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Source: Weed Science, 70(3) : 341-352

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wsc.2022.14

Weed Science

www.cambridge.org/wsc

Research Article

Cite this article: McCollough MR and Melander B (2022) Improving upon the interrow hoed cereal system: the effects of crop density and row spacing on intrarow weeds and crop parameters in spring barley. Weed Sci. **70**: 341–352. doi: 10.1017/wsc.2022.14

Received: 6 September 2021
Revised: 14 January 2022
Accepted: 22 February 2022
First published online: 7 March 2022

Associate Editor:
Sharon Clay, South Dakota State University

Keywords:
Crop–weed competition; crop yield; grain quality; intrarow weed management; seeding rate; weed biomass

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Improving upon the interrow hoed cereal system: the effects of crop density and row spacing on intrarow weeds and crop parameters in spring barley

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Abstract

Automated guidance systems have advanced precise interrow hoeing in narrowly spaced cereals. Compared with other direct mechanical strategies, hoeing provides superior weed control and improved yields. However, weeds in the uncultivated intrarow zone may survive and compete intensely with the crop, causing yield loss. Therefore, improved intrarow weed management strategies in hoed cereals must be investigated. In spring barley (*Hordeum vulgare* L.), the effect of crop density was assessed at four levels (200, 300, 400, and 500 plants m^{-2}); interrow spacing at two levels (15 and 20 cm), relevant to the abilities of current automated equipment to hoe between narrowly spaced rows; and weed management treatment at three levels (no additional controls, herbicide, and preemergence tine harrowing). All treatments received interrow hoeing, and a surrogate weed (white mustard, *Sinapis alba* L.) was sown and monitored throughout experiments. The manipulation of crop density was a reliable method for suppressing the growth of intrarow weeds. As barley density increased from the target 200 to 500 plants m^{-2}, percent reduction in intrarow surrogate and ambient weed biomass (g m^{-2}) increased from 49% to 82% and 53% to 99%, respectively. Increasing crop density caused a decrease in grain bulk density (kg hl^{-1}) both years, and grain protein (%) and 1,000-kernel weight (g) in one year; whether these changes constitute a loss in grain quality depends upon end use. While row spacing had no effect on intrarow weeds, crop yields were 7% to 8% lower at 20 cm compared with 15 cm, incentivizing narrow row sowing. Barley yields were unaffected by increasing crop density, and the effect of preemergence tine harrowing was inconsistent. In one year, harrowing reduced surrogate and ambient weed biomass and increased barley yield; however, in another year, ambient weed biomass increased, and harrowing did not affect yield or surrogate weed biomass.

Introduction

In cereal crops, tine harrowing has long served as the go-to method for mechanical weed control. However, within the last decade, the adoption of interrow hoeing has increased among organic cereal growers in Europe. The rise in popularity of the hoed cereal system is not unwarranted; there are numerous drawbacks associated with postemergence harrowing (see Kurstjens and Pedok 2000; Rasmussen et al. 2010). In addition, significant technological advances in GPS- and camera-guidance systems have made precise interrow hoeing possible at satisfactory speeds up to 10 km h^{-1} (Gerhards et al. 2020; Melander 2006; Tillet and Hague 1999). Advantages associated with interrow hoeing include greater and less variable efficacy (Gallandt et al. 2018) across a wider range of field conditions and weed species compared with harrowing (Melander et al. 2003). In addition, hoeing cultivates only the interrow zone, while postemergence harrowing disturbs both the inter- and intrarow zones uniformly, inflicting crop damage. Conventional cereal growers also seek out mechanical weed management solutions; the relevance of interrow hoeing is likely to increase as herbicide use becomes more restricted, occurrence of herbicide resistance increases, and prospects remain poor for the commercialization of herbicides with new sites of action (Kudsk and Mathiassen 2020).

The hoed cereal system provides improved weed control at field scale compared with harrowing but may not provide sufficient weed control in the intrarow zone (Melander et al. 2018). Depending on the competitive abilities of weed species present, remaining intrarow weeds can compete intensely with the crop due to their close proximity. In hoed spring barley (*Hordeum vulgare* L.), Melander and McCollough (2020) reported that an intrarow surrogate weed, white mustard (*Sinapis alba* L.), reduced crop yields by 4% to 7 %, 14% to 26%, and 21% to 40% when densities of 5, 25, and 50 plants m^{-2} were recorded, respectively. Therefore, it is necessary to investigate further how intrarow weed management can be improved to optimize the hoed cereal system. The present study evaluates preemergence tine harrowing and the alteration of crop density and row spacing as strategies for controlling intrarow weeds within hoed spring barley.

The modification of crop density and spatial arrangement are common cultural weed management strategies in competitive cereal crops (Kolb and Gallandt 2012; Weiner et al. 2001). If crop density is fixed, sowing in narrower rows will increase the equidistance between crop plants, also known as rectangularity of the crop spatial pattern, and reduce crop density in the intrarow zone (Regnier and Bakelana 1995). A decrease in row spacing and rectangularity of the crop's spatial arrangement will simultaneously reduce intraspecific competition between crop plants and increase interspecific competition between crop plants and weeds (Fischer and Miles 1973), enhancing weed suppression and improving crop yields (Kolb et al. 2010). If row spacing is fixed, increasing crop density can both improve crop yield, due to an elevation in population (Weiner et al. 2010), and reduce weed biomass, due to increased competition (Mason and Spaner 2006; Weiner et al. 2001).

In northern Europe, the standard interrow spacings for growing small-grain cereals is 12.5 cm. The practice of widening interrow spacings to distances ranging from 15 to 30 cm to accommodate interrow hoeing while maintaining seeding rate constitutes a recent topic of research (Gerhards et al. 2020; Kolb et al. 2010, 2012; Machleb et al. 2018; McCollough et al. 2020a; Melander and McCollough 2020; Melander et al. 2003, 2018). Wide row sowing and hoeing effectively reduce weed biomass compared with standard cropping practices (Melander et al. 2018) and may improve yields, depending upon the severity of weed pressure (Kolb et al. 2010; Rasmussen 2004). However, a disadvantage associated with wide row sowing is the potential for yield loss resulting from elevated intraspecific competition and the non-optimal utilization of nutrients, light, and water (Melander et al. 2003; Rasmussen 2004). To avoid yield and crop quality losses, sowing at narrower row spacings is preferred. However, the ability to hoe efficiently between narrowly spaced rows is limited by a lack of automated steering systems capable of cultivating at row spacings below 20 cm (Gerhards et al. 2020; Machleb et al. 2018). While the development of technologies able to accurately guide hoes between 15-cm rows is underway, this equipment is not yet widely available (Gerhards et al. 2020). Therefore, in the present study, row spacings of 15 and 20 cm were selected for evaluation, representing distances suited to interrow hoeing now and in the near future. In addition, yield penalties may not be present among row spacings less than 25 cm (Blair et al. 1997) and differing by 5 cm only.

The effect of adjusting seeding rate and row spacing has been well described when standard cropping practices are employed, namely, when weeds are uniformly managed across the inter- and intrarow zones using full-width tine harrowing or chemical control (Olsen et al. 2004). However, within the hoed cereal system, it is necessary to describe the effects of row spacing and crop density on intrarow weeds, crop yield and biomass, and grain quality parameters.

Materials and Methods

Site Characteristics and Field Preparation

Two field experiments were conducted at the Flakkebjerg Research Center, Denmark (55.33°N, 11.39°E), one in 2019 (EXP_{2019}) and one in 2020 (EXP_{2020}). In both years, trials were carried out in a field possessing a sandy loam soil texture. Soil fertility was amended with 550 kg ha^{-1} of YaraMila 21-4-10 (DLG, Axelborg, Vesterbrogade 4A, DK-1620, Copenhagen V, Denmark) to achieve a nitrogen rate of 115.5 kg ha^{-1}; this fertility rate was selected to ensure that nitrogen would not limit crop growth among the row spacings tested.

