Received: 12 August 2020 | Accepted: 17 September 2020

DOI: 10.1111/wre.12452

ORIGINAL ARTICLE

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

WILEY

Influence of intra-row cruciferous surrogate weed growth on crop yield in organic spring cereals

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Funding information This study was part of the RowCrop project No 34009-13-0685 funded under Organic RDD 2 co-ordinated by the International Centre for Research in Organic Food Systems (ICROFS). The grant was provided by the Green Growth and Development Programme (GUDP) under the Danish Ministry of Environment and Food. Funding was also received from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727321 (project acronym, IWMPRAISE).

Subject Editor: Francesco Tei
University of Perugia, Perugia, Italy

Abstract

In Northern Europe, inter-row hoeing has become a popular tactic for controlling weeds in organic cereals. Hoeing is highly effective and can be implemented from crop emergence until stem elongation to maintain a nearly weed-free inter-row zone. However, hoeing has a lesser effect on weeds growing in the intra-row zone, where crop–weed proximity results in heightened competition. In the hoed cereal system, it is investigated whether tall-growing, competitive, cruciferous weeds in the intra-row zone affect crop biomass, yield and thousand kernel weight (TKW). An additive experimental design is employed to enable the fitting of rectangular hyperbolas, describing and quantifying the effects of increasing intra-row surrogate weed density on crop growth parameters. Regressions were studied under the influence of crop (spring barley and spring wheat), row spacing (narrow [12.5 or 15.0 cm] and wide [25.0 cm]) and nitrogen rate (50 and 100 kg NH_4-N/ha). Cruciferous surrogate weeds were found to impact crop yield and quality severely. For example, ten intra-row plants/m^2 of surrogate weed *Sinapis alba* reduced grains yields by 7%–14% in spring barley and by 7%–32% in spring wheat with yield losses becoming markedly greater in wheat compared to barley as weed density increases. Compared to wheat, barley limited yield and quality losses and suppressed intra-row weed growth more. Row spacing did not have a consistent effect on crop or weed parameters; in one of six experiments, the 25 cm row spacing reduced yields and increased intra-row weed biomass in wheat. Nitrogen rate did not affect crop or weed parameters. Results warrant the implementation of additional tactics to control intra-row weeds and limit crop losses.

KEYWORDS

crop, weed competition, *Hordeum vulgare* L., inter-row hoeing, inter-row spacing, nitrogen rate, thousand kernel weight, *Triticum aestivum* L.

1 | INTRODUCTION

The standard cropping strategy used to grow organic cereals in Northern Europe is to sow at an inter-row spacing of 12.5 cm; weeds are controlled physically by implementing both pre- and post-emergence weed harrowing. Pre-emergence harrowing is performed after sowing and before crop emergence, reducing the number of weeds that establish alongside the crop. Post-emergence harrowing is performed after crop emergence (Lundkvist, 2009; Rasmussen, 2004). Weed harrowing has both its advantages and disadvantages, as argued in Melander et al. (2018); variable efficacy, crop damage and potential yield loss are

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significant drawbacks that have motivated many growers to look for hoe-based solutions. Hoeing is more aggressive against weeds than harrowing, and the crop is not directly impacted by the weeding tool (Melander et al., 2018).

The practice of widening row spacings to distances ranging from 15 to 30 cm to accommodate inter-row hoeing with aggressive shares constitutes a recent topic of research (Kolb et al., 2010, 2012; McCollough et al., 2020; Melander et al., 2003, 2018). In the hoed system, cereals are cultivated much like a row crop; this practice has started to garner adoption as an improved weed management strategy among growers in Northern Europe. Not unlike the standard cropping strategy, there are both advantages and disadvantages associated with increasing inter-row spacing and hoeing in cereals.

Adverse field conditions have less impact on hoeing efficacy when compared with weed harrowing (Kolb et al., 2010, 2012). Compared to harrowing, hoeing is also more effective at controlling tall well-anchored weeds, including perennial and deeply rooted or taprooted species (Melander et al., 2003). Harrowing targets weeds across both inter- and intra-row zones. Hoeing, while highly effective in the inter-row zone (Melander et al., 2003, 2018), has a lesser effect on intra-row weeds (Vanhala et al. 2004). Elevating tractor speed and upward share angle can increase sideward soil movement and may control some small-sized intra-row weeds via burial (Kouwenhoven and Terpstra, 1979; Terpstra and Kouwenhoven, 1981). However, if one wishes to throw soil into the intra-row as a control tactic, the crop must be considerably taller than the weeds to avoid injury (Melander et al., 2018). The practice of wide-row sowing and hoeing has shown to effectively reduce weed biomass and may improve cereal yields when compared with standard cropping practices (Melander et al., 2018) dependent upon the severity of weed pressure (Kolb et al., 2010; Rasmussen, 2004). However, at wide-row spacings there is potential for reduced yields resulting from elevated intra-specific competition and non-optimal spatial utilisation of nutrients and water (Regnier and Bakelana 1995; Weiner et al., 2001); this effect seems particularly profound for conventionally grown cereals (Melander et al., 2003; Rasmussen, 2004).

As inter-row spacing increases, a larger proportion of soil surface area can be cultivated while hoeing, conceivably improving weed control. Melander et al. (2018) investigated the effects of altering both nitrogen rate and inter-row spacing in the hoed cereal system. Two nitrogen rates, commonly used for spring cereals on stockless arable farms (50 NH_4-N/ha) and dairy farms (100 kg NH_4-N/ha) in Denmark, and five inter-row spacings (12.5, 15, 20, 25 and 30 cm) were studied in spring barley (*Hordeum vulgare* L.) and spring wheat (*Triticum aestivum* L.). Improved weed control at wide inter-row spacings was not consistently observed, although increasing nitrogen rate resulted in a greater proportion of crop biomass relative to total plant biomass (crop + weeds).

