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Camera-guided inter-row hoeing in winter oilseed rape with different inter-inter-row spacing

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Abstract: New cropping practices such as single-grain seeding, lower seed densities with stronger cultivars, wide inter-row spacings and camera-guided side-shift control for weed hoeing facilitate mechanical weed control in oilseed rape. In a two-year field study in Southwestern Germany, camera-guided inter-row hoeing was compared to standard herbicide treatments and untreated control. Seeding with 12.5, 25 and 50 cm inter-row spacing was included as a second factor in the experiment. Weed and crop density were measured directly after treatment. Weed and crop biomass, oilseed rape root diameter and nitrogen uptake were assessed before winter. Seed yield was measured at harvest with a plot combine harvester. In 2021, hoeing in 50 cm inter-row spacing achieved equal weed control efficacy as the herbicide treatment (65–75%). In 2022, hoeing did not reduce weed density, probably due to heavy rainfalls during the first and second pass of hoeing. However, herbicide treatments controlled 92% of the weeds. In 2021, hoeing significantly increased oilseed rape shoot biomass and root diameter compared to the herbicide treatment and the untreated control. Hoeing in 50 cm inter-row spacing resulted in equal yield as the herbicide treatment. In 2022, weed control treatments and inter-row spacing had no effect on oilseed rape biomass, root diameter and yield. This study shows the potential and limitations of weed hoeing in oilseed rape. It also underlines the strong ability of modern oilseed rape cultivars to suppress annual broadleaved weeds.

Keywords: crop protection; precision farming; robotic weeding; camera guidance; integrated weed management

Winter oilseed rape can suppress weeds due to early canopy closure before winter and rapid shoot elongation in spring (Lemerle et al. 2017). Yield of winter oilseed rape in the untreated control was therefore often not different form the herbicide treatment (Wahmhoff 1994). However, poorly developed oilseed rape with many gaps between oilseed rape plants can be heavily infested by typical oilseed rape weeds for Germany, such as *Matricaria inodora* L., *Stellaria media* Vill., *Viola arvensis* Murray and *Galium aparine* L. (Goerke et al. 2008, Hanzlik and Gerowitt 2012). Some of them can cause up to 90% yield loss. In purely winter-annual crop rotations with winter cereals and winter oilseed rape, volunteers of winter cereals and herbicide-resistant grass weeds such as *Alopecurus myosuroides* Huds. and *Lolium multiflorum* L. can also cause severe weed problems (Wahmhoff 1994, Blackshaw et al. 2005, Hanzlik and Gerowitt 2012, Fried et al. 2015, Hamouzová et al. 2023). Therefore, more than 75% of German oilseed rape fields are sprayed with pre-emergence herbicides containing metazachlor or/and clomazone. If grass-weed populations are still sensitive to post-emergence herbicides, acetyl-CoA-carboxylase (ACCase)-inhibitors are used (JKI 2023). Together with regular fungicide, growth regulator and insecticides treatments, oilseed rape has reached a treatment frequency index (TFI) of 6.4, which is among the highest of all arable crops in Europe (JKI 2023). Alternative crop protection methods need to be investigated to reduce the dependence on pesticides in oilseed rape. One such approach was the development of new oilseed rape cultivars that allow a significant reduction of seed density from approxi-

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mately 80 to 30 oilseed rape seeds per m^2 with stable yield. Such plants produce more biomass and are more tolerant to lodging, pests and diseases (Różyło and Pałys 2014, Ratajczak et al. 2017, Mwendwa et al. 2020). Lower seeding rates were often combined with wider inter-row spacing from 12.5 cm to 25 and 50 cm. Another improvement was a new single-grain sowing technology for oilseed rape to precisely place seeds at homogeneous distances in the row and equal sowing depth (Dhillon et al. 2022). This resulted in higher and uniform emergence and faster canopy closure.