Experimental Design and Treatment Specifications

Experiments possessed a full factorial, randomized complete block design with four replications. Experimental factors included (1) interrow spacing at two levels: 15 (RS_{15}) and 20 cm (RS_{20}); (2) crop density at four levels: 200 (CD_{200}), 300 (CD_{300}), 400 (CD_{400}), and 500 plants m^{-2} (CD_{500}); and (3) weed management treatment at three levels: plots receiving postemergence herbicide treatment ($WMT_{herbicide}$), plots receiving no herbicide treatment (WMT_{weedy}), and plots receiving preemergence tine harrowing ($WMT_{tineharrow}$). In total, 96 plots were present in the experiment for each year (2 interrow spacings × 4 crop densities × 3 weed management treatments × 4 blocks). Plot dimensions were 2.5 by 20 m, and a two-row spring malting barley ('KWS Irina') served as the test crop.

Postemergence interrow hoeing was implemented in all plots using a Schmotzer hoe (Maschinenfabrik Schmotzer GmbH, Bad Windsheim, Germany) possessing flat rigid shares, designed to limit sideward soil movement. Share width varied to accommodate differences in row spacing among treatments; 8-cm-wide shares for RS_{15}, and 13 cm for RS_{20}, resulting in a 7-cm uncultivated zone surrounding the row at both row spacings. *Sinapis alba* 'Lotus' was sown as a surrogate weed, perpendicular to crop rows, in a 2.5-m horizontal strip through the center of each plot. Surrogate weeds were sown on the same date as barley, at a target density of 40 plants m^{-2}. A summary of the dates on which key field operations and assessments were performed as well as crop, surrogate weed, and ambient weed growth stages at the time of implementation is provided in Table 1.

Postemergence herbicide applications consisted of Starane XL at 0.5 L ha^{-1} (florasulam 1.25 g ai ha^{-1} and fluroxypyr 50 g ai ha^{-1}, Dow AgroSciences Danmark A/S, Abedvej 39, 4920 Søllested, Denmark), Express at 10 g ha^{-1} (tribenuron-methyl at 5 g ai ha^{-1} and tribenuron at 4.82 g ai ha^{-1}, Du Pont Danmark ApS, Edwin Rahrs Vej 38, DK-8220 Brabrand, Denmark), and Agropol at 0.15 L ha^{-1} (spreading adhesive at 150 g ha^{-1}, UPL Europe, Engine Rooms, Birchwood Park, Warrington, Cheshire, WA3 YN, UK). Herbicides were applied with a custom-built unit, designed specifically for use in plot experiments. The sprayer was equipped with shields and HARDI ISO LD-110 LowDrift nozzles (RAJ & Associates, Crystal River, FL, USA); carrier volume was 150 L ha^{-1}, boom height was approximately 0.5 m, and pressure was 360 kPa.

Data Collection

Data collected throughout these experiments included crop density, ambient weed density, surrogate weed density, crop biomass, intrarow surrogate weed biomass, intrarow ambient weed biomass, crop yield, grain protein content, grain bulk density, and 1,000-kernel weight (TKW; g). To avoid edge effects, samples were not collected from the outermost rows on either side of each plot or the first 50 cm at the top and bottom of each plot. Achieved in-field densities of the spring barley crop, surrogate weeds, and ambient weeds were recorded before implementing herbicide or interrow hoeing treatments. All crop and weed density (plants m^{-2})

Table 1. Summary of dates, and crop (barley), surrogate weed (*Sinapis alba*), and ambient weed growth stages at the implementation times of critical field operations and data-collection events performed in 2019 (EXP_{2019}) and 2020 (EXP_{2020}).

Experiment	Field operations and data-collection events	Date	Crop growth stage[a]	Surrogate weed growth stage[b]	Ambient weed growth stage[c]
EXP_{2019}	Fertilize	April 10	—	—	—
	Plant crop and surrogate weeds	April 16	—	—	—
	Preemergence tine harrowing	April 24	5–7	8–10	5–10
	Crop stand count	May 2–3	12	10–12	10–13
	Surrogate weed count	May 7–8	12–13	10–12	10–13
	Ambient weed count	May 14	14, 21–22	10–12	10–16
	Herbicide application	May 15	14, 21–22	10–14	10–16
	Interrow hoeing	May 16	14, 21–22	10–14	10–16
	Fungicide application	June 19	49	—	—
	Crop, surrogate weed, and ambient weed biomass sampling	June 27–July 2	73–75	67–69	—
	Thistle stand count	July 26	85–87	—	—
	Barley crop harvest	August 22	89	97	—
EXP_{2020}	Fertilize	March 31	—	—	—
	Plant crop and surrogate weeds	April 7	—	—	—
	Preemergence tine harrowing	April 16	3–6	5–10	5–10
	Crop stand count	April 29–May 1	13, 20–21	12	10–14
	Surrogate weed count	May 3–6	13, 20–21	12	10–14
	Ambient weed count	May 3–6	13, 20–21	12	10–14
	Interrow hoeing	May 7	13–14, 20–22	13	10–16
	Herbicide application	May 13	13–14, 20–22	13	10–16
	Crop, surrogate weed, and ambient weed biomass sampling	June 23–24	61	67–69	—
	Thistle stand count	July 21	85–87	—	—
	Barley crop harvest	August 12	89	—	—

[a]Barley growth stages are reported according to Lancashire et al. (1991) BBCH decimal codes.
[b]Surrogate weed (*Sinapis alba*) growth stages are reported according to Lancashire et al. (1991) BBCH decimal codes.
[c]Ambient weed (assorted species) growth stages are reported according to Hess et al. (1997) BBCH decimal code.

measures were carried out in 7 by 100 cm quadrats, centered on random sections of crop rows. For all treatments, interrow hoeing was implemented 3.5 cm from either side of the crop row, resulting in an uncultivated 7-cm-wide zone defining the intrarow zone for all data-collection purposes. In each plot, crop densities were recorded within four quadrats, intrarow surrogate weed densities were recorded within two quadrats in the surrogate weed strips, and intrarow ambient weed densities were recorded by species within four quadrats. Weed density counts were not performed in the interrow zone, because the focus of this study is to evaluate intrarow weed effects only.

Intrarow crop, surrogate weed, and ambient weed biomass samples were cut from six (7 by 100 cm) quadrats per plot. In $WMT_{herbicide}$ plots, six cuts were made randomly throughout the plot and combined into a single sample. In WMT_{weedy} and $WMT_{tineharrow}$ plots, four biomass cuts were made outside the surrogate weed strip, and two cuts were made inside the surrogate weed strip; samples from these two zones were kept separate. All plant biomass samples were divided into three categories: (1) crop, (2) surrogate weeds, and (3) ambient weeds. Samples were dried for at least 24 h at a temperature of 80 C and then weighed to obtain plant biomass dry matter measures.

Before barley was harvested, 50 cm from the ends of each plot was cut away, as was the surrogate weed strip in each plot's center. Because the plot width was wider than the combine head, the outermost rows on either side of each plot were not harvested. Final plot length and number of rows were recorded, and crop yields (kg ha^{-1}) were calculated based on harvested area. Harvested grain was cleaned, and final yield weights were standardized to 15% moisture content. Barley grain quality measures were obtained following harvest. Protein content (%) and bulk density (kg hl^{-1}) were measured for a subsample of whole barley grains using a near-infrared spectroscopy analyzer (Infratec^{TM} 1241 Grain Analyzer, Foss A/S, Nils Foss Allé 1, 3400 Hilleroed, Denmark; Buchmann et al. 2001), and TKWs (g) were extrapolated from an average of four 200-kernel weight measures taken per plot. Temperature and precipitation data were retrieved from the Danish Meteorological Institute's weather station located in Flakkebjerg, Denmark (DMI 2022).

