IWMPRAISE

Integrated Weed Management: PRActical Implementation and Solutions for Europe

EXPERIMENTAL TRIALS IN EUROPE

2022 FINAL EDITION

This project has received funding from the European Union's Horizon 2020
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IWMPRAISE - H2020-SFS-2016-2017/H2020-SFS-2016-2

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2022 FINAL EDITION

IWMPRAISE

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Integrated Weed Management: PRActical Implementation and Solutions for Europe

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The Netherlands
United Kingdom

Partners

IWM is the future

Integrated Weed Management (IWM) is the way forward for sustainable and resilient agriculture. IWMPRAISE is a five-year Horizon 2020 project that began in June 2017 and will terminate in November 2022. It was coordinated by professor Per Kudsk, Department of Agroecology, Aarhus University, Denmark.
The project was granted € 6.6 M and it aims to support and promote the implementation of IWM in Europe. Weed management in Europe will become more environmentally friendly, if the concept of integrated weed management takes a better hold on European farms.

The IWMPRAISE workgroup.

The project aims to demonstrate that IWM supports more sustainable cropping systems, that are resilient to external impacts and do not jeopardize profitability or the steady supply of food, feed and biomaterials. The project consortium consists of 39 partners from eight different European countries and includes 11 leading universities and research Institutes within the area of weed management, 14 SMEs and industrial partners, and 12 advisory services and end-user organisations.

Focus on four scenarios

The project develops, tests and assesses management strategies delivered across whole cropping systems for four contrasting management scenarios representing typical crops in Europe. By adopting this categorical approach, it was possible to establish principles and develop IWM strategies that can be applied beyond the case studies that the project deals with. The four scenarios that the project focuses on are:

- WP3: annually drilled crops in narrow rows (e.g. small grain cereals, oilseed rape);
- WP4: annually drilled crops in wide rows (e.g. maize, sunflowers, field vegetables);
- WP5: perennial herbaceous crops (e.g. grasslands, alfalfa, red clover);
- WP6: perennial woody crops (e.g. pome fruits, citrus fruits, olives).

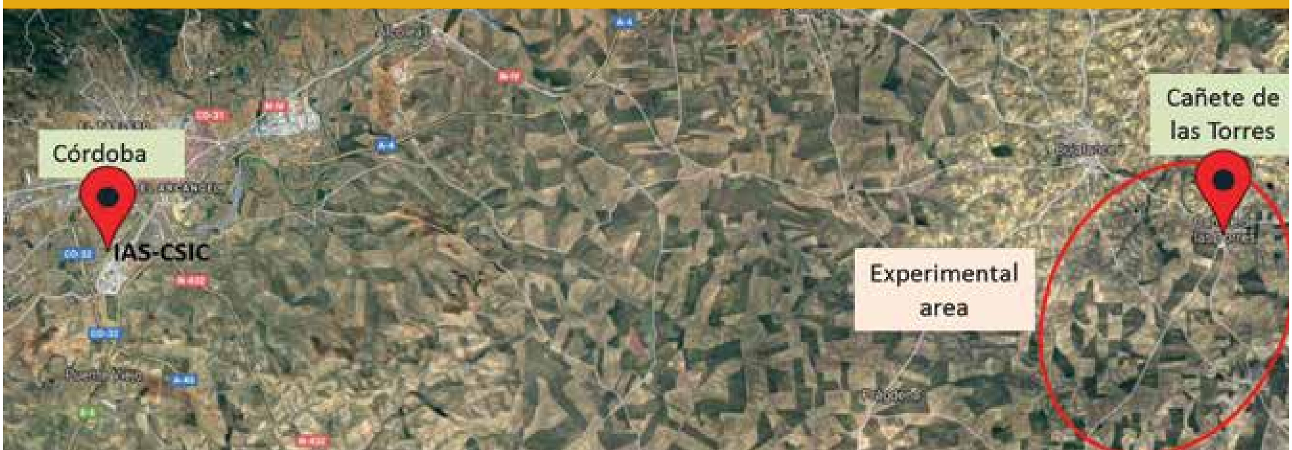
Overcoming barriers and spreading the word

The project reviews current socio-economic and agronomic barriers to the uptake of IWM in Europe and develops and optimizes novel alternative weed control methods. On this basis, the project creates a toolbox of validated IWM tools. The project also designs, demontrates and assesses the performance and environmental and economic sustainability of context specific IWM strategies for the various management scenarios that addressed the needs and concerns of end users and the public at large. The final output of the project makes the results available to end users via online information, farmer field days, educational programmes, dissemination tools and knowledge exchange with rural development operational groups dealing with IWM issues.