Both improvements in the production of oilseed rape, the cultivars with stronger individual plants and the precise single-grain seeding, facilitated mechanical weed hoeing in oilseed rape. Wider inter-row spacing may increase weed infestation and extend the time period until the crop canopy is closer. However, it allows for two-three hoeing passes until early spring. If a camera is used for crop row detection, hoeing blades can be guided closer to the straight seeding lines of the single-grain seeders than in conventionally drilled fields (Tillett et al. 2002, Nilsson et al. 2014, Schwabe et al. 2022). If camera-guidance with automatic side-shift control was used for inter-row hoeing, the blades can be steered 20 mm along the crop row (Gerhards et al. 2020, Machleb et al. 2020). This automatic guiding technology increased weed control efficiency (WCE) in cereals from 70% to 85%, allowing up to 8 km/h driving speed. Besides weed control, hoeing can reduce evaporation and increase nitrogen availability for the crop (Woyessa 2022). However, mechanical weed hoeing in autumn and early spring can be limited by wet soil conditions (van der Weide et al. 2008). The objective of this study was to analyse weed control efficiency and crop response to weed hoeing in winter oilseed rape planted in different inter-row spacings.

MATERIAL AND METHODS

Experimental site. Experiments were conducted in Southwest Germany at the Research Station Ihinger Hof near Renningen (48°44'23"N, 8°55'43"E). The soil texture is a silty loam with subsoil clay with 1.22% organic carbon content and a pH value 6.7. The soil is classified as a Cambisol. The long-term mean temperature at Ihinger Hof is 9.1 °C, and the average annual rainfall is 685 mm. In 2021, the field received 790 mm of rainfall. In 2022, precipitation was slightly lower than the long-term mean, with 658 mm. However, autumn in 2022 was very wet, with 100 mm rainfall in September and 80 mm in October 2022. The average temperature in 2021 was 1.7 °C higher than the long-term mean. 2022 the average annual temperature was 1.4 °C above the long-term mean.

Experimental design. A two-factorial split-plot design with four replications was selected for both experiments in 2021 and 2022. The plots were 20 m long in the direction of sowing and 3 m wide, which corresponds to the working width of the seeder and hoe. Winter barley was the preceding crop in both experiments. All field operations related to the experiments are summarised in Table 1.

Data assessments. Weed density was counted immediately after hoeing and approximately 28 days after herbicide application. A frame of 33 cm × 33 cm was placed six times in each plot. This study presents data of weed densities 45 and 49 DAS (after the second hoeing treatment) and 171 DAS (immediately after the third hoeing treatment). Weed control efficacy was calculated according to Eq. 1.

$$\text{WCE} = 100\ (1 - w_t/w_u) \qquad (1)$$

where: w_t – weed density in the treated plots; w_u – density of weeds in untreated plots.

Three samples per plot of shoot biomass were collected using a 50 cm × 50 cm in late autumn, 71 DAS. Samples were separated into oilseed rape, weeds and barley volunteers. Dry biomass was measured after 32 h in a drying chamber (Vötsch Industrietechnik, VTU 125/200, Reiskirchen, Germany) at 80 °C. The root diameter of eight oil-seed rape plants per plot was measured in the transition zone between shoot and root 71 DAS. Nitrogen (N)-uptake of oilseed rape was measured at 78 DAS. Four oilseed rape plants were harvested from each plot. Roots and shoots were dried at 60 °C for 48 h, milled (ZM 200 Retsch, Haan, Germany), and N-content was measured (Vario Macro Cube, Elementar Analysensystem, Langenselbold, Germany). N-uptake was determined according to the Eq. 2:

$$\text{N-uptake (kg/ha)} = \text{oilseed rape dry weight (kg/ha)} \times \text{N-content (\%)}/100 \qquad (2)$$

Plots were harvested with a combine harvester at the end of July when seeds had a moisture content of 8%. Seed yield was recorded for each plot.