Analysis

Experiments possessed an additive design, meaning that for every combination of weed management strategy and row spacing tested, all four levels of the continuous variable, crop density, were represented, thus permitting analysis via linear and nonlinear regression. Notably, data were analyzed separately for each year (EXP_{2019} and EXP_{2020}). In both years, low crop and surrogate weed densities were observed among five plots possessing the same experimental footprint; plant density measures from each of these plots qualified as outliers, and data were excluded from analyses. Inadequate seedbeds resulting from an outcropping of stones within the field are the likely culprit for poor establishment.

Mixed model variables for the analysis of crop- and weed-response data included the random term, block, as well as fixed terms, crop density, row spacing, weed management treatment, crop density by row spacing, crop density by weed management treatment, row spacing by weed management treatment, and crop density by row spacing by weed management treatment. In all cases, achieved in-field crop density (plants m^{-2}) per plot served as the continuous explanatory variable during analysis.

Crop-related effects were analyzed using a linear function, and weed-related effects were analyzed using exponential functions. The fit of all regression models was confirmed via the visual assessment of plotted data points and residuals by predicted plots. In addition, comparisons of regression and ANOVA models were made via lack of fit tests, properly classifying crop density as a continuous or categorical explanatory variable (Ritz et al. 2015).

First, full models were fit, initially consisting of 6 lines (2 interrow spacings × 3 weed management treatments) with 12 corresponding parameter estimates for the analyses of crop-related effects, and 4 curves (2 interrow spacings × 2 weed management treatments) with 8 corresponding parameter estimates for analyses of weed-related effects. Second, each model was reduced stepwise, omitting all factors that had no significant effect on parameter estimates ($P \geq 0.05$; stepwise reduction procedures are detailed below). Thus, for each figure and table presented, treatments described by the same regression line and parameter estimates are not statistically different, and treatments described by differing regression lines and parameter estimates are statistically different.

Across all data sets, the assumption of normally distributed residuals was evaluated using the Shapiro-Wilk test (Shapiro and Wilk 1965). In the presence of a linear or curvilinear relationship, homoscedasticity was assessed via the visual inspection of residuals by predicted plots. In the absence of a linear or curvilinear relationship, homoscedasticity was assessed using the Levene test (Levene 1960). To resolve issues of nonnormality or heteroscedasticity, log and $\log(x+1)$ transformations were implemented using the transform-both-sides method.

Linear regressions correctly described the relationship between crop density and all crop-related effects, except for spring barley yield in EXP_{2019} and EXP_{2020}, in which cases three-way ANOVAs were carried out, wherein crop density was treated as a categorical variable, and subsequent means comparisons via Tukey's HSD were made ($\alpha = 0.05$). In all other instances, the relationship between crop density and crop-related effects, $f_1\ (x)$, including spring barley biomass, grain protein, grain bulk density, and TKW, were described using the linear model:

$$f_1\ (x) = a_{(rw)} + b_{(rw)}*c \qquad r = 1,2;\ w = 1,2,3 \qquad [1]$$

where a represents the level of the dependent crop measure when crop density equals zero, b is the change in crop measure as crop density increases, and c is crop density; $r1$ and $r2$ represent RS_{15} and RS_{20}, and $w1$, $w2$, and $w3$ represent WMT_{weedy}, $WMT_{tineharrow}$, and $WMT_{herbicide}$, respectively. Crop response data sets were analyzed with the restricted maximum-likelihood approach in JMP® (version Pro 15.0.0, SAS Institute, Cary, NC, USA). Stepwise model reduction was warranted by nonsignificant effect tests ($P \geq 0.05$) and reductions in the model Akaike information criterion (AIC).

Curvilinear relationships between crop density and weed-related effects were also confirmed via the visual assessment of plotted data points and residuals by predicted plots for the fitted regression model. In all cases, the relationship between crop density and weed biomass measures, $f_2\ (x)$, including surrogate and ambient weed biomass, was described using the exponential function:

$$f_2\ (x) = d_{(rw)}*exp\ \left(-e_{(rw)}*c\right) \qquad r = 1,2;\ w = 1,2 \qquad [2]$$

where d represents the amount of weed biomass when crop density equals zero, and e is the rate of weed biomass reduction as crop density increases.

Table 2. Mean spring barley crop densities achieved in 2019 (EXP_{2019}) and 2020 (EXP_{2020}) across treatment plots with target densities of 200 (CD_{200}), 300 (CD_{300}), 400 (CD_{400}), and 500 (CD_{500}) plants m^{-2}.

Experiment	Treatment	Crop density[a]	
		no. m^{-2}	
EXP_{2019}	CD_{200}	224	(±6)
	CD_{300}	317	(±8)
	CD_{400}	419	(±10)
	CD_{500}	538	(±14)
EXP_{2020}	CD_{200}	159	(±5)
	CD_{300}	248	(±6)
	CD_{400}	315	(±13)
	CD_{500}	379	(±15)

[a]SEs are presented in parentheses.

Percent reduction in weed biomass as crop density increases, $f_3\ (x)$, can then be calculated using the function:

$$f_3\ (x) = 100\ \left[1 - exp\left(-e_{(rw)}*c\right)\right] \qquad r = 1,2;\ w = 1,2 \qquad [3]$$

Weed biomass data were analyzed using the nonlinear mixed model PROC NLMIXED in SAS® (v. 9.4, SAS Institute, Cary, NC, USA). Contrasts among parameter estimates, changes in model AIC, and nonsignificant likelihood-ratio tests ($P \geq 0.05$) guided stepwise model reduction.

Results and Discussion

An adequate range of spring barley densities (plants m^{-2}) were achieved in both years (Table 2). While populations were lower than expected in EXP_{2020}, crop densities ranging from 109 to 493 plants m^{-2} were observed, sufficient for conducting the intended analyses. Achieved surrogate weed densities were 51 (±6) plants m^{-2} in EXP_{2019} and 49 (±2) plants m^{-2} in EXP_{2020} (data not shown), comparable to the target of 40 plants m^{-2}. In EXP_{2019}, the average within-field ambient weed density was 531 (±14) plants m^{-2}, with the three most abundant ambient weed species being common lambsquarters (*Chenopodium album* L.), speedwell (*Veronica* sp.), and common chickweed [*Stellaria media* (L.) Vill.], comprising 55%, 11%, and 10% of weed seedlings, respectively. In EXP_{2020}, average ambient weed density was 353 (±6) plants m^{-2}, 61% *C. album*, 11% prostrate knotweed (*Polygonum aviculare* L.), and 7% mustard (*Brassica* sp.) were present.

Average monthly temperatures from April to August, when experiments were implemented, were comparable with one another and with the 10-year average (Supplementary Table 1). Differences in monthly precipitation totals for EXP_{2019} and EXP_{2020} are not presumed to have impacted experimental outcomes, with the exception of there being 70% less rainfall in May 2020 compared with May 2019 (Supplementary Table 2), which likely affected preemergence tine-harrowing efficacy; this is addressed in the following section.