Despite increasing adoption of inter-row hoeing in Northern Europe, questions remain as to whether weeds, persisting in the intra-row zone after inter-row hoeing, have significant effects on crop yield and quality. Personal communications with organic growers in Denmark who implement the hoed cereal system suggest the general belief is that intra-row weeds have negligible effects on the crop. This might hold true for weed species that are small in stature, such as *Veronica persica* Pior., *Viola arvensis* Murray, *Spergula arvensis* L. and *Poa annua* L., estimated to have little or even negligible suppressive effects on cereals (Weaver and Ivany, 1998; Wilson and Wright, 1990). However, tall-growing weed species that generate a significant amount of biomass are known to affect cereal growth even at moderate densities. Cruciferous weed species, *Raphanus raphanistrum* L., *Sinapis arvensis* L. and *Brassica rapa* L., have growth patterns synchronised with the spring cereals they infest, can cause devastating yield losses and are known to be particularly troublesome in organic farming (Melander et al., 2018). The competition studies referred to here describe the impact of weeds on crop growth when weeds occur randomly within the crop, that is both as intra- and inter-row weeds. However, only intra-row weeds are left to compete with the crop in a hoed system, and the literature does not explain the suppressive ability of weeds in this specific situation. To avoid yield loss associated with wide-row sowing, previous studies recommend that crop density per m^2 be held constant when increasing row spacing. When crop density is held constant, and inter-row spacing is widened, both intra-row crop density and light penetration into the inter-row zone increase. Light conditions and intra-row crop density affect crop growth and intra-row weed suppression, as well as weed growth and the competitive effect of weeds on the crop. These interactions are further influenced by the tillering capacity of the cereal species, as was observed by Melander et al. (2018) in a comparison of spring barley and spring wheat.

Using an applied approach, this study aims to improve understanding of the hoed cereal system: first, by quantifying the crop yield impact of tall-growing and cruciferous intra-row weeds, and second, by analysing the interacting effects of cereal species, inter-row spacing and nitrogen rate on the relationship between cereal crop yields and increasing intra-row weed density using an additive experimental design (Cousens, 1985). The hypothesised outcomes of the study are as follows: (a) tall-growing cruciferous intra-row surrogate weeds will significantly affect crop yield and quality; (b) tall-growing cruciferous intra-row surrogate weed growth will reduce crop yield more in spring wheat than in spring barley; (c) the adjustment of inter-row spacings between 15 cm and 25 cm will have no effect on weed or crop response; and (d) increasing nitrogen rate from 50 kg to 100 kg NH_4-N/ha will disproportionately increase crop growth relative to weed growth.

It was decided that surrogate weeds would be used in this study to simulate the responses likely typical for *R. raphanistrum*, *S. arvensis* and *B. rapa*. The seeds of these natural weed species possess complex mechanisms of dormancy (Garbutt and Witcombe, 1986; Tricault et al., 2018); thus, establishing the range of weed densities required for an additive design, and ultimately fitting a rectangular hyperbola, would be difficult to achieve. The agronomic crop species used as surrogates in this study, rape (*Brassica napus* L.) and white mustard (*Sinapis alba* L.), have seeds with lesser dormancy or non-dormant seeds, are tall-growing, and demonstrate growth habits similar to the natural cruciferous species (Melander et al., 2003; Kolb et al., 2010; Kolb et al. 2012; Brown and Gallandt, 2018).

2 | MATERIALS AND METHODS

2.1 | Experimental layout and treatments

In total, six experiments were conducted on a sandy loam soil at the Flakkebjerg Research Centre, Denmark (55°19′ N, 11°23′ E). Experimental factors are as follows: inter-row spacing, N input and increasing density of the surrogate weeds (*B. napus* and *S. alba*) were investigated in terms of their impact on crop and surrogate weed growth in spring barley and spring wheat grown under organic production practices. In all site-years, the preceding crop was spring barley, fertilised with 50 kg NH_4-N/ha. Table S1 shows the mean temperatures and rainfall for each month (April to July) and year (2014 to 2017) of the experiment. Table 1 provides an overview of those factors studied for each combination of test crop and experimental year. Two-row spring barley, variety *Evergreen* (KWS Scandinavia A/S, Vejle, DK), was sown at 3-4 cm soil depth on 2 May 2014, 9 April 2015, 20 April 2016 and 26 April 2017. Spring wheat, variety *Bittern* (Nordic Seed A/S, Holeby, DK), was sown at 3-4 cm soil depth on the same dates as barley in 2016 and 2017. Seeding rates were adjusted in both crops to obtain the same target density of 400 plants/m^2 irrespective of inter-row spacing, to achieve this, the seeding rate per metre of row was increased proportionally to the widening of inter-row spacing (Table 2). Equal crop stands were, however, not fully achieved as crop densities (plants/m^2) were greater at the narrow-row spacings compared to wide-row in 2015 and 2016. Narrow-row crop density was 16% greater in 2015 spring barley crop, and 8% and 15% greater in the 2016 spring barley and wheat crops respectively (Table 2). Surrogate weed species were sown immediately after the crop at 0–1 cm soil depth using a seeding machine with seeding rates set to achieve target intra-row weed densities (Table 1). Nutrients were applied as anaerobically digested slurry at rates providing 50 kg NH_4-N/ha (87 kg total nitrogen (N), 14 kg phosphorus (P), 33 kg potassium (K) per ha) and 100 kg NH_4-N/ha (174 kg total N, 28 kg P, 65 K kg/ha) according to the commonly used nitrogen rates on organic stockless arable farms and organic dairy farms respectively (Melander et al., 2018). Slurry

TABLE 1 Experimental details showing the crops and the years they were grown. The factors N input, inter-row spacing and increasing surrogate weed density were conducted in all crops and years

Year	Crops	Surrogate weed	Inter-row spacings (cm)	Nitrogen rate (NH_4-N kg/ha)	Target intra-row surrogate weed density (plants/m^2)
2014	Spring barley	*Brassica napus* L.	12.5, 25.0	50, 100	0, 50, 150, 500
2015	Spring barley	*Brassica napus* L.	12.5, 25.0	50, 100	0, 50, 150, 500
2016	Spring barley, spring wheat	*Sinapis alba* L.	15.0, 25.0	50, 100	0, 50, 150, 500
2017	Spring barley, spring wheat	*Sinapis alba* L.	15.0, 25.0	50, 100	0, 50, 150, 500

TABLE 2 Least square means of crop plant numbers per square metre (plants/m^2) and per linear metre of crop row (plants/m) shown for each year (barley crop stand was not recorded in 2014), crop and inter-row spacing

			Inter-row spacing (cm)			
Year	Crop	Crop density	12.5	15	25	SED
2015	Spring barley	Plants/m^2	358[a]		309[b]	9.7
		Plants/m	45[a]		77[b]	2.1
2016	Spring barley	Plants/m^2		383[a]	356[b]	5.7
		Plants/m		57[a]	89[b]	1.1
	Spring wheat	Plants/m^2		394[a]	342[b]	14.9
		Plants/m		59[a]	85[b]	3.1
2017	Spring barley	Plants/m^2		401[a]	381[a]	20.3
		Plants/m		60[a]	95[b]	2.0
	Spring wheat	Plants/m^2		402[a]	397[a]	20.5
		Plants/m		60[a]	99[b]	1.5

Note: Differences between nitrogen levels (50 and 100 NH_4-N kg/ha) were insignificant in all cases; therefore, crop density data sets were combined across nitrogen levels. Different letters alongside means in rows within year, crop and the two nitrogen levels indicate significant differences at $P \leq .05$. SED is the maximum standard errors of differences between means.

was injected to a depth of 5-8 cm shortly before final seedbed preparation and sowing.

