Dastgheib 2004; Johnson and Holm 2010). Johnson and Holm (2010) conducted a study examining the effects of seeding date and preemergent weed control practices (harrowing and rod-weeder) in field pea. They found that mechanical weed control decreased weed density only for certain planting dates when weed emergence coincided with cultivation.

Effects of preemergent weed control in organic chickpea have not been well studied. In our previous study, flame weeding did not reduce weed biomass, but tillage consistently reduced weed biomass when combined with higher seeding rates (Mohammed et al. 2020). The variable efficacy of preemergent weed control practices is not surprising, given that efficacy depends on several factors, including the growth stage of the plant, the regrowth potential of weed species, and climatic conditions (Datta and Knezevic 2013). Efficacy of preemergent weed control practices should be greatest when applied just as weed seedlings are emerging. But the shallow tillage or flame weeding must be applied before crop emergence. If weed emergence does not occur in that window between planting and crop emergence, then these practices would not provide good weed control. Therefore, timing of both crop planting and application of weed control practices, weed community composition, and weather are expected to influence the effectiveness of preemergent weed control practices.

Overall, these variable effects of IWM practices on weed biomass emphasize the importance of integration for redundancy. If efficacy of an individual practice on weed control varies with climate, soil, or weed community, integration with other practices would increase the likelihood of weed suppression. Although efficacy of individual weed control practices varied between trials, integrating early planting, increased seeding rate, and either type of preemergent weed control practice consistently reduced weed biomass by 84%, from an average of 135.5 g m^{-2} without these practices to 22.3 g m^{-2} when all three practices were combined (Table 4).

Yield

In contrast to the variable effects of IWM treatments on weed biomass, the effects of individual weed control practices on chickpea yield were independent and consistent between trials (Table 2). Although early planting consistently increased yields over later planting, the magnitude of these effects was larger in 2018 than 2019 (Table 2). In 2018, early-planted chickpea yields were 2,016 kg ha^{-1}, 3.6 times greater than the late-planted treatment (mean = 563 kg ha^{-1}). In 2019, early planting increased yields by 1.8 times from 653 kg ha^{-1} in the late-planted treatment

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Table 4. Effects of physical, preemergent weed control (control, flame weeding, and shallow tillage), planting date (early and late), and seeding rate (SR: 1.5× = HI; 1× = STD) on weed biomass (g m^{-2}) between two years (2018–2019)[a]

		2018		
SR-HI	Control	Flame	Till	Efficacy rating[b]
		g m^{-2}		
early	89 abcde	22 ij	31 jk	Control < flame = till
late	106 ab	28 ijk	65 cdef	Control < till < flame
SR-STD				
early	116 abc	27 hij	51 fgh	Control < till = flame
late	149 a	22 ijk	45 fgh	Control < till < flame
		2019		
SR-HI	Control	Flame	Till	Efficacy rating
		g m^{-2}		
early	44 efg	12 k	24 hij	Control < till < flame
Late	112 ab	70 bcdef	52 defg	Control < till; flame similar to both
SR-STD				
Early	43 efg	22 ijk	28 ghi	Control < flame, till similar to both
Late	122 ab	86 abcd	90 abc	Similar among treatments

[a]Means that do not share a lowercase letter differed in post hoc means test.
[b]Efficacy rating compares the effects of flame weeding and shallow tillage on weed biomass to the control in each planting date and seeding rate combination in each year.

to 1,143 kg ha^{-1} in the early-planted treatment. Effects of planting date on yields have not been studied previously in organic chickpea, but earlier planting has been shown to increase yields in chickpeas in conventionally managed systems (Auld et al. 1988; Machado et al. 2006; Rugerri et al. 2017). In the Northern Great Plains and Pacific Northwest regions, earlier planting of conventionally managed chickpea increased yields by 5% to 30%. Our results suggest that effects of early planting may be larger in organically managed than conventionally managed chickpea.

The mechanisms for early planting resulting in higher chickpea yields include increasing crop competitive ability, access to water, and length of time for flowering and seed formation. Early planting may allow the chickpeas to emerge before summer annual weeds, increasing the crop's sized-based competitive ability (Connolly and Wayne 1996). Although not a factor in this study, early planting may also increase yields by allowing the crop to emerge early when levels of plant-available water are higher in rainfed production (Machado et al. 2006). Given that chickpea is an indeterminate plant that continuously adds pods throughout the growing season, earlier planting may increase yields by extending the flowering period and reducing impacts of heat stress (Wang et al. 2006).