Intrarow Weed Biomass

Outcomes from the present study support our central hypothesis; increasing crop density reliably reduced intrarow surrogate (Figure 1; Table 3) and ambient weed biomass (Figure 2; Table 4) within the hoed cereal system. Our findings complement effects summarized by Mohler (2001), who found that increasing crop density consistently decreased weed biomass across the inter- and intrarow zones among 12 experiments in barley. Notably, the

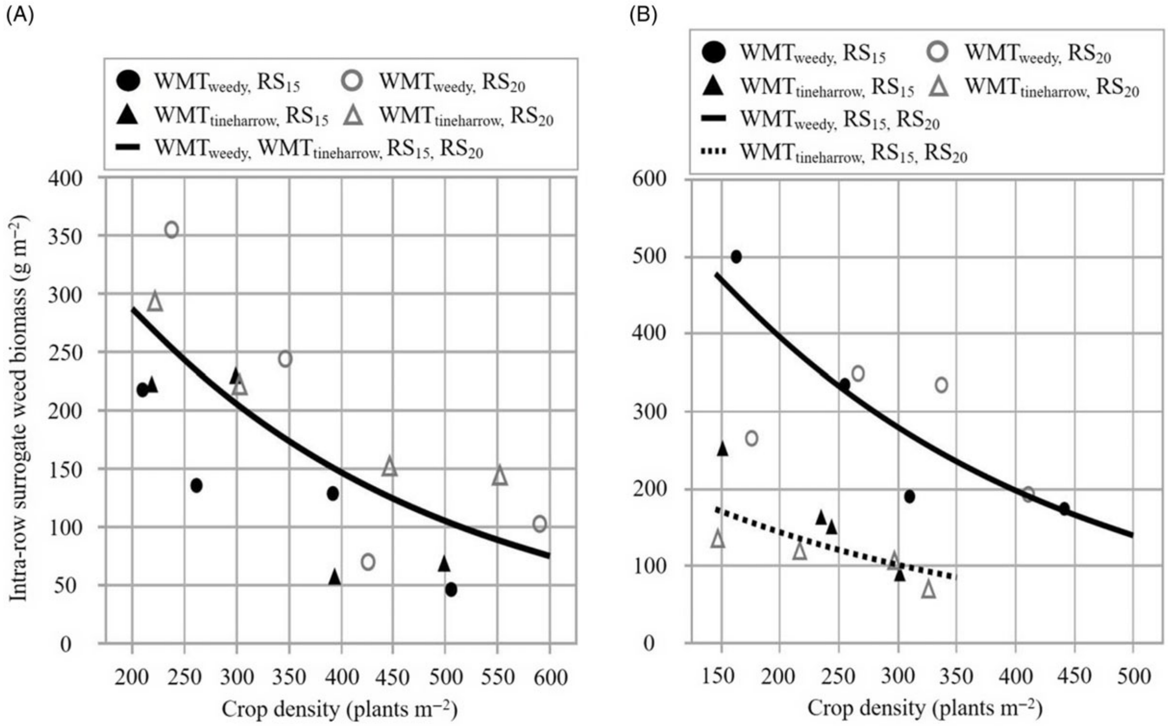

Figure 1. The relationship between intrarow surrogate weed biomass (g m^{-2}; *Sinapis alba*) and crop density (plants m^{-2}; barley). Observed values represent back-transformed means for two row spacings, 15 cm (RS_{15}) and 20 cm (RS_{20}), and two weed management treatments, receiving no additional weed management treatment (WMT_{weedy}) and preemergence tine harrowing ($WMT_{tineharrow}$), in 2019 (A, EXP_{2019}) and 2020 (B, EXP_{2020}). All plots received interrow hoeing. Data underwent a $\log(x+1)$ transformation.

rate of intrarow weed biomass reduction (parameter e in Equations 2 and 3) was very similar across years, irrespective of weed management treatment and row spacing (Figure 3). The only instance where e deviated considerably was for EXP_{2019} ambient weed biomass in $WMT_{tineharrow}$ RS_{15} plots, when the parameter was 2.26 to 2.64 times greater compared with other estimates (Table 4). Excluding EXP_{2019} $WMT_{tineharrow}$ RS_{15} ambient weed biomass results, within the range of crop densities tested (CD_{200} to CD_{500}), intrarow surrogate and ambient weed biomass were reduced by 49% to 82% and 53 to 86%, respectively (Figure 3). The effect that increasing seeding rate has on suppressing intrarow weeds is an important result, one that improves our understanding of how to limit potential yield and crop quality losses resulting from remaining competitive intrarow weeds in hoed cereals (Melander and McCollough 2020).

Percent reduction of intrarow weed biomass was slightly higher for ambient weeds compared with surrogate weeds, comprising differences of 4.5% and 4.3% at CD_{300} in EXP_{2019} and EXP_{2020}, respectively. The difference in response can be attributed to variation among ambient and surrogate weed groups in their competitive response and timing of weed seedling emergence relative to crop emergence (Håkansson 2003). The ambient group is composed of numerous annual weeds differing in emergence periodicity and competitive ability; both tall and low-growing weeds were among the three most abundant species in each year. In contrast, the surrogate weed, *S. alba*, was selected to ensure a uniform stand of competitive brassica species, possessing a tall and erect growth habit and resembling problematic wild weeds common in organic cereals: wild radish (*Raphanus raphanistrum* L.), field mustard (*Brassica rapa* L.), and charlock mustard (*Sinapis arvensis* L.). Studies evaluating the effects of crop density on weed biomass originating from both intra- and interrow zones have also observed greater control among weeds emerging later than the crop and less competitive species (Håkansson 2003); therefore, it is unsurprising to observe a similar effect here. The response of both ambient and surrogate weeds is very similar; this strongly suggests that increasing crop density is a reliable management strategy for suppressing intrarow weeds of varying morphologies and competitive abilities.

Notably, the greatest reductions in intrarow weed biomass are achieved by increasing from low to moderate crop densities, with diminishing returns as seeding rate increased. For example, excluding EXP_{2019} $WMT_{tineharrow}$ RS_{15} ambient weed biomass data and rounding to the nearest whole number among all other treatments, increasing from CD_{200} to CD_{300} reduces intrarow surrogate and ambient weed biomass by 15%, whereas increasing from CD_{300} to CD_{400} and CD_{400} to CD_{500} corresponds with 10% and 7% reductions, respectively. Although an economic evaluation is not within the scope of the present study, the severity of weed infestation will determine whether increasing crop density beyond the standard 300 plants m^{-2} is viable. For example, in organic spring barley, Kolb et al. (2010) reported that due to the high cost of organic seed, increasing seeding rate as a weed control strategy was only economically viable in situations where weed density was high.

The effect of preemergence tine harrowing on weeds was variable among years. In EXP_{2020}, $WMT_{tineharrow}$ reduced surrogate weed density and ambient weed density by 43% ($P < 0.0001$; data not shown) and 20% ($P = 0.0003$; data not shown) relative to WMT_{weedy}, respectively. This decrease in weed density corresponded with a decrease in intrarow surrogate (Figure 1; Table 3) and ambient weed biomass (Figure 2; Table 4) of 64% and 52%, respectively, at CD_{300}. In EXP_{2019}, $WMT_{tineharrow}$ did not reduce surrogate or ambient weed density relative to WMT_{weedy} ($P \geq 0.05$; data not shown). Intrarow surrogate weed biomass was not affected by weed management treatment

Table 3. Estimates of parameters *d* and *e* for intrarow surrogate weed (*Sinapis alba*) biomass from Equation 2, where *d* represents the amount of weed biomass when crop density equals zero, and *e* is the rate of weed biomass reduction as crop density increases.[a]

Experiment	Treatment		Intrarow surrogate weed biomass	
			d	*e*
			g m^{-2}	g m^{-2} plant^{-1}
EXP_{2019}	RS_{15}	WMT_{weedy}	562.3	0.00335
	RS_{15}	$WMT_{tineharrow}$	562.3	0.00335
	RS_{20}	WMT_{weedy}	562.3	0.00335
	RS_{20}	$WMT_{tineharrow}$	562.3	0.00335
EXP_{2020}	RS_{15}	WMT_{weedy}	791.6	0.00347
	RS_{15}	$WMT_{tineharrow}$	287.6	0.00347
	RS_{20}	WMT_{weedy}	791.6	0.00347
	RS_{20}	$WMT_{tineharrow}$	287.6	0.00347

[a]Parameter estimates of the reduced model are shown for experiments performed in 2019 (EXP_{2019}) and 2020 (EXP_{2020}) among plots sown to 15 cm (RS_{15}) and 20 cm (RS_{20}) row spacings, receiving no additional weed management treatment (WMT_{weedy}), and pre-emergence tine harrowing ($WMT_{tineharrow}$). All plots received inter-row hoeing. Data underwent a log $(x + 1)$ transformation.