Experimental factors are as follows: nitrogen rate, inter-row spacing and surrogate weed density were arranged in a randomised split–split-plot design with N rate as the main plot factor, inter-row spacing as the sub-plot factor and weed density as the sub–sub-plot factor; all treatments were replicated within four complete blocks. In total, 64 plots (2 N rates × 2 inter-row spacings × 4 weed densities × 4 blocks) were included for each combination of crop and year. Plot size was 2.5 × 10 m, with each plot separated by 2.5 m wide safeguards at plot ends. Both surrogate and natural weeds in the inter-row zone were removed as early as possible after emergence by hoeing. A 2.5 m wide Schmotzer hoe (Maschinenfabrik Schmotzer GmbH, Bad Windsheim, DE) was used at low driving speed (1 km/hr) to avoid sideward soil throw and ridging in the crop rows. Share widths of 7.5 cm for 12.5 cm inter-row spacing, 10 cm for 15 cm spacing and 20 cm for 25 cm spacing were used; therefore, the width of the uncultivated intra-row zone was 5 cm across treatments. Hoeing was supplemented with hand weeding wherever inter-row weeds survived; this ensured a situation where only intra-row weeds were left to compete with the crop. Natural intra- and inter-row weeds were removed manually in the weed-free plots (where surrogate weeds were not established). Intra-row weeds were defined as those growing both in the crop line and 2.5 cm to either side of the crop line.

2.2 | Data recording

Crop establishment was recorded at the one- to two-leaf stage (BBCH 11-12) (Lancashire et al., 1991) by counting the number of emerged crop plants within six randomly selected 1-metre row lengths in each plot (plant counts were not made in 2014). Crop and weed biomasses were recorded when the crops reached anthesis (BBCH 65-69), typically in late June or early July. Four linear metres of intra-row plant biomass were cut at ground level in all plots and separated into crop, surrogate weed and natural weed biomass fractions. The number of surrogate weed plants was counted as well. Crop and weed biomass fractions were oven-dried for 24 hours at 80°C to obtain dry matter content (DM). The principal natural weed flora in all years consisted of *Sinapis arvensis*, *Chenopodium album* L., *Capsella bursa-pastoris* (L.) Medik., *Bilderdykia convolvulus* (L.) Dumort and *Polygonum aviculare* L.

Crops were harvested by hand in two randomly placed 0.5 m^2 quadrats per plot on 14 August 2014 (barley), 20 August 2015 (barley), 17 August 2016 (barley), 25 August 2016 (wheat), 22 August 2017 (barley) and 24 August 2017 (wheat). The plant material was threshed, and dry matter of the grain was determined using a near-infrared spectroscopy analyser (Infratec^{TM} 1,241 Grain Analyzer, Foss A/S, Hillerød, DK) (Buchmann et al., 2001). Grain yields were adjusted to 85% dry matter content. Thousand kernel weight (TKW) was obtained in 2016 and 2017 for both wheat and barley by weighing three samples of 100 kernels per plot.

2.3 | Data analyses

Crop–weed interaction data were obtained from an additive design, and crop and weed responses with increasing surrogate weed density were analysed using a rectangular hyperbola (Cousens, 1985). The proportion of total weed biomass (surrogate weed + natural weeds) relative to total plant biomass (crop + surrogate weed + natural weeds) f_1 (x) at anthesis, and its relationship with increasing surrogate weed density was described as:

$$f_1(x) = \frac{g_{(j,k)} * d}{1 + g_{(j,k)} * d / h_{(j,k)}} \quad j = 1, 2; k = 1, 2, 3 \tag{1}$$

where *d* is surrogate weed density, parameter *g* is the increase in the proportion of total weed biomass f_1 (x) per unit surrogate weed density as *d* approaches 0, parameter *h* is maximum total weed biomass proportion as *d* approaches infinity, and *j* is 50 N and 100 N, respectively, and *k*1 is 12.5 cm (2014 and 2015 only), *k*2 is 15 cm (2016 and 2017 only) and *k*3 is 25 cm inter-row spacing (all years) respectively.

For grain yield responses f_2 (x) to increasing surrogate weed density, another version of the hyperbola was used to describe data:

$$f_2(x) = Y_{wf(j,k)} * \left[1 - \frac{i_{(j,k)} * d}{100 * \left(1 + i_{(j,k)} * d / a_{(j,k)}\right)} \right] \quad j = 1, 2;\ k = 1, 2, 3 \tag{2}$$

Y_{wf} is the weed-free crop yield, parameter *i* is the percentage yield loss per unit surrogate weed density as *d* approaches 0, and parameter *a* is the maximum percentage yield loss as *d* approaches infinity.

The impact of surrogate weed interference on the TKW f_3 (x) of the grain was analysed by a linear model:

$$f_3(x) = TKW_{wf(j,k)} - b_{(j,k)} * d \quad j = 1, 2; k = 1, 2, 3 \tag{3}$$

where TKW_{wf} is weed-free TKW, and *b* is the slope for increasing surrogate weed density.