A seeding rate of 1.5× the standard rate increased yields compared with those planted at the standard rate (1×), and these effects were consistent across all other treatments and trials (Table 2). Yields of plots planted with 1.5× seeding rate averaged 1,304 kg ha^{-1}, 47% greater than the standard seeding rate, which averaged 889 kg ha^{-1}. In 2019, the yields at the 1.5× rate and 2× rate were similar. Many studies have shown that increasing plant densities in both conventional as well as organic cropping systems may increase a crop's competitive ability and yields (Benaragama and Shirtliffe 2013; Weiner 2001; Siddique et al. 1998). Given yields observed in the present study, the increased seed input cost associated with increasing the seeding rate would be justified by increased net profits of US\$528 ha^{-1}. Farmers would be purchasing an additional 50 kg of seed ha^{-1} but should expect yields averaging 450 kg ha^{-1}greater than those planted at the standard rate. With organic chickpea prices at US\$1.32 kg^{-1}, this gain translates into approximately US\$594 ha^{-1} before subtracting the increased seed cost (US\$66).

The effect on yields of increasing the seeding rate 50% was larger than what we found in our previous study (~25% increase; Mohammed et al. 2020) and what has been reported in the literature. Previous studies conducted on organically managed cereals found that doubling the seeding density resulted in around 10% increases in yields (Benaragama and Shirtliffe 2013; Mason et al. 2007). In organically managed lentils, increasing the seeding rate (~2×) has increased yields 16% to 18% (Alba et al. 2020; Baird et al. 2009).

Physical weed controls consistently increased yields both years, and the effects of flame weeding and preemergent tillage were not modified by other treatments (Table 2). Overall, yields were 47% greater in shallow-tillage plots (1,283 kg ha^{-1}) and 39% greater in flamed plots (1,208 kg ha^{-1}) than in control plots (871 kg ha^{-1}). Preemergent tillage increased yields relative to flame weeding.

Effects of preemergent weed control on organic chickpea yields also have not been well studied. In recent trials at this site, shallow tillage increased yields by 1.5-fold, and flame weeding increased yields by 68% in one year but were not effective in another (Mohammed et al. 2020). Previous studies have found variable efficacy of preemergent mechanical weed control on crop yields (Dastgheib 2004; Johnson and Holm 2010). The variable efficacy of preemergent mechanical weed management has been attributed to timing (Johnson and Holm 2010). Weeds can be managed if they emerge before the crop and can be removed by flaming or cultivation. These researchers found mechanical preemergent weed control decreased weed density and increased yields at some of the combinations of planting dates and weed control practices.

Practical Implications

The objective of this study was to evaluate the effects of integration of mechanical and cultural weed control practices on weed control and yields in organic chickpea. The effects of individual weed control practices on crop densities and yields were independent and consistent between trials. We saw clear effects of stacking weed management practices on yields. Overall, early planting had the largest effects on yields, likely due to increased stand densities emerging before weeds. Our results showed up to a 2.6-fold increase in yields when the Black Butte chickpeas were planted

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earlier in the spring compared with planting 10 to 14 d later. Early planting may have also had additional direct effects on yield that were not related to weed competition. Integrating increased seeding rate by 50% pushed yield up another 47%, and adding preemergent weed control increased yields a further 40% to 50%. With integration of all three practices, yields of organic chickpea increased greater than 6-fold from 318 kg ha^{-1} in the controls to 2,006 kg ha^{-1}. The effects of these practices on weed biomass were more variable. It may be that these weed management practices affected weed–crop competition during the critical period of weed control that has been reported to be 2 to 4 wk after emergence in the Pacific Northwest (Lake and Sadras 2014; Smitchger 2010) and before weed biomass was sampled in this study. Although efficacy of individual weed control practices varied, integrating early planting, increased seeding rate, and either type of preemergent weed control practice consistently reduced weed biomass by 84%. Both results lend support to the concept of integrating multiple weed management practices to achieve weed control and high yields in organically managed crops.

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