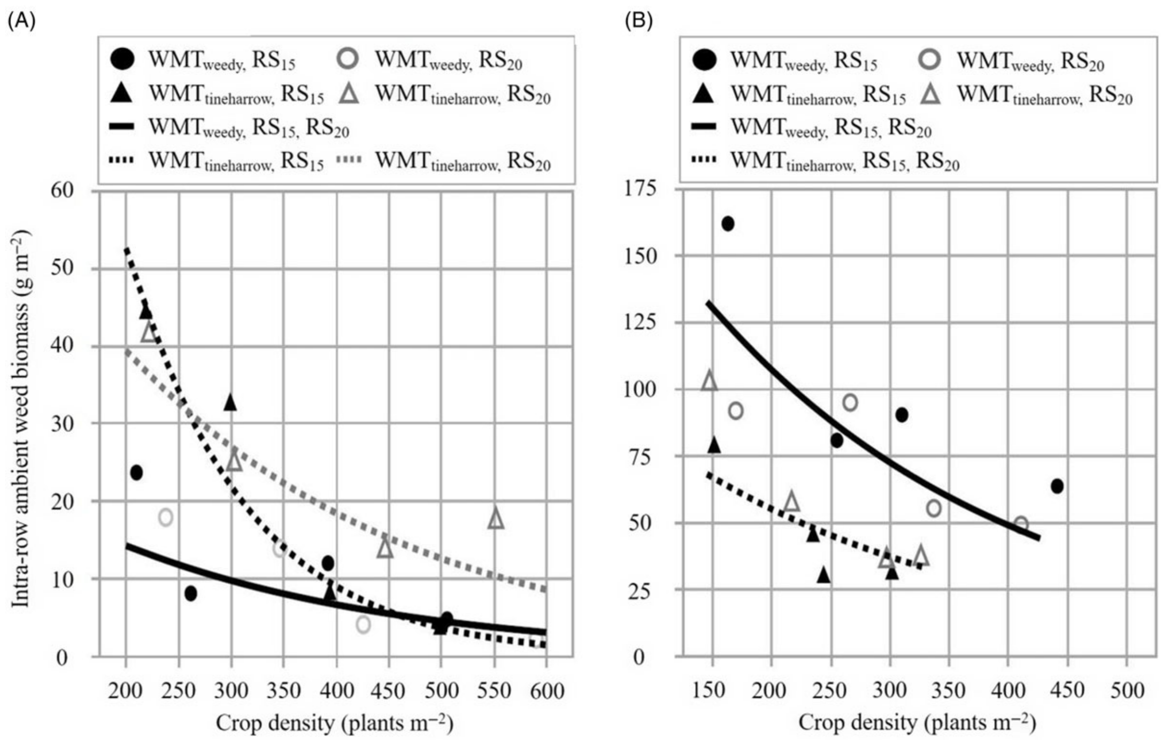

Figure 2. The relationship between intrarow ambient weed biomass (g m^{-2}; assorted species) and crop density (plants m^{-2}; barley). Observed values represent back-transformed means for two row spacings, 15 cm (RS_{15}) and 20 cm (RS_{20}), and two weed management treatments, receiving no additional weed management treatment (WMT_{weedy}) and preemergence tine harrowing ($WMT_{tineharrow}$), in 2019 (A, EXP_{2019}) and 2020 (B, EXP_{2020}). All plots received interrow hoeing. Data underwent a log$(x + 1)$ transformation.

(Figure 1; Table 3), and a 175% increase in ambient weed biomass was observed at CD_{300} for $WMT_{tineharrow}$ RS_{20} when compared with WMT_{weedy} RS_{15} and RS_{20} plots (Figure 2; Table 4). Divergent results are emblematic of the variability in treatment outcomes resulting from tine harrowing. The success of harrowing partially depends on weed community composition; both the presence of established weed seedlings before crop emergence and the absence of late-emerging weeds (Lundkvist 2009). Field and weather conditions also play a decisive role in determining weed establishment before harrowing. Harrowing may be an effective weed management strategy, killing 21% to 90% of weed seedlings present (Gallandt et al. 2018; Jabran et al. 2017); however, the uniform shallow soil disturbance caused by tine harrowing can also stimulate weed seed germination (Cirujeda and Taberner 2004; Kees 1962), especially if precipitation follows cultivation. In both experimental years, rainfall likely affected the efficacy of preemergence tine harrowing. Low precipitation in May 2020 (63% less than the 10-yr average; Supplementary Table 2), following preemergence tine harrowing (Table 1), likely contributed to the positive outcome of reduced intrarow ambient weed biomass in EXP_{2020} $WMT_{tineharrow}$ plots. In May 2019, total precipitation was 231% greater compared with May 2020, likely contributing the increase in ambient weed biomass observed among EXP_{2019} $WMT_{tineharrow}$ plots.

Notably, ambient weed biomass in $WMT_{tineharrow}$ RS_{15} plots responded differently from $WMT_{tineharrow}$ RS_{20} in EXP_{2019}; this

Table 4. Estimates of parameters *d* and *e* for intrarow ambient weed (assorted species) biomass from Equation 2, where *d* represents the amount of weed biomass when crop density equals zero, and *e* is the rate of weed biomass reduction as crop density increases.[a]

Experiment	Treatment		Intrarow ambient weed biomass	
			d	*e*
			g m^{-2}	g m^{-2} plant^{-1}
EXP_{2019}	RS_{15}	WMT_{weedy}	30.65	0.00380
	RS_{15}	$WMT_{tineharrow}$	312.6	0.00885
	RS_{20}	WMT_{weedy}	30.65	0.00380
	RS_{20}	$WMT_{tineharrow}$	84.46	0.00380
EXP_{2020}	RS_{15}	WMT_{weedy}	248.4	0.00391
	RS_{15}	$WMT_{tineharrow}$	120.4	0.00391
	RS_{20}	WMT_{weedy}	248.4	0.00391
	RS_{20}	$WMT_{tineharrow}$	120.4	0.00391

[a]Parameter estimates of the reduced model are shown for experiments performed in 2019 (EXP_{2019}) and 2020 (EXP_{2020}) among plots sown to 15-cm (RS_{15}) and 20-cm (RS_{20}) row spacings, receiving no additional weed management treatment (WMT_{weedy}), and preemergence tine harrowing ($WMT_{tineharrow}$). All plots received interrow hoeing. Data underwent a $\log(x + 1)$ transformation.