SPAIN

EXPERIMENTAL TRIALS IN SOUTHERN SPAIN

The Institute for Sustainable Agriculture in Córdoba, a centre of the Spanish National Research Council (IAS-CSIC), has established a collaboration with the Virgen del Campo olive-growing cooperative for the last three years. This cooperative is located in the town of Cañete de las Torres, 60 km from Córdoba, and it has more than 800 members. One of its main economic activities is olive-grove cultivation (Picual olive cultivar with farm size averaging 4-6 ha), which is mostly based on soil management by tillage or spontaneous grass cover crops. The experimental farms belong to members of the olive-growing cooperative and are located in Cañete de las Torres.



Address:
Cooperative "Virgen del Campo"
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EXPERIMENTAL TRIALS IN NORTHERN SPAIN

INTIA

The Navarre Institute of Transfer and Innovation in the Agri-food Sector (INTIA) is a public company created by the Government of Navarra to help improve agricultural viability and sustainability, and to keep the rural environment alive while respecting the environment and offering quality food to society. It has signed agreements with many companies and it also has a number of partners comprising more than 48 cooperatives, 11,400 farmers and 1,138 ranchers. Many of these farmers are olive farmers whose groves are distributed in two different areas (average size 1-5 ha per farm): 'La Ribera', where the Empeltre olive cultivar is grown, and 'La zona media' where Arróniz is the most important olive cultivar. However, both areas are commonly managed by tillage or spontaneous cover crops, mainly composed of crucifers, and will be the experimental farms in the north of Spain.