Data were analysed using the NLMIXED-procedure in SAS (SAS version 9.4, SAS Institute, Cary, USA), which enables the analysis of non-linear mixed models. Data were assumed to be normally distributed, and estimations were based on maximum likelihood. Parameter values and standard errors in Equations (1), (2) and (3) were obtained by the transform-both-sides technique (Carroll and Ruppert, 1988), wherever transformation was necessary to stabilise variances. Decisions concerning the choice of transformation were based on visual assessments of residual plots; typically, either logarithmic or square root transformations were used. Good initial estimates of the fixed effects for the maximum-likelihood estimation in NLMIXED were obtained with the procedure

NLIN. First, a full model was set up in which parameters *g* and *h* in Equation (1); Y_{wf}, *i* and *a* in Equation (2); and TKW_{wf} and *b* in Equation (3) were dependent on the two categorical variables nitrogen rate and row spacing. Random effects were assumed to be normally distributed and to include the terms block, as well as the interactions block * nitrogen rate, and block * row spacing * nitrogen rate. Main effects and two-way interaction effects of nitrogen rate and row spacing were contrasted for each of the parameters in Equations (1), (2) and (3) respectively. Based on these contracts, the full model was then successively reduced (Brown and Rothery, 1993). Justification of model simplifications was based on likelihood ratio tests ($P < 0.05$) and changes in the Akaike information criterion (AIC) for model selection (Akaike, 1974).

3 | RESULTS

3.1 | Crop and weed biomass responses

In 2014, only treatments with the highest *B. napus* density had enough plants/m^2 for making statistical analyses; biomass production of *B. napus* was very low; however, and natural weed biomass was negligible. Experimental factors had no effect on *B. napus* density, total plant biomass (crop + surrogate weed + natural weeds) or the proportion of total weed biomass relative to total plant biomass; these variables averaged 23 (±3.5) *B. napus* plants/m^2, 631.4 (±18.8) g/m^2 and 1.5 (±0.002) % respectively. In addition, crop biomass was not reduced by the presence of weeds (surrogate weed + natural weeds) (data not shown).

Natural weed biomasses were also small and negligible in the other years: for barley, < 15 g/m^2 in 2015, < 3 g/m^2 in 2016 and < 2 g/m^2 in 2017; and for wheat, < 23 g/m^2 in 2016 and < 22 g/m^2 in 2017. There is no indication that natural weed biomasses had any influence on crop biomasses or crop yield responses (see below). Surrogate weeds, however, strongly drove significant crop effects.

Nitrogen rate 100 N significantly ($P < 0.05$) increased crop biomasses at anthesis of both barley and wheat in the weed-free treatment in 2015, 2016 and 2017 as compared with 50 N (Table 3). For example, barley biomasses were increased by 30% in 2016 and 10% in 2017 while the increases for wheat were 13% and 11% respectively. The distinct responses of the two nitrogen rates on crop growth indicate that there were no instances of surplus nitrogen that might have negated the effects of 50 N. In contrast, inter-row spacing had mostly negligible and insignificant effects on crop biomasses.

In spring barley, the proportion of total weed biomass (surrogate weed + natural weeds) relative to total plant biomass (crop + surrogate weed + natural weeds) was minor in 2015 and greatest in 2017 when the surrogate weed (*S. alba*) competed severely with barley, reaching an *h*-value of 98% (Table 3 and Figure 1a and c respectively). Nitrogen

TABLE 3 Estimates of parameters *g* and *h* from Equation (1) for the proportion of total weed biomass (surrogate weed *B. napus* in 2015 and *S. alba* in 2016 and 2017 + natural weeds) relative to total plant biomasses (crop + surrogate weed + natural weeds)

Year	Crop	Nitrogen rate (Kg NH_4-N/ha)	Inter-row spacing (cm)	Crop biomass (g/m^2)	*g* (% plant^{-1} m^{-2})	*h* (%)
2015	Spring barley	50	12.5	566 (84.2)	0.238 (0.0560)	6.062 (0.625)
			25.0	516 (99.7)	0.238 (0.0560)	6.062 (0.625)
		100	12.5	719 (81.5)	0.064 (0.0052)	39.22 (13.82)
			25.0	799 (86.3)	0.064 (0.0052)	39.22 (13.82)
2016	Spring barley	50	15.0	410 (57.4)	0.510 (0.0978)	37.65 (4.704)
			25.0	513 (66.9)	0.510 (0.0978)	37.65 (4.704)
		100	15.0	553 (51.2)	0.510 (0.0978)	37.65 (4.704)
			25.0	660 (46.1)	0.510 (0.0978)	37.65 (4.704)
	Spring wheat	50	15.0	445 (42.3)	0.429 (0.0569)	45.15 (4.396)
			25.0	392 (6.6)	0.429 (0.0569)	45.15 (4.396)
		100	15.0	456 (15.7)	0.429 (0.0569)	45.15 (4.396)
			25.0	491 (39.0)	0.429 (0.0569)	45.15 (4.396)
2017	Spring barley	50	15.0	550 (8.5)	1.129 (0.1175)	98.39 (6.574)
			25.0	564 (18.7)	1.129 (0.1175)	98.39 (6.574)
		100	15.0	636 (20.4)	1.129 (0.1175)	98.39 (6.574)
			25.0	590 (16.1)	1.129 (0.1175)	98.39 (6.574)
	Spring wheat	50	15.0	525 (14.4)	2.157 (0.1923)	91.80 (3.825)
			25.0	532 (24.1)	3.189 (0.2855)	91.80 (3.825)
		100	15.0	584 (24.8)	2.157 (0.1923)	104.3 (4.395)
			25.0	596 (44.5)	3.189 (0.2855)	104.3 (4.395)

Note: Estimates are shown by year, crop, nitrogen rate and inter-row spacing. Means of crop biomasses in the absence of weeds are shown for each combination of year, crop, nitrogen input and inter-row spacing. Standard errors of parameter estimates and means are shown in parentheses.