Statistical analysis. The statistical software R (version 2023.06.0+421, RStudio Team, Boston, USA) was used for data analysis. Before analysis, the data were checked for homogeneity of variance and nor

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Table 1. Summary of all field operations in the experiments

Operation	Experiment 1	Experiment 2
Mouldboard ploughing, 30 cm deep (Lemken Opal7, Germany)	–	24. 08. 2022
Cultivator, 15 cm deep	25. 08. 2021	–
Seedbed preparation (Rotary harrowing, HR-Kuhn, Saverne, France)	26. 08. 2021	25. 08. 2022
Sowing (Zürn D32-PN, Schöntal, Westernhausen Germany)	27. 08. 2021	12. 09. 2022 (because of drought)
Sowing density, cv. Ludger	35 seeds/m^2	35 seeds/m^2
Row distances	15, 25, 50 cm	15, 25, 50 cm
Fertilisation	150 kg N/ha, 40 kg P/ha, 83 kg K/ha, 18 kg Mg/ha, 55 kg S/ha	160 kg N/ha, 40 kg P/ha, 99.6 kg K/ha, 18 kg Mg/ha, 55 kg S/ha
Hoeing (K.U.L.T. vision control, Kürnbach, Germany, no-till sweeps, 9 cm width, 2 cm deep)	25, 45, 171 DAS	26, 49, 172 DAS
Herbicide treatment	2.5 L/ha Butisan® Gold (200 g/L Metazachlor + 200 g/L, Dimethenamid-P, 100 g/L Quinmerac, SC, BASF) + 2.0 L/ha Fusilade Max® (107 g/L Fluazifop-P, EC, Nufarm), 1.875 L/ha Kerb™ Flo (400 g/L Propyzamid, SC, Corteva), 10, 34, 76 DAS	2.1 L/ha Butisan® Top (375 g/L Metazachlor + 125 g/L Quinmerac, SC, BASF), 11 DAS
Fungicide and insecticide treatment	6 kg/ha Delicia (30 g/kg Metaldehyd, WG, Frunol) 14 DAS, 170 g/ha Avaunt (150 g/L Indoxacarb, EC, FMC) 221 DAS, 0.8 L/ha Tilmor (80 g/L Prothioconazol + 160 g/L Tebuconazol, EC, Bayer CropScience) 55 DAS, 0.2 L/ha Mavrik Vita (240 g/L Tau-Fluvalinat, EM, Adama) 252 DAS	3 kg/ha Delicia 12 DAS, 0.8 L/ha Tilmor 61 DAS, 0.2 L/ha Mavrik Vita 244 DAS
Assessment	assessment weed density, 45, 171 DAS; assessment biomass and root diameter, 71 DAS; assessment N-uptake, 78 DAS	assessment weed density 49, 171 DAS; assessment biomass and root diameter 71 DAS; assessment N-uptake 78 DAS
Harvest (Zürn150, Schöntal, Westernhausen Germany)	20. 07. 2022	26. 07. 2023

DAS – days after sowing

mal distribution of residuals. If necessary, data were transformed square root to homogenise variances and normalise the distribution. The ANOVA included inter-row spacing, weed control treatment, and their interaction as fixed effects. The block was taken as a random effect. Multiple mean comparison tests were performed using the Tukey *HSD* (honestly significant difference) test at a significance level of α ≤ 0.05.

RESULTS AND DISCUSSION

All tested parameters showed significant effects for the factor weed control in 2021 but only for weed density and weed biomass in 2022. Inter-row spacing was significant for weed density 171 DAS and yield in 2021 and for weed density 49 DAS and weed biomass in 2022. Significant interactions were calculated for weed density and yield in 2021, weed density 49 DAS, and weed biomass in 2022. For better illustration, mean comparisons of interactions are shown for all parameters in the figures.

Weed assessments. The dominant weed species in both experiments were *S. media*, *Lamium purpureum* L., *Veronica persica* Poir., *G. aparine* and *M. inodora*. *Cirsium arvense* (L.) Scop. was the only perennial weed species with less than 5% frequency in the untreated controls. *Hordeum vulgaris* L. (volunteer from the previous crop) was the dominant weed in

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2021, with a frequency of 64%. In 2022, volunteer winter barley had only a frequency of 2.5%.