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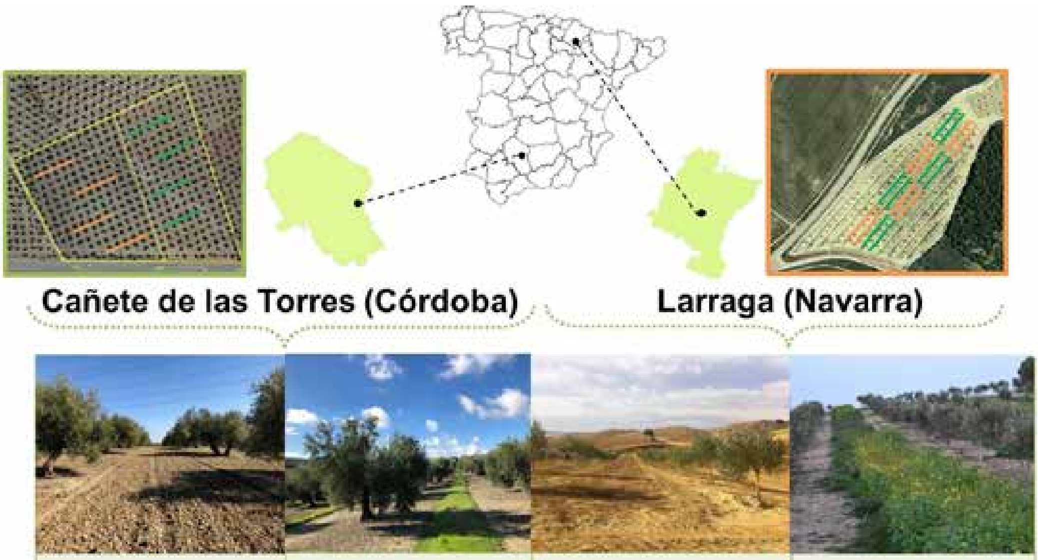
The olive (*Olea europaea* L.) is one of the most important perennial woody crop plants, occupying over 10 million hectares worldwide, 95% of which are in the Mediterranean region. Spain has the largest olive-growing area in the world, with 2.7 million hectares, an authentic "sea of olive trees". Given the broad geographical area that olive orchards cover within the country, soil- and weed-management decisions are significantly influenced by location, climatic conditions, soil, topography and grower preferences. In all of them, soil-management techniques aim to promote high profitability and quality production, with proper weed control being essential to preventing them from competing with olive trees for water, light, rooting space and other mineral resources. However, there is now a greater need than ever to combine crop production with the protection of the agroecosystem and the conservation of the soil's productive potential.
The combination of a Mediterranean-type climate, sloping areas and management practices with scarce herbaceous vegetation cover has led to severe problems of water availability and soil erosion over the years. Moreover, we are facing a growing problem of herbicide resistance, the expectation that many of the currently used herbicides will be withdrawn from the European market, and the negative effects of herbicides on farmland biodiversity.
These issues have sparked interest in Integrated Weed Management (IWM), which allows farmers to use alternative control approaches that focus on reducing the use of herbicides, replacing them, totally or partially, with non-chemical methods. Farmers typically manage weeds with repeated tillage and/or no-tillage methods. But a combination of agricultural, mechanical, biological and chemical practices is increasingly used on farms, since most of the olive orchards have two clearly distinctive areas: the bare soil beneath the olive trees, which facilitates harvesting, and the area along the lanes (intra-row and inter-row spacing), with higher susceptibility to soil degradation. Both systems can be less dependent on herbicides due to the weed-suppressing effects of a permanent soil organic cover on the surface, with a 30% minimum of soil cover being recommended by the principles of conservation agriculture. This ground coverage is usually achieved by establishing cover crops, incorporating mulch, leaving wood residues from pruning, or all three methods together. These strategies can help to reduce not only the need for chemical weed control but also soil erosion, in addition to improving soil structure and fertility in the long-term and increasing overall sustainability of the farming system. In fact, the inclusion of spontaneous or sown cover crops in the cropping system provides multiple benefits to the agroecosystem (Hartwig and Ammon, 2002), from weed and pest control to soil protection, depending on the cover crop species and their adaptability to local environmental conditions.
Therefore, proper IWM strategy should take into account not only the efficacy of weed control, but also how these practices affect weed population, the olive-cropping system and the agro-ecosystem. According to the IWMPRAISE goals, the study of perennial woody crops in Spain aims to develop, test and assess sustainable and cost-effective IWM strategies for olive orchards in order to reduce the dependence on chemical weed control without jeopardising profitability or the steady supply of food, feed and biomaterials. The specific objectives are to evaluate the effects of different IWM practices on 1) the installation and development of weeds; 2) crop yields and quality; and 3) the soil.

Materials and methods

A three-year study with four IWM strategies in three plots and a randomised complete block design with four replications per strategy were established, considering inter-row and intra-row spacing as sampling areas (Figure 1). Silty-loam and clay soils with a plot size of 528 (11×48) m^2 were selected in the south, corresponding to the distance between five trees under rainfed conditions. In northern Spain, the study was carried out with silty clay loam soils and a plot size of 429 (13×33) m^2, corresponding to the distance between six trees under irrigated conditions (minimum water application of 198 m^3/ha and a maximum of 438 m^3/ha). In southern Spain, Strategy TL involved 'tillage' combined with pruning wood residues, which were incorporated each year, alternately in one area or another.
Strategy GCC included 'no tillage with chemical control' in the intra-row spacing and spontaneous grasses (*Bromus* spp.) in an inter-row spacing of 2 m wide where killing methods were not necessary because the cover crop dried naturally in late April-early May each year. Intra-row weeds were controlled by post-emergence herbicides composed of glyphosate 36% + oxyfluorfen 24% at a rate of 2 $L \cdot ha^{-1}$. In addition, inter-row cover-crop management included broadleaf weed control by patch spraying (a mixture of fluroxypyr and MCPA). In northern Spain, Strategy NT included 'no tillage with chemical control' in both areas, using glyphosate 36% at a rate of 3-4 $L \cdot ha^{-1}$. Strategy CCC involved 'no tillage with chemical control' in the intra-row spacing and sown cover crops composed of white mustard (*Sinapis alba*) in the inter-row spacing, which were