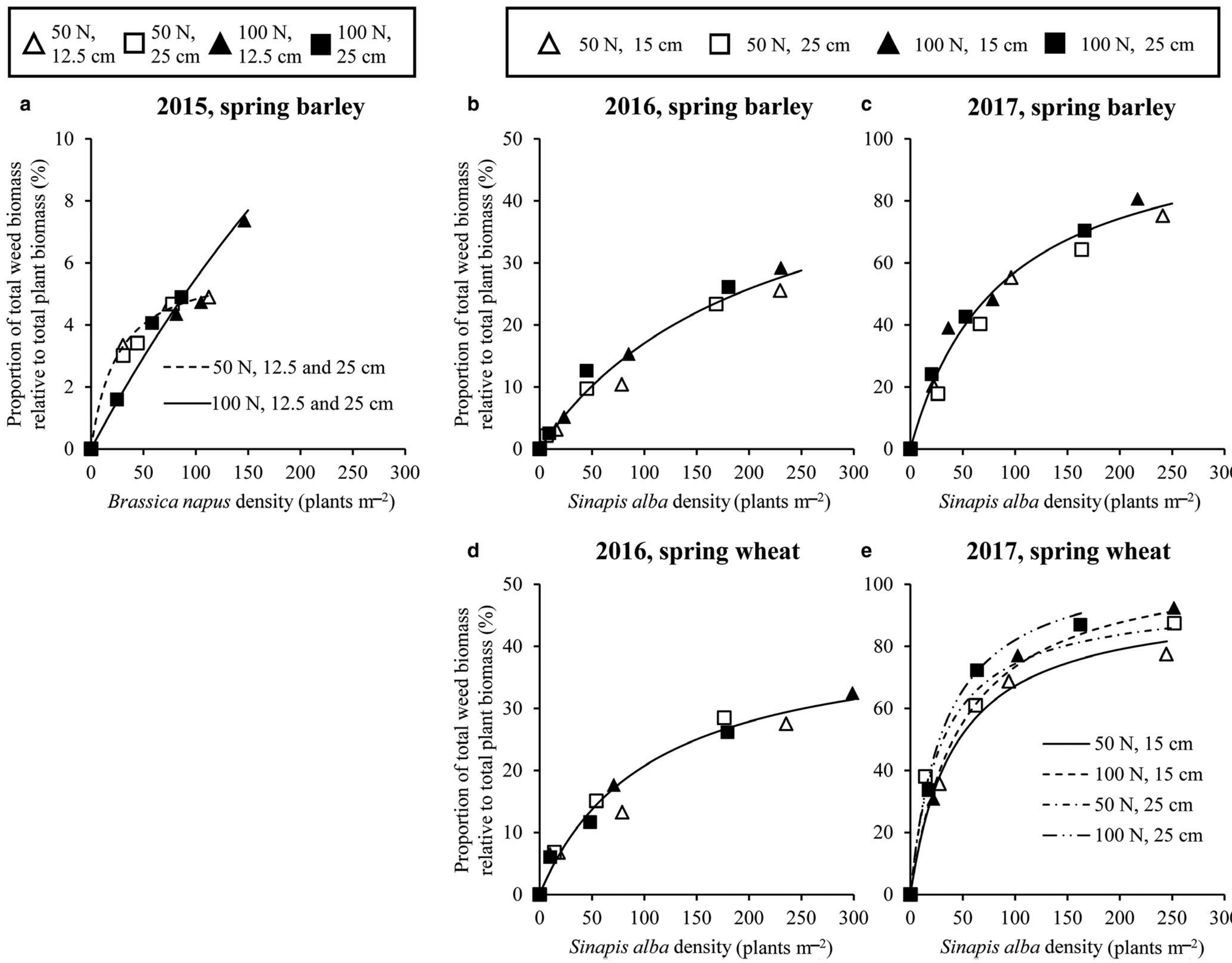

FIGURE 1 The relationship between the proportion of total weed biomass (surrogate weed + natural weeds) relative to total plant biomass (crop + surrogate weed + natural weeds) and surrogate weed (*Brassica napus* or *Sinapis alba*) density. Observed values represent means across two nitrogen rates (50 N and 100 N) and two row spacings in 2015 (12.5 cm and 25 cm) and in 2016 and 2017 (15 cm and 25 cm)

level and inter-row spacing did not affect the relationships between increasing intra-row surrogate weed density and the proportion of total weed biomass relative to total plant biomass in either 2016 or 2017 (Figure 1a and c respectively). However, nitrogen level did interact with the relationship in 2015 when increasing surrogate weed density (*B. napus*) resulted in a greater proportion of total weed biomass relative to total plant biomass at 100 N than at 50 N (Figure 1a).

Spring wheat was generally less suppressive against weed growth than barley. With increasing *S. alba* density in wheat, the proportion of total weed biomass relative to total plant biomass was unaffected by nitrogen rate or inter-row spacing in 2016 (Table 3 and Figure 1d). In contrast, both categorical variables interacted with the relationship in 2017, where 100 N and 25 cm inter-row spacing had the greatest total weed biomass, while 50 N and 15 cm spacing had the least (Table 3 and Figure 1e). In 2017, the wheat inter-row spacing of 15 cm was slightly more suppressive against weed growth at the higher *S. alba* densities compared to the wider 25 cm spacing (Figure 1e).

Increasing inter-row spacing from narrow (12.5 or 15 cm) to wide (25 cm) reduced the number of intra-row surrogate weed plants/m^2 (data not shown). The denser intra-row crop stand achieved at the 25 cm spacing and decreased intra-row surrogate weed density by approximately 30% in both crops and all site-years, 2015, 2016 and 2017. However, this reduction in surrogate weed density was offset; intra-row surrogate weeds at the 25 cm spacing grew larger, possessing a greater average weight per plant (data not shown).

3.2 | Grain yield effects

Barley grain yield was not affected by increasing *B. napus* intra-row density in 2014 and 2015 (data not shown), while *S. alba* severely reduced grain yields in both barley and wheat in 2016 and 2017 (Figure 2a,b respectively). Yield reduction resulting from increasing *S. alba* density was greater in wheat than in barley, with