Weed density in the untreated control was higher in 2021, with more than 100 weeds/m^2 than in 2022, with less than 30 weeds/m^2, probably due to inversion tillage. Wider inter-row spacings did not increase weed density in both years. Herbicides significantly reduced weed density in both years, with an average of 75% WCE in 2021 and 92% WCE in 2022. Three passes of camera-guided inter-row hoeing significantly reduced weed density in 2021 but had no effect in 2022. The average WCE of hoeing in 2021 was 65% and only 2% in 2022. The efficacy of camera-guided hoeing increased with increasing inter-row spacing. In 2021, hoeing in 50 cm inter-row spacings resulted in equal weed densities as in the herbicide treatments (Figure 1). The first two passes of hoeing removed most of the dicot weeds and barley volunteers. Hoeing in wide-row spacings also offers a great potential to control volunteer oil seed rape in narrow crop rotations, which can be very problematic in lower seeding rates canopies.

The efficacy of inter-row hoeing in weed control varied significantly between the two experiments. Under dry soil conditions in autumn 2021, camera-guided hoeing at 50 cm inter-row spacing achieved equal WCE (65%) as the herbicide treatment, which is in agreement with Nilsson et al. (2014). Weed control efficacy could have been further increased if inter-row hoeing was combined with in-row band spraying (Kunz et al. 2018). Mechanical weeding was more effective against dicot weeds than against barley volunteers and other grass weeds. This is in agreement with Wahmhoff (1994) and Melander et al. (2013). However, in 2022, under wet soil conditions in autumn, weed hoeing completely failed