	Strategy TL	Strategy GCC	Strategy NT	Strategy CCC
Inter-row spacing	TILLAGE + Pruning wood residues	Grass cover crops (*Bromus* spp)	No tillage with chemical control	Cover crops of white mustard (*Sinapis alba*) and spontaneous species
Intra-row spacing		No tillage with chemical control + Pruning wood residues		No tillage with chemical control

Figure 1 - Field trial details in southern and northern Spain.

killed by mechanical mowing in May. Given the poor installation of white mustard during Years 1 and 2, the CCC inter-rows were only composed of spontaneous vegetation in Year 3.

Effects on the weed community, olive crop and soil were evaluated in both locations. Weeds were assessed at two different times: December-February, before applying the two weed-control methods; and February-April, 3-4 weeks after applying the control methods. Main assessments include:

- **Weed plant density, dry biomass production and phenological growth stage**. They were estimated considering weed species in four randomly selected 0.5 m^2 areas of each sampling area per plot. Additionally, richness, diversity (Shannon index) and equity (Pielou evenness index) were calculated from plant density data in southern Spain. In northern Spain, weed evaluations were also carried out in late spring, and all the assessments after applying weed control methods were visually estimated as the ground coverage percentage occupied by each species due to its great development. Moreover, due to the high presence of the *Conyza* spp. in the experimental trials, an extra evaluation of its plant density was carried out during the autumn of Years 2 and 3, counting the number of plants in half of each elementary plot;
- **Cover-crop ground cover and phenological growth stage**;
- **Olive yield** (kg/ha) **and quality** (oil content, fruit moisture, fat content and acidity);
- **Soil fertility**: N, OM, K and P content were obtained from eight soil samples per plot in southern Spain (four soil samples in the north) at a depth of 0-15 cm during the autumn. Each sample consisted of two sub-samples from two positions located in a fixed pattern across each sampling area and block.

In southern Spain, linear mixed effects models were used to test for differences between IWM strategies and were adjusted using the lmer function from the lme4 library in the R environment. In all cases, the variable ‘plot’ was included as a random effect and the variables ‘IWM strategy’ and ‘sampling area’ were included as fixed effects. The statistical significance of the effects was obtained by ANOVA and the Tukey test at a 5% significant level. In northern Spain, data were analysed using Student’s t test at a 5% significant level.

RESULTS IN SOUTHERN SPAIN (IAS-CSIC)

Weed community

Significant effects of the use of the different IWM strategies were observed on the weed community before the two weed control methods were applied (Table 1). The results were presented individually for each year and sampling area, given the existence of significant differences between them (Table 1). Richness values were greater in both sampling areas of Strategy GCC than in TL areas in all the cases studied, except for the inter-rows during Year 3 when there were no significant differences (Table 1). Abundance showed significant differences in the

		Richness		Abundance		Diversity		Equity	
		INTER	INTRA	INTER	INTRA	INTER	INTRA	INTER	INTRA
Year 1	**TL**	5 b[1]	5 b	24 a	25 b	0.97 b	0.95 b	0.60 a	0.53 a
	GCC	12 a	12 a	23 a	50 a	1.91 a	1.59 a	0.78 a	0.68 a
Year 2	**TL**	3 b	2 b	24 a	13 b	0.49 b	0.32 a	0.63 a	0.69 a
	GCC	6 a	7 a	24 a	286 a	1.05 a	0.69 a	0.65 a	0.30 a
Year 3	**TL**	4 a	3 b	4 a	5 b	0.97 a	0.66 a	0.92 a	0.77 a
	GCC	4 a	5 a	19 a	103 a	0.64 a	0.59 a	0.61 b	0.39 b

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Tukey test, P < 0.05)

Table 1 - Richness (no. of species), abundance (no. of plants·m^{-2}), diversity (Shannon index H’) and equity (Pielou index J’) for each IWM strategy and sampling area in southern Spain.
TL = Tillage + pruning wood residues; GCC INTER = Grass Cover Crops; GCC INTRA = No tillage + chemical control.