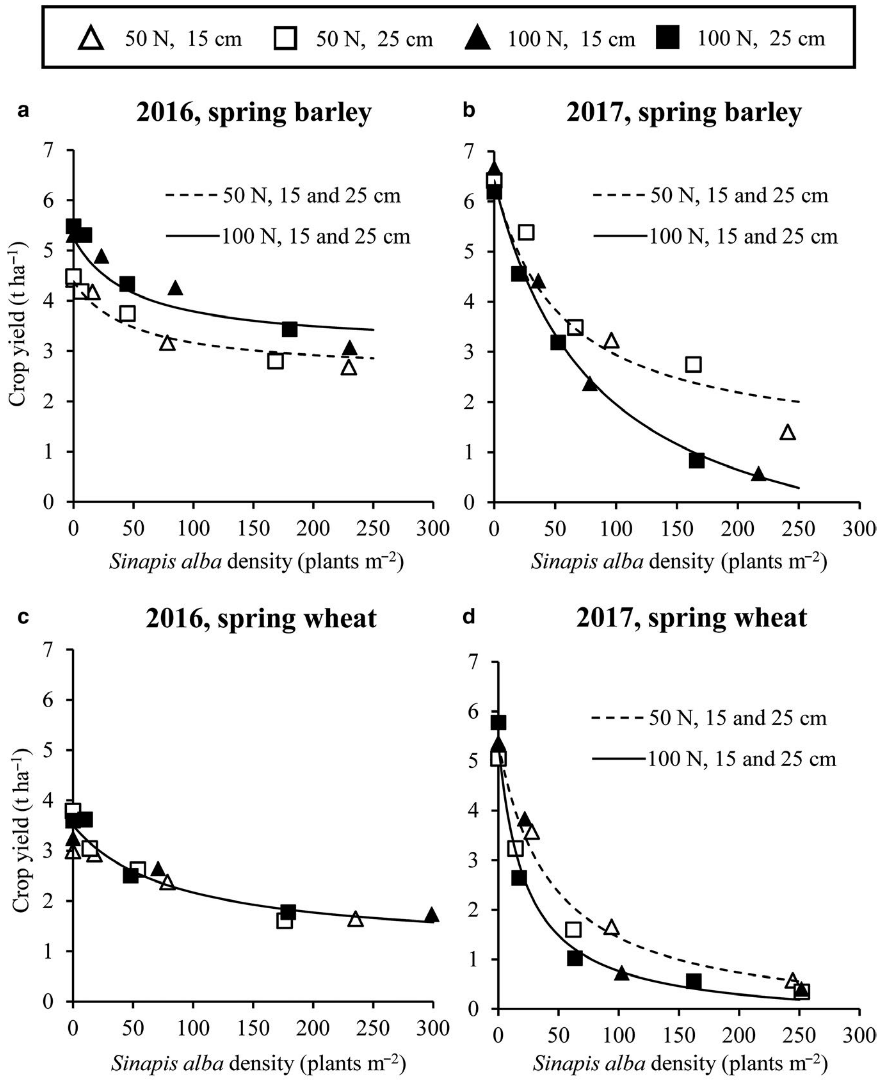

FIGURE 2 The relationship between crop yield and surrogate weed (*Sinapis alba*) density. Observed values represent means of two nitrogen rates (50 N and 100 N) and two row spacings (15 cm and 25 cm) in 2016 and 2017

devastating yield losses occurring in 2017 for both crops. While nitrogen level and inter-row spacing did not affect the yield-density relationships for either crop in 2016, interactions were evident in 2017 (Table 4). In 2017, barley yield losses at the higher intra-row *S. alba* densities were greater for 100 N than for 50 N, irrespective of inter-row spacing (Figure 2b); in wheat, the inter-row spacing of 25 cm resulted in greater yield loss than the 15 cm spacing (Figure 2d).

3.3 | Thousand kernel weight effects

Competition from *S. alba* reduced barley TKW significantly with increasing surrogate weed density in both 2016 and 2017; Equation (3) described data reasonably well (Figure 3a,b). The slope (parameter *b* in Equation (3)) was unaffected by nitrogen rate and inter-row spacing in 2016 (Figure 3a). In 2017, however, the slope interacted with nitrogen rate resulting in more TKW reduction for 100 N than for 50 N irrespective of the inter-row spacing (Figure 3b). The general TKW (parameter TKW_{wf} in Equation (3)) was greater for 50 N than for 100 N in 2017, and inter-row spacing had no influence on TKW_{wf} (Table 5).

TKW_{wf} was also greater for 50 N in wheat in 2016, but the slope *b* was not influenced by either categorical variables (nitrogen rate and inter-row spacing) (Table 5). Surrogate weed competition reduced TKW of wheat more than TKW of barley in 2016. Equation (3) did not describe the data on wheat TKW appropriately in 2017 (data not shown). Still, TKW was not significantly lower than the weed-free treatment when *S. alba* suppressed the wheat crop.

4 | DISCUSSION

4.1 | Intra-row weeds effect on crop quality and yield

Results support our first hypothesis: (a) both crop quality and yield were affected by intra-row cruciferous surrogate weeds. Significant TKW and yield losses were observed in both 2016 and

TABLE 4 Estimates of parameters Y_{wf}, i and a from Equation (2) for grain yields of barley and wheat correlated to increasing *S. alba* density and as affected by year, crop, nitrogen rate and inter-row spacing

Year	Crop	Nitrogen rate (Kg NH_4-N/ha)	Inter-row spacing (cm)	Y_{wf} (t/ha)	i (% plant^{-1} m^{-2})	a (%)
2016	Spring barley	50	15	4.388 (0.2372)	0.837 (0.3719)	41.80 (6.735)
			25	4.388 (0.2372)	0.837 (0.3719)	41.80 (6.735)
		100	15	5.251 (0.2676)	0.837 (0.3719)	41.80 (6.735)
			25	5.251 (0.2676)	0.837 (0.3719)	41.80 (6.735)
	Spring wheat	50	15	3.477 (0.1687)	0.831 (0.2237)	70.42 (7.115)
			25	3.477 (0.1687)	0.831 (0.2237)	70.42 (7.115)
		100	15	3.477 (0.1687)	0.831 (0.2237)	70.42 (7.115)
			25	3.477 (0.1687)	0.831 (0.2237)	70.42 (7.115)
2017	Spring barley	50	15	6.576 (0.2556)	1.535 (0.2107)	83.75 (6.391)
			25	6.576 (0.2556)	1.535 (0.2107)	83.75 (6.391)
		100	15	6.576 (0.2556)	1.535 (0.2107)	127.1 (11.500)
			25	6.576 (0.2556)	1.535 (0.2107)	127.1 (11.500)
	Spring wheat	50	15	5.373 (0.2763)	2.402 (0.3750)	105.3 (4.605)
			25	5.373 (0.2763)	4.627 (0.7849)	105.3 (4.605)
		100	15	5.373 (0.2763)	2.402 (0.3750)	105.3 (4.605)
			25	5.373 (0.2763)	4.627 (0.7849)	105.3 (4.605)

Note: Standard errors of parameter estimates and means are shown in parentheses.

2017. In 2016, TKW was reduced by 0.014 g in barley, and 0.026 g in wheat, as surrogate weed density increased by one plant per m^2 in the intra-row zone. In 2017, TKW reductions were 0.019 g for barley and 0.032 g for wheat. As intra-row surrogate weed density increased from the weed-free situation, corresponding per cent yield loss ranged from 0.84% to 1.54% in barely and 0.83% to 4.63% in wheat (parameter i in Equation (2)). In support of our second hypothesis (b), yield loss was greater in wheat compared to barley, indicating that the selection of competitive crop cultivars or species may help to mediate the adverse effects of intra-row weeds. Differences in the weed suppressive ability of barley and wheat may be due to wheat's lower tillering capacity and slower initial growth rate compared to barley (Melander et al., 2018; Peltonen-Sainio et al., 2008).