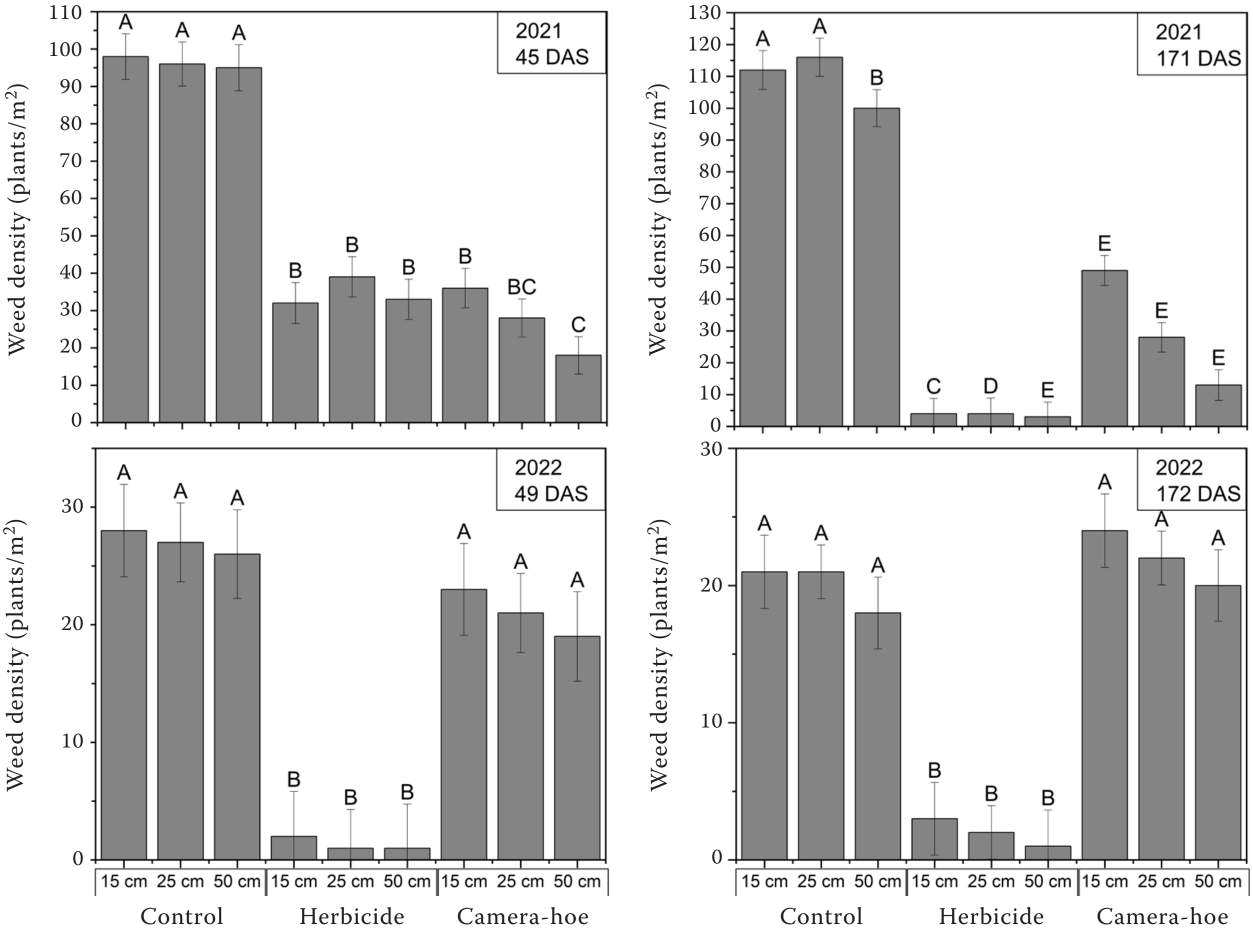

Figure 1. Weed densities (plants/m^2) in oilseed rape 45/49 and 171/172 days after sowing (DAS) with different inter-row spacing of 15, 25 and 50 cm and weed control treatments in 2021 and 2022. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

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and did not reduce weed density compared to the untreated control, regardless of inter-row spacing. Effective weeding, especially during the first passes of hoeing in autumn, is extremely important for successful mechanical weed control in oilseed rape (Wahmhoff 1994).

Weed and crop biomass. Inter-row spacing had no effect on oilseed rape shoot biomass in both years. Dry shoot biomass of oilseed rape in 2021 was highest in the hoeing treatments, followed by the herbicide treatment. The lowest shoot biomass was measured in the untreated control. Steinmann (2002) and Melander et al. (2013) also reported that hoeing can stimulate crop development and increase crop competitiveness against weeds. Those findings were supported only by the 2021 experiment of this study. In 2022, weed control treatments had no effect on oilseed rape shoot biomass. Weed biomass in 2021 was equal in all weed control treatments but lower than in the untreated controls. In 2022, weed biomass was reduced by herbicide treatments in all three inter-row spacings. Hoeing with 50 cm inter-row spacing resulted in the highest weed biomass (Figure 2).

Oilseed rape root diameter. The root diameter of oilseed rape was increased only by weed control treatments in 2021. Hoeing resulted in the highest root diameter. In 2022, weed control treatment and inter-row spacing had no effect on the root diameter of oilseed rape (Figure 3).

Oilseed rape nitrogen uptake. Nitrogen uptake of oilseed rape until 78 DAS in 2022, with up to 80 kg N/ha, was more than twice as high as in 2021. Nitrogen uptake was increased by all weed control treatments in 2021, but it was not affected by treatments in 2022. Hoeing resulted in the highest nitrogen uptake in 2021. A row distance of 50 cm combined with weed