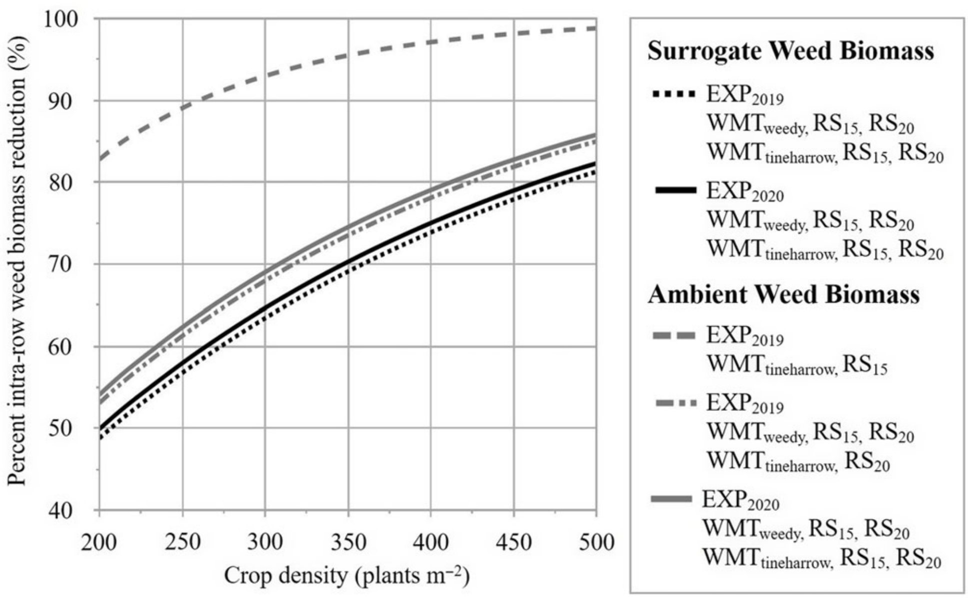

Figure 3. Prediction of percent reduction (%) in intrarow surrogate (gray; *Sinapis alba*) and ambient weed biomass (black; assorted species) as crop density (plants m^{-2}; barley) increases. Curves are calculated on the basis of parameter estimates in Tables 3 and 4 for two row spacings, 15 cm (RS_{15}) and 20 cm (RS_{20}), and two weed management treatments, receiving no additional weed management treatment (WMT_{weedy}) and preemergence tine harrowing ($WMT_{tineharrow}$), in 2019 (dotted; EXP_{2019}) and 2020 (solid; EXP_{2020}). All plots received interrow hoeing.

is the only instance where row spacing impacted weed biomass. In this case, an interaction was present between row spacing and weed management treatment, whereby *e*, the rate of ambient weed biomass decline in response to increasing crop density, was estimated to be far greater than all other treatments (Figures 2 and 3; Table 4).

While decreasing row spacing is an effective method for suppressing the growth of weeds (Mohler 2001; Regnier and Bakelana 1995); the effect of increasing crop density from 200 to 500 plants m^{-2} should be far greater than that of reducing interrow row distance by 5 cm (Zimdahl 2004), as was observed in the present study. Also, the weed suppressive effect of decreasing row spacing within hoed cereals may be less significant when compared with instances in which full-width tine harrowing or no additional direct control tactics are used (Rasmussen and Svenningsen 1994). When interrow weeds are controlled by hoeing, increasing row spacing while maintaining seeding rate has opposing effects on intrarow weeds, simultaneously (1) delaying crop canopy closure and increasing light penetration into the intrarow zone (Kolb et al. 2012) and (2) increasing intrarow crop density and the crop's competitive advantage over weeds. Because light capture is a primary driver of competition in cereals (Didon and Boström 2003), wide row sowing in hoed cereals can improve growth among surviving intrarow weeds (Kolb et al. 2010; McCollough et al. 2020a).

Crop Yield and Biomass

Spring barley yield (kg ha^{-1}) did not increase with increasing crop density in either year. While a lack of relationship between crop yield and crop density is unexpected (Mohler 2001), it is not unfounded (O'Donovan et al. 2011; Pageau 1991). Spring barley has the capacity to tiller readily, which contributes to the crop's ability to stabilize yield. As crop density increases, the number of tillers per plant (Simmons et al. 1982), fertile heads per plant, and kernels per head decrease (Pageau 1991; Thomason et al. 2009). Due to a lack of yield response in the present study, we cannot recommend optimized seeding rates for hoed cereals based on

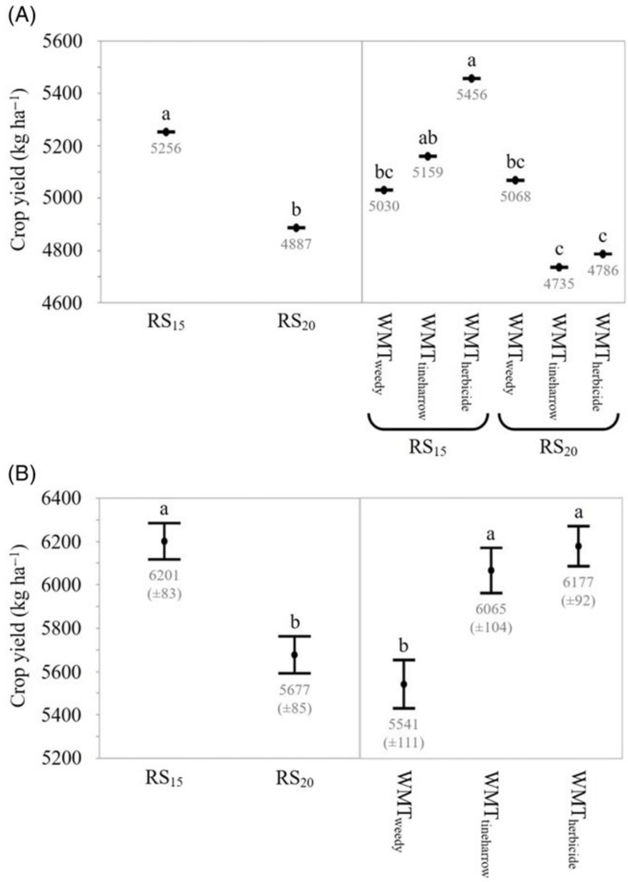

Figure 4. The effect of row spacing and weed management treatment on crop yield (g m^{-2}; barley). Crop density (plants m^{-2}) did not affect crop yield in either site year. Observed values represent means of the reduced model for two row spacings, 15 cm (RS_{15}) and 20 cm (RS_{20}), and three weed management treatments, receiving treatment with herbicide ($WMT_{herbicide}$), no additional weed management treatment (WMT_{weedy}), and preemergence tine harrowing ($WMT_{tineharrow}$), in 2019 (A, EXP_{2019}) and 2020 (B, EXP_{2020}). All plots received interrow hoeing. EXP_{2019} data underwent a log_{10} transformation; back-transformed means are presented.

Mohler's (2001, p. 276) definition, that optimal density is achieved when "a further increment of seed costs more than the expected increase in yield is worth." Instead of optimizing for economic return, increasing seed costs must be weighed against other favorable outcomes, including reduced weed biomass and possible weed seedbank withdrawals (Jabbour et al. 2017; Liebman and Gallandt 1997).

The main effect of row spacing was consistent across years; RS_{20} yields were on average lower than RS_{15} by 7% in EXP_{2019} and 8% in EXP_{2020} (Figure 4). Yield loss at RS_{20} can be attributed to the intensification of intrarow crowding and intraspecific competition as row spacing increases and density is maintained (Weiner et al. 2001). For example, as row spacing widened from RS_{15} to RS_{20} within the present study, crop density in the intrarow zone would be expected to increase by 33%. See Supplementary Table 3 comparing full-width and intrarow target and achieved crop densities for RS_{15} and RS_{20} plots. Sowing at narrower row spacings typically improves crop yields; however, the effect can be inconsistent (Mohler 2001). Olsen et al. (2004) proposed that the intensity of intraspecific competition resulting from wide row sowing is reduced as weed density decreases due to the improved ability of the crop to readily access interrow resources when weeds are absent. However, in EXP_{2019}, when an interaction between row spacing and weed management treatment was present, yield loss resulting from increasing interrow spacing was greatest in $WMT_{herbicide}$ plots. Crop yields at RS_{20} were 8% and 12% less than at RS_{15} in $WMT_{tineharrow}$ $WMT_{herbicide}$, respectively, and no difference was observed among row spacings for WMT_{weedy}. In EXP_{2019}, crop yield in RS_{15} $WMT_{herbicide}$ was also 8% greater than in RS_{15} $WMT_{tineharrow}$. Results that diverge from the scenario described by Olsen et al. (2004) reflect our working within the hoed cereal system; interrow weeds are controlled across weed management treatments with aggressive cultivation, diminishing the expected benefits of herbicide use. In EXP_{2020}, an effect of weed management treatment was present: crop yields in $WMT_{tineharrow}$ and $WMT_{herbicide}$ were 9% and 10% less than in WMT_{weedy}, respectively; this outcome was not expected.