Yield loss was greater in 2017 compared to 2016. In 2017, increased precipitation likely contributed to improved resource capture by surrogate weeds relative to the crop; this is reflected in the maximum proportion of total weed biomass relative to total plant biomass, ranging from 37.65% in barley to 45.15% in wheat in 2016% versus 98.39% in barley to 104.30% in wheat in 2017 (parameter of h in Equation (1)). In some cases, parameters h in Equation (1) and a in Equation (2) exceeded 100% due to insufficient data in the high weed density range, resulting in unsatisfactory fits of the two asymptotes.

Yield effects were absent in 2014 and 2015 when *B. napus* was used as a surrogate weed. Since surrogate weed species is confounded with experimental year, it is not possible to compare the effects of *B. napus* and *S. alba* directly. Differences in competitive ability amongst surrogate weeds are expected due to differing growth rates, fecundity and growth characteristics such as capture of resources; however, the poor establishment of *B. napus* in 2014 and 2015 is likely responsible for the absence of effects. While *B. napus* seed was previously considered to be non-dormant, Soltani et al. (2019) provide evidence that disproves this assumption. It is reported that *B. napus* seed possess both primary and secondary dormancy (Soltani et al., 2019); this helps to explain the poor germination and lack of yield effects observed in 2014 and 2015. In addition, the future use of *B. napus* as a surrogate weed is not advisable.

Surrogate weeds were sown to simulate competition from natural cruciferous species; in previous research, the use of *S. alba* and *B. napus* is well-established among field studies (Brown and Gallandt, 2018; Kolb et al., 2010, 2012; Melander et al., 2003). Although explicit comparisons have not been made between natural weed species and their surrogate counterparts, crop yield response to surrogate versus natural weeds can be compared post hoc. Notably, the articles referred to in this paragraph describe the impact of weeds occurring across both the intra- and inter-row zones. Corresponding to the i-parameter in Equation (2), as the density of natural weed, *R. raphanistrum*, increases by one plant per square meter, spring wheat yields are reduced by 0.51% to 5.50% (Eslami et al., 2006; Tavares et al., 2019). In the present study, yield effects resulting from increasing intra-row surrogate weed density is comparable to *R.raphanistrum*; *S. alba* reduced spring wheat yield by 0.83% to 4.63% (Table 4). Weaver and Ivany (1998) compared spring barley yield losses resulting from the introduction of the first weed plant into the crop stand, among four natural species; *R. raphanistrum* had the greatest impact, lowering yield by 0.19%, whereas *Avena fatua*

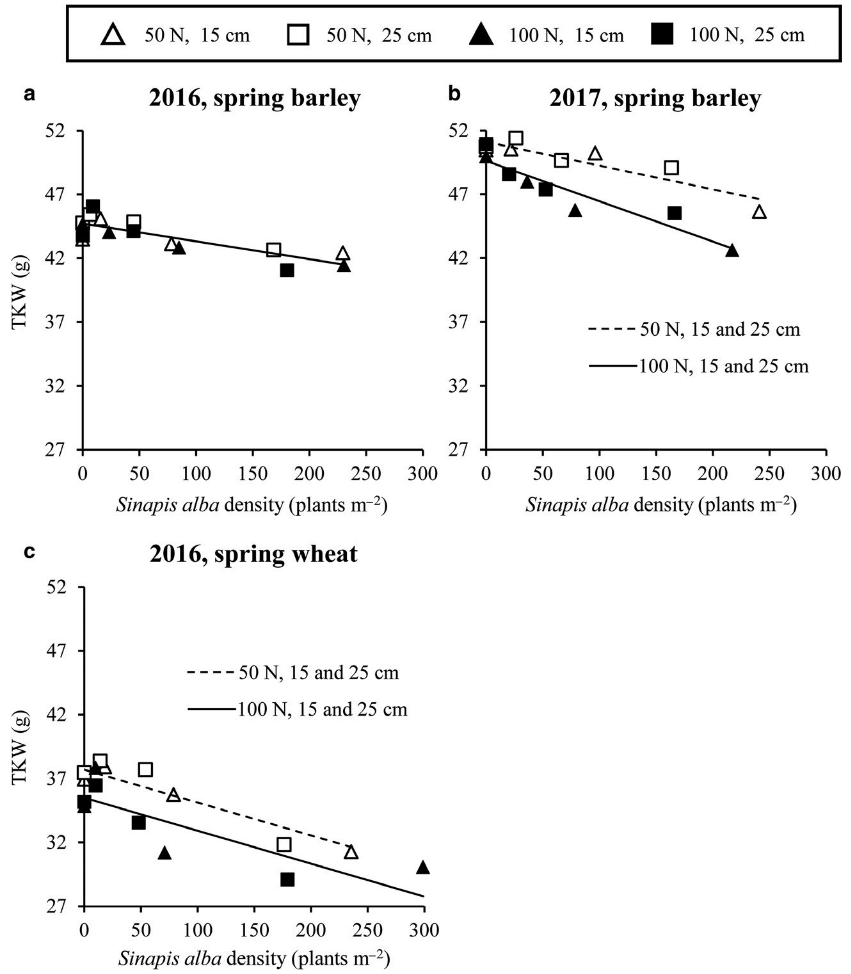

FIGURE 3 The relationship between crop thousand kernel weight (TKW) and surrogate weed (*Sinapis alba*) density. Observed values represent means of two nitrogen rates (50 N and 100 N) and two row spacings (15 cm and 25 cm) in 2016 and 2017

L., *Galeopsis tetrahit* L. and *Spergula arvensis* reduced yield by 0.16%, 0.05% and 0.02% respectively. In the present study, *S. alba* reduced spring barley yield by 0.84% to 1.54% (Table 4). Results indicate that intra-row weeds must be controlled to reduce adverse crop effects; however, whether additional management is necessary depends upon the competitiveness of problem weed species. For example, *Spergula arvensis* would not typically require additional control measures in spring cereals; hoeing provides sufficient protection against adverse effects. It is worth noting that there is a need for studies comparing surrogate and natural weed morphology, growth, competitive ability and response to physical weed control. Such a contribution would greatly serve weed science, allowing researchers to select surrogate weeds that closely resemble the natural weeds of their interest.