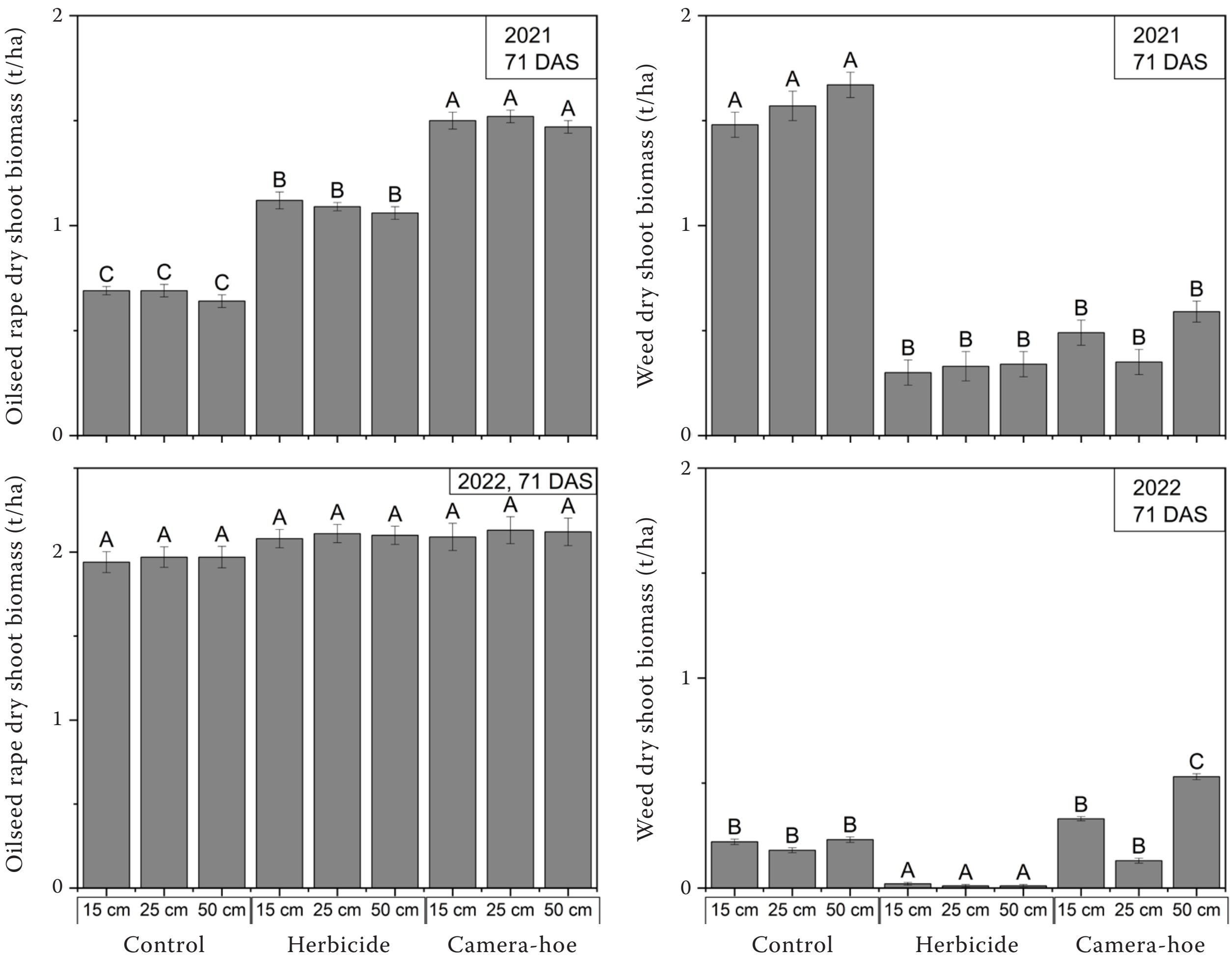

Figure 2. Oilseed rape and weed dry shoot biomass 71 days after sowing (DAS) with different inter-row spacing of 15, 25 and 50 cm and weed control treatments in 2021 and 2022. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

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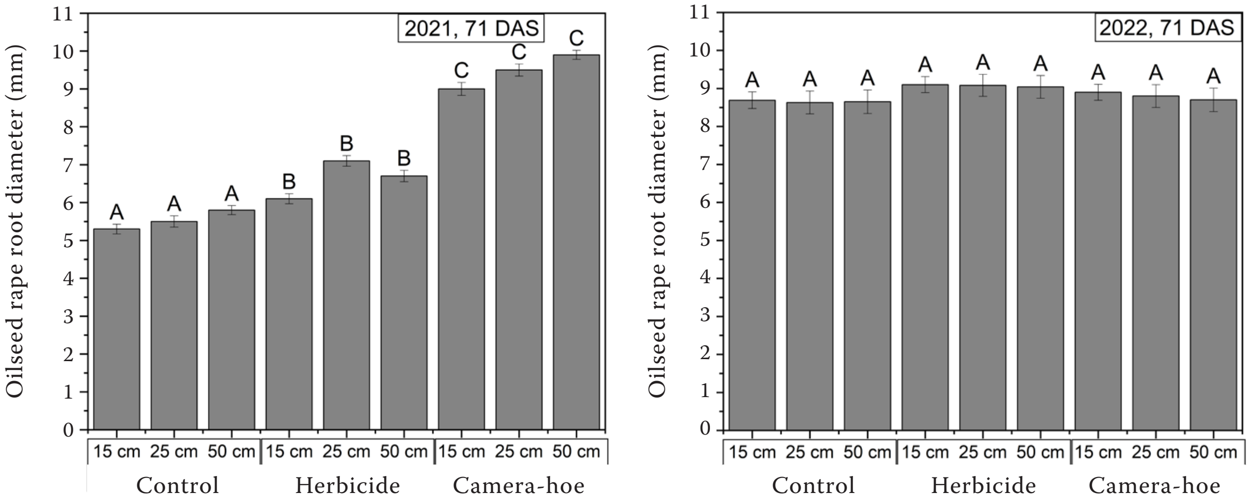