Crop biomass (g m^{-2}) was unaffected by treatment variables in EXP_{2019}. Again, spring barley's plasticity and tillering capacity likely contributed to the absence of expected effects in this year. In $EXP_{2020,}$ in alignment with expected outcomes (Håkansson 2003), barley biomass increased with increasing crop density at a rate of 35.5 g m^{-2} per 100 plants m^{-2} (Supplementary Figure 1; Supplementary Table 4). Crop biomass was also 6% greater in $WMT_{herbicide}$ plots than in WMT_{weedy} and $WMT_{tineharrow}$. Crop biomass did not, however, differ among row spacings tested.

Grain Quality Parameters

Grain protein (%) in EXP_{2019} decreased slightly in response to increasing crop density, at a rate of −0.12% per 100 plants m^{-2}; however, no correlation was observed in EXP_{2020} (Supplementary Figure 2; Supplementary Table 5). While it was expected that grain protein would decline with increasing crop density due to the intensification of intraspecific competition, both negative and null effects among cereals have been observed (Boström et al. 2012; McKenzie et al. 2005). Weed management treatment did not affect grain protein in EXP_{2019}, whereas in EXP_{2020}, protein was reduced by 3% and 2% in $WMT_{tineharrow}$ plots compared with WMT_{weedy} and $WMT_{herbicide}$, respectively. In addition, row spacing did not influence grain protein in either year. Increases in grain protein among cereal crops at wider interrow spacings have been reported, likely due to a corresponding increase in nutrient availability (Boström et al. 2012; Hiltbrunner et al. 2005; Siemens 1963); however, a difference in interrow spacing of 5 cm may not be enough to see results. The interpretation of protein response depends upon the crop's intended use. To meet malting barley quality standards in Europe, grain protein must fall within the range of 9.5% to 11.5% (Pettersson 2006); whereas, barley exceeding 11.5% is regularly sold as livestock feed (Bhatty et al. 1974). Notably, there is a financial incentive to achieve malting quality; selling price was 15% greater than for feed barley in 2020 among reporting member states of the European Union (EuroStat 2021). Given that surplus protein often prevents growers from achieving malting quality standards (Mills et al. 2021), a reduction in protein may be interpreted as a positive effect in many cases.

Barley TKW (g) response to increasing crop density (parameter *b*) differed among weed management treatments in EXP_{2019} (Figure 5; Table 5). An increase in 100 plants m^{-2} corresponded with a TKW increase of 0.97 g and 0.35 g in WMT_{weedy} and $WMT_{tineharrow}$ treatments, respectively; however, for $WMT_{herbicide}$, a slight decrease of −0.27 g per 100 plants m^{-2} was observed. TKW is expected to decline in the absence of weeds

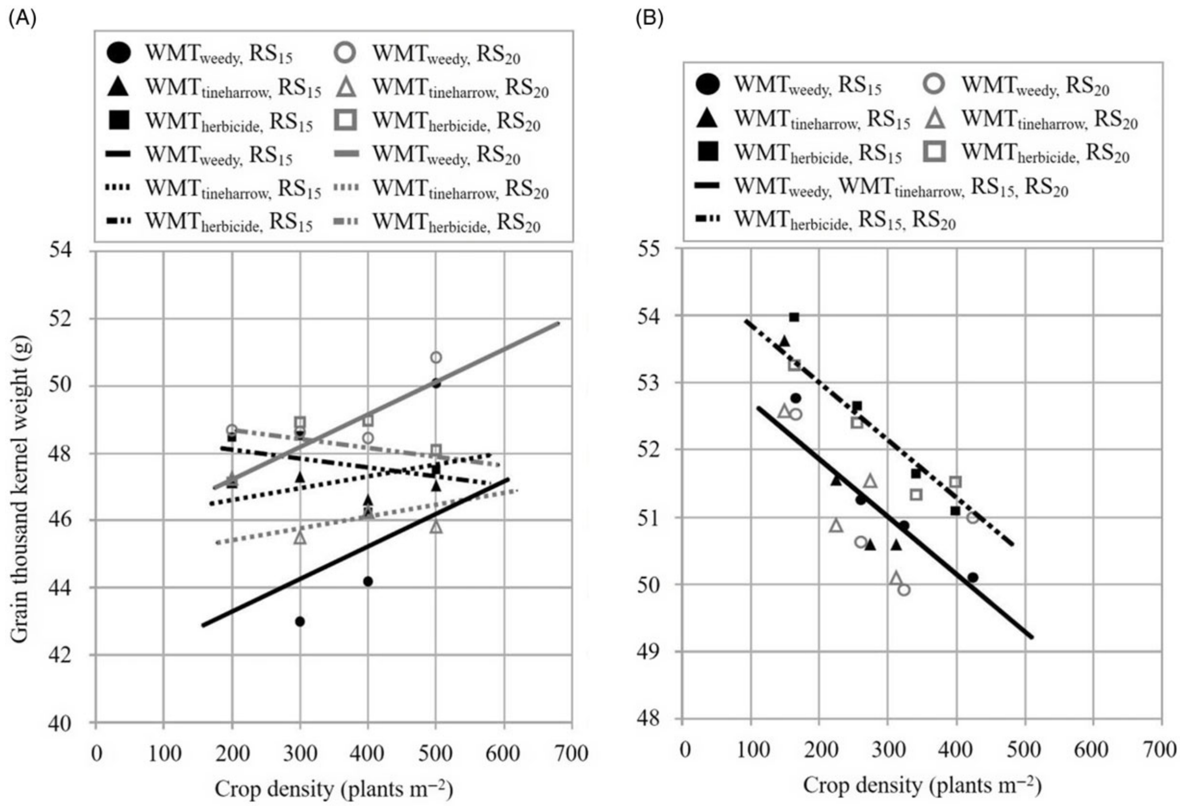

Figure 5. The relationship between grain 1,000-kernel weight (g; barley) and crop density (plants m^{-2}). Observed values represent means for two row spacings, 15 cm (RS_{15}) and 20 cm (RS_{20}), and three weed management treatments, receiving treatment with herbicide ($WMT_{herbicide}$), no additional weed management treatment (WMT_{weedy}), and preemergence tine harrowing ($WMT_{tineharrow}$), in 2019 (A, EXP_{2019}) and 2020 (B, EXP_{2020}). All plots received interrow hoeing.

as crop density and intraspecific competition increase (Mills et al. 2021; O'Donovan et al. 2012). However, in the presence of weeds, the negative effects of increasing crop density may be offset by the suppression of intrarow weeds. Melander and McCollough's (2020) results indicate that an increase in intrarow weed density has a greater negative impact on barley TKW than increasing crop density; as the intrarow surrogate weed *S. alba* increased by 100 plants m^{-2}, a decrease in TKW of 1.4 to 3.2 g was observed. In the present study, TKW response to row spacing differed among weed management treatments; as row spacing increased, TKW decreased in $WMT_{tineharrow}$ and increased in WMT_{weedy} and $WMT_{herbicide}$. The observed increase in TKW as row spacing increased from RS_{15} to RS_{20} was also 5.8 times greater in WMT_{weedy} than $WMT_{herbicide}$. Inconsistent effects of row spacing on barley TKW have been previously reported (Melander et al. 2018), with both positive (Siemens 1963) and negative (Pageau 1991) effects observed. In EXP_{2020}, differences in *b* were not observed; across treatments, TKW decreased at a rate of −0.86 g per 100 plants m^{-2}. Less ambient weed biomass overall in EXP_{2019} may also help to explain stronger TKW effects in EXP_{2020}. On average, TKW was 2% greater in $WMT_{herbicide}$ plots than in WMT_{weedy} and $WMT_{tineharrow}$, and no differences among row spacings were observed.