4.2 | Inter-row spacing and nitrogen level effect on crop and weed response

Results largely support our third hypothesis (c): inter-row spacing did not have consistent effects on weed and crop response. There was no effect on yield, TKW or weed suppression for wheat in 2016, or for barley, in 2015, 2016 or 2017. Effects were only observed in the 2017 wheat crop. The 25 cm inter-row spacing resulted in 2.2% greater yield loss per unit surrogate weed density (parameter i in Equation (2)) compared to the 15 cm spacing, and 1.032% greater weed biomass relative to total plant biomass (parameter g in Equation (1)) per unit surrogate weed density.

Reduced wheat yield and increased relative weed biomass in 2017 may have been caused by the sum effects of larger intra-row weeds, heightened intra-specific competition, cool and wet weather (especially in June and July compared to the same months in 2016), as well as wheat's lesser competitive ability. Widening row spacing while maintaining the seeding rate has opposing effects on intra-row resource availability, simultaneously increasing light penetration into the crop canopy (Kolb et al., 2012) and intensifying competition (Regnier and Bakelana, 1995; Weiner et al., 2001). In wide-row hoed cereal systems, Kolb et al. (2010, 2012) and McCollough et al. (2020) observed that weeds remaining in the intra-row zone were larger, with increased individual biomass and height compared to narrow-row and standard cropping strategies. Heightened intra-specific competition is also associated with the wide-row sowing; when seeding rate is maintained while row spacing is increased, crop density in the intra-row becomes more crowded, resulting in greater competition between individual crop plants (Regnier and Bakelana, 1995). In addition, the reduced

TABLE 5 Estimates of intercepts, TKW_{wf} and slopes b from linear regression of TKW of barley and wheat with increasing *S. alba* density (Equation (3))

Year	Crop	Nitrogen rate (Kg NH_4-N/ha)	Inter-row spacing (cm)	TKW_{wf} (g)	b (g plant^{-1} m^{-2})
2016	Spring barley	50	15	44.7 (0.27)	−0.014 (0.0025)
			25	44.7 (0.27)	−0.014 (0.0025)
		100	15	44.7 (0.27)	−0.014 (0.0025)
			25	44.7 (0.27)	−0.014 (0.0025)
	Spring wheat	50	15	37.7 (0.82)	−0.026 (0.0036)
			25	37.7 (0.82)	−0.026 (0.0036)
		100	15	35.5 (0.80)	−0.026 (0.0036)
			25	35.5 (0.80)	−0.026 (0.0036)
2017	Spring barley	50	15	51.1 (0.51)	−0.019 (0.0032)
			25	51.1 (0.51)	−0.019 (0.0032)
		100	15	49.6 (0.52)	−0.032 (0.0036)
			25	49.6 (0.52)	−0.032 (0.0036)
	Spring wheat	50	15	-	-
			25	-	-
		100	15	-	-
			25	-	-

Note: Parameter values are shown for year, crop, nitrogen and inter-row spacing. '-' means that no relationship was found. Standard errors of parameter estimates are shown in parentheses.

competitive ability of spring wheat compared to spring barley, and wet field conditions in 2017, likely contributed to greater crop–weed competition, enough so, that results were detectable.

Our fourth hypothesis (d) was not supported, increasing nitrogen rate from 50 kg to 100 kg NH_4-N/ha did not correspond with an increase in crop growth relative to weed growth. Nitrogen level interacted with the ratio of total weed to total plant biomass on two occasions. The 100 N treatment resulted in a 0.174% greater proportion of total weed biomass in barley in 2015 (parameter g in Equation (1)), and a 12.5% greater maximum weed biomass proportion in wheat in 2017 (parameter h in Equation (1)). As was previously discussed, wet conditions in 2017 likely contributed to improved nutrient capture by surrogate weeds in wheat. In response to increased nutrient inputs, previous studies have reported both positive effects on crop growth relative to weeds (Melander et al., 2018), as well as no effect and negative effects (Olesen et al., 2009).

Studying the effects of nitrogen rate on a surrogate weed crop (*S. alba*) instead of natural weed species may have also contributed to the unexpected results. Crop yield results (see section 4.1) suggest that many natural weeds are not as competitive as *S. alba* (Weaver and Ivany, 1998); this may be why Melander et al. (2018) reported a positive increase in crop growth relative to natural weeds when nitrogen rate was increased. In addition, 2017 barley yield data support the notion that surrogate weed, *S. alba*, competed strongly for available nitrogen, resulting in a 43% greater maximum yield loss for the 100 N treatment (parameter a in Equation (2)); high-density surrogate weed stands, therefore, appear to have benefitted more the high nitrogen rate (100 N), compared to the low (50 N) (Figure 2).

5 | CONCLUSIONS

This study does not provide an in-depth understanding of the mechanisms behind inter-row spacing and nitrogen rate on crop–surrogate weed interactions owing to its applied nature. However, our overarching claim is supported, and aggressive weed species remaining in the intra-row zone negatively affect crop growth, yield and quality (TKW) in the hoed cereal system. This has been proven for inter-row spacings and nitrogen rates relevant to current cropping strategies in Danish organic farming. The choice of a more competitive crop can help to reduce the adverse effects of intra-row weeds. Barley was more suppressive of weeds and less susceptible to grain yield and quality losses when compared to wheat. Inter-row spacings of 20 cm or less are suggested for less competitive crops, such as spring wheat, to avoid severe crop–weed competition and potential yield losses. Results do not support the practice of increasing nutrient input to improve weed suppression; however, this finding conflicts with previous studies.

The next logical consideration is how additional cultural, physical or preventative strategies may be applied in the hoed cereal system to better control for intra-row weeds. We suggested that future research focus on the interacting effects of row spacing and seeding rate for improved weed suppression through elevated crop–weed competition. Targeted timing of nutrient application based on crop life stage and depth of placement may also help to improve uptake by the crop while limiting uptake by weeds. Finally, the inclusion of pre- and post-emergence weed harrowing in the hoed cereal system should be investigated, and the resulting reduction in intra-row weed emergence quantified.

ACKNOWLEDGEMENTS

We would like to thank technicians Eugene Driessen and Karen Bjørn Heinager for their skilful technical assistance.

CONFLICT OF INTEREST

No conflicts of interest have been declared.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/wre.12452.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Melander B, McCollough MR. Influence of intra-row cruciferous surrogate weed growth on crop yield in organic spring cereals. *Weed Res*. 2020;60:464–474. https://doi.org/10.1111/wre.12452