Figure 3. Oilseed rape root diameter 71 days after sowing (DAS) with different inter-row spacing of 15, 25 and 50 cm and weed control treatments in 2021 and 2022. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

control treatments resulted in the highest nitrogen uptake in both years compared to the other inter-row distances (Figure 4).

Oilseed rape yield. Oilseed rape yield was increased by herbicide treatment and camera-guided hoeing in 2021. Hoeing, in combination with a wide inter-row spacing of 50 cm, resulted in equal yield as all herbicide treatments. In 2022, treatments had no effect on oilseed rape yield (Figure 5).

Annual dicot weeds in 2022, with an average density of 30 plants/m^2, did not reduce the yield of oilseed rape. However, volunteer winter barley with 70 plants/m^2 reduced oilseed rape yield by 50% in 2021. Volunteer barley is a very competitive weed in oilseed rape, producing equal shoot biomass per plant as oilseed rape. Early applications of ACCase inhibitors were very effective in controlling volunteer barley, which is in agreement with Freeman and Lutman (2004) and Schwabe et al. (2022). The efficacy of herbicide treatments was high in both years, regardless of weather conditions. In 2022, volunteer winter barley was suppressed by moldboard ploughing between the harvest of winter barley and the sowing of oilseed rape. Other weed species were suppressed by oilseed rape, which is in agreement with Wahmhoff (1994).

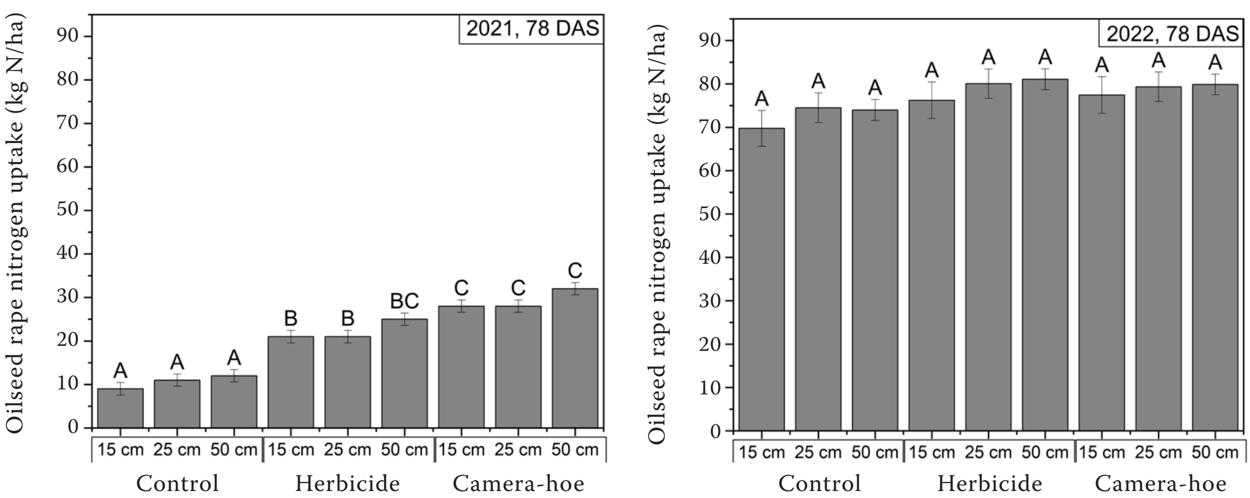

Figure 4. Oilseed rape nitrogen uptake 78 days after sowing (DAS) with different inter-row spacings of 15, 25 and 50 cm and weed control treatments in 2021 and 2022. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