Grain bulk density (kg hl^{-1}) decreased with increasing crop density in both years, an increase in crop density of 100 plants m^{-2} corresponded with a reduction of −0.606 in EXP_{2019} and −0.541 kg hl^{-1} in EXP_{2020} (Supplementary Figure 3; Supplementary Table 6). Results are consistent with anticipated outcomes. Increasing a crop's population in-field typically has a negative effect on grain bulk density (Mills et al. 2021), although variable and null effects have also been observed (Pageau 1991; Thomason et al. 2009). In EXP_{2020}, grain bulk density was only slightly greater in $WMT_{herbicide}$ (1%) compared with WMT_{weedy} and $WMT_{tineharrow}$; row spacing had no effect in either year.

Additional Intrarow Weed Management Strategies in the Hoed Cereal System

In addition to preemergence tine harrowing and the adjustment of crop density and row spacing, other suitable intrarow weed management strategies exist for the hoed cereals system. Postemergence tine harrowing remains a valuable tactic to be used alone or in combination with preemergence harrowing (Brandsæter et al. 2012); however, crop damage (Lundkvist 2009) and variable efficacy (Gallandt et al. 2018; Jabran et al. 2017) exist as drawbacks to employing this tactic. Stacking hoeing and postemergence tine-harrowing cultivation events has shown promising results, providing some control in the intrarow zone while increasing efficacy in the interrow by 14% to 22% compared with hoeing alone (Gerhards et al. 2020). Combining hoeing and harrowing may also provide a greater boost in efficacy against taprooted weeds, such as scentless mayweed [*Tripleurospermum maritimum* ssp. *inodorum* (L.) Appleq.], than shallowly rooted weeds, such as *S. media* (Rasmussen and Sveningsen 1994).

Hoeing with rigid flat shares, as was done in the present study, limits sideward soil movement into the crop row, reducing crop soil cover and limiting intrarow weeds' burial (Machleb et al. 2018). In contrast, Gerhards et al. (2020) purposefully threw soil into the crop row by hoeing at high speeds with ducks-foot shares, achieving intrarow weed control of 21% to 54% when hoeing at

Table 5. Estimates of parameters *a* and *b* for spring barley grain 1,000-kernel weight (TKW) from Equation 1, where *a* represents TKW when crop density equals zero, and *b* is the change in TKW as crop density increases.

Experiment	Treatment		Grain TKW *a*	Grain TKW *b*
			g	g plant^{-1}
EXP_{2019}	RS_{15}	$WMT_{herbicide}$	50.64	−0.002644
	RS_{15}	WMT_{weedy}	43.36	0.009683
	RS_{15}	$WMT_{tineharrow}$	47.91	0.003519
	RS_{20}	$WMT_{herbicide}$	51.22	−0.002644
	RS_{20}	WMT_{weedy}	47.28	0.009683
	RS_{20}	$WMT_{tineharrow}$	46.71	0.003519
EXP_{2020}	RS_{15}	$WMT_{herbicide}$	54.71	−0.008563
	RS_{15}	WMT_{weedy}	53.57	−0.008563
	RS_{15}	$WMT_{tineharrow}$	53.57	−0.008563
	RS_{20}	$WMT_{herbicide}$	54.71	−0.008563
	RS_{20}	WMT_{weedy}	53.57	−0.008563
	RS_{20}	$WMT_{tineharrow}$	53.57	−0.008563

[a]Parameter estimates of the reduced model are shown for experiments performed in 2019 (EXP2019) and 2020 (EXP2020) among plots sown to 15-cm (RS15) and 20-cm (RS20) row spacings, receiving treatment with herbicide (WMTherbicide), no additional weed management treatment (WMTweedy), and preemergence tine harrowing (WMTtineharrow). All plots received interrow hoeing.

4 km h^{-1} and 31% to 91% at 8 km h^{-1}. Furthermore, the adoption of new technologies that enable the accurate operation of hoe blades closer to the crop row will also improve weed control by reducing the area of the uncultivated intrarow zone. To attain the degree of intrarow weed control cited earlier, Gerhards et al. (2020) used improved methods for row detection (Tillet et al. 2002). As a result, they successfully hoed between 15-cm rows with 10-cm shares, leaving a narrow uncultivated 5-cm intrarow zone.

A robust theoretical argument also exists for further optimizing the crop's spatial arrangement (Fischer and Miles 1973; Regnier and Bakelana 1995; Weiner et al. 2001). Instead of planting in standard rows where the crop is crowded into a narrow line, sowing in a random pattern within a 5- to 20-cm wide band may reduce competition among crop plants while increasing intraband weed suppression. However, outcomes have varied among studies evaluating band sowing and hoeing (McCollough et al. 2020a, 2020b; Speelman 1975), and further research is needed to validate the theoretical benefits of this strategy.

Methods evaluated in the present study are also highly relevant within integrated weed management (IWM). By combining herbicide use with physical and cultural control strategies (e.g., interrow hoeing, preemergence tine harrowing, and the alteration of crop density and row spacing), one can delay and reduce the risk of herbicide resistance developing (Riemens et al. 2022). For example, combining interrow hoeing and intrarow band spraying can effectively decrease herbicide use while maintaining crop yields (Abu-Hamdeh 2003; Loddo et al. 2020). Similarly, suppressing weed growth via the alteration of crop density and row spacing and implementing preemergence tine harrowing are each highly applicable for IWM programs.

In summary, increasing crop density is an effective and reliable method for controlling intrarow weeds in hoed cereals; both intrarow surrogate and ambient weed biomass were consistently reduced across years. However, increasing crop density did not improve crop yields and resulted in increased crop biomass in only one of two years. Because yield was not affected by increasing crop density, it is not possible to recommend an optimal seeding rate. It is also important to consider the effects that increasing crop density has on grain quality parameters; protein content and TKW were reduced by crop density increase in one of two years, whereas bulk density was negatively affected in both years. While increasing crop density may decrease average kernel size, malting quality may not be compromised; at higher seeding rates, barley grain kernels possess greater uniformity, an especially important quality parameter of malting barley (Edney et al. 2012; O'Donovan et al. 2011). While the observed decline in grain protein may be a negative outcome for growers producing animal feed, it is likely to be interpreted as beneficial for growers producing malting barley, for whom high protein content is often a limiting factor.

Results of preemergence tine harrowing were variable; both positive and negative effects were observed. Whether or not preemergence harrowing improves weed management outcomes will depend upon site-specific variables, including weather and soil conditions following sowing, crop growth stage, and weed species present.

Increasing interrow row spacing reduced barley yield consistently across years and did not reduce intrarow weeds. Improved yields represent an incentive for the manufacturers of automated hoeing equipment to continue to develop systems capable of accurately functioning at row spacings less than 20 cm. Higher yields may also serve as an incentive for growers to adopt narrow row sowing in the hoed cereal system once these technologies become available. In addition, furthering the advance of precision guidance equipment to function at standard row spacings of 12.5 cm would represent a significant accomplishment that would likely facilitate greater adoption of interrow hoeing among cereal growers.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2022.14

Acknowledgments. An immense amount of gratitude is extended to technicians Karen Bjørn Heinager and Eugene J. G. G. Driessen, without whom the success of this project would not have been possible. Thank you for your skilled assistance, dedication, and camaraderie. Thank you also to Betina Anitta Bendsten and Garth Douston, who assisted in processing biomass samples for experiments. Finally, this study was funded by the European Union's Horizon 2020 research and innovation program under grant agreement no. 727321 (project acronym: IWMPRAISE); we thank the funding body for its financial support. No conflicts of interest have been declared.

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