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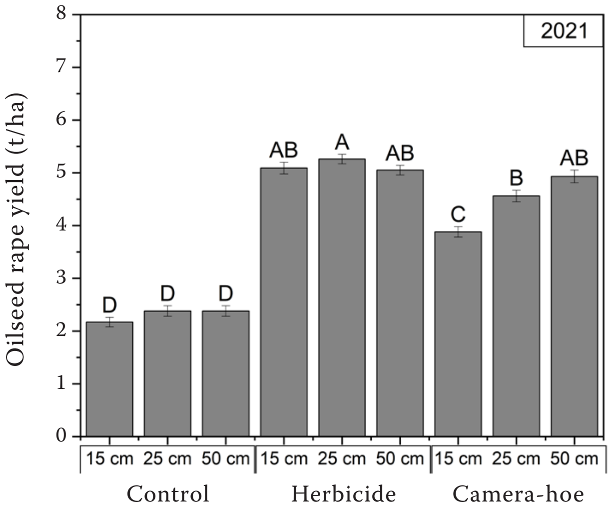

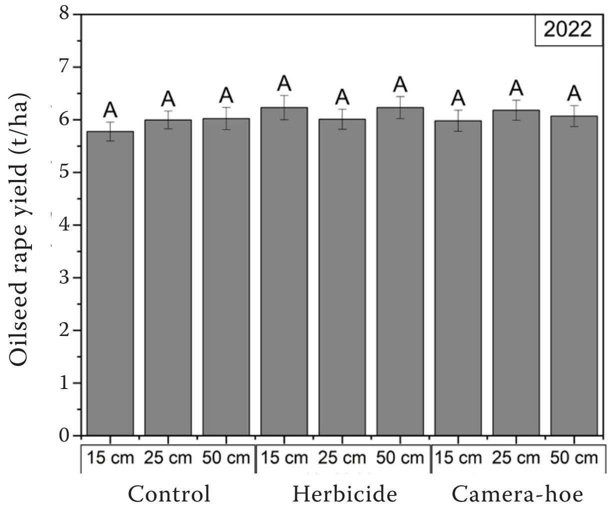

Figure 5. Oilseed rape yield after sowing with different inter-row spacings of 15, 25 and 50 cm and weed control treatments in 2021 and 2022. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

It was demonstrated in this study that oilseed rape sown in wide inter-row spacing resulted in equal yield as with conventional narrow inter-row spacing. Crop biomass, N-uptake, root diameter and yield were equal and partly higher in the wide inter-row spacing of 25 cm and 50 cm compared to the conventional 15 cm inter-row spacings. Weed densities were equal in wide inter-row spacings as in conventional narrow inter-row spacings. Różyło and Pałys (2014) observed a higher leaf area index of oilseed rape at 55 cm inter-row spacing compared to 33 cm. Harker et al. (2003) and Cacan and Kokten (2017) found that modern oilseed rape cultivars can compensate for lower seed densities with higher biomass of the individual plants. It can be assumed that single-grain seeding technologies with low densities and wide inter-row spacing will become the common cropping practice for oilseed rape. This new cropping practice will facilitate weed hoeing in oilseed rape because it increases the treated area, extends the time period for hoeing until spring and allows to guide hoeing blades closer along the crop rows (Lemerle et al. 2017, Machleb et al. 2020). Whereas Wahmhoff (1994) reported that weed hoeing in oilseed rape with narrow inter-row spacing and conventional drilling machines could cause crop damage, camera-guided inter-row hoeing in the present study did not cause any oilseed rape plant damage. Andersson and Bengtsson (1992) also observed the positive effect of inter-row hoeing on weed suppression and oilseed rape yield with almost no plant losses. However, they observed a 15% yield reduction of wide inter-row spacing, which can be explained by the fact that they used older and less competitive oilseed rape cultivars.

It can be concluded form this study that wide inter-row spacing in oilseed rape facilitated mechanical inter-row weeding and partly increased oilseed rape, weed shoot biomass, root diameter and yield. However, the success of weed hoeing strongly depends on dry soil conditions in early autumn and the quality of the seedbed.

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