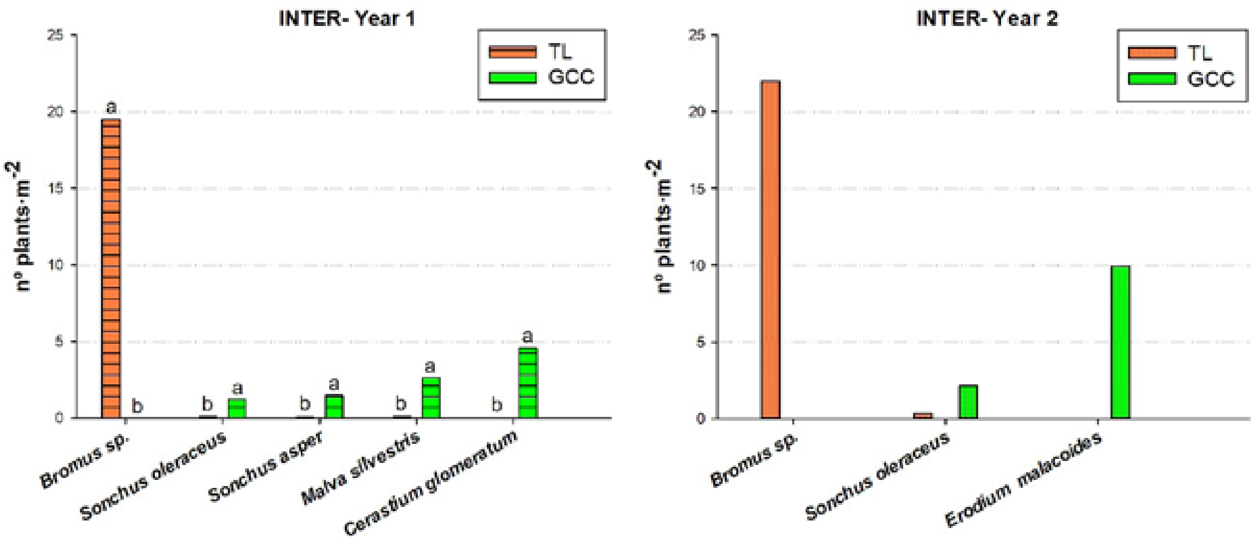


Figure 2 - Weed plant density (no. of plants·m^{-2}) showing significant differences between IWM strategies before weed-control methods were applied: grass and broadleaf weeds in the inter-rows during Years 1 and 2. Different letters within each species indicate that the differences between treatments were statistically significant (Tukey test, P < 0.05).

intra-row spacing during the three years of study, with higher values in the no-tillage intra-rows than with tillage practices (50 and 286 pl·m^{-2} vs. 13 and 25 pl·m^{-2}). The *Poaceae* family had a predominance in both sampling areas of Strategy TL over the three-year study (≈67%), followed by the *Asteraceae* family, especially in Year 3 (45%). In fact, *Bromus* spp. was the only species showing a significantly higher plant density in the inter-rows of Strategy TL than in GCC for Years 1 and 2 (Figure 2). Similarly, a higher abundance of the *Poaceae* family was observed in the intra-rows of Strategy GCC (≈80%), and *Bromus* spp. was again more abundant in GCC than in TL in all cases (Figure 3). This result could be explained by its ease of establishment, since this cover crop species is allowed to grow and dry naturally in the GCC inter-rows for self-seeding each year, and wind action can disperse the seeds to neighbouring areas. The GCC inter-rows showed a higher abundance of species belonging to the Asteraceae family during Year 1 (26%) and to the *Geraniaceae* family during Years 2 and 3 (≈40%). However, significantly higher weed-plant density was only observed in GCC for *Sonchus oleraceus*, *Sonchus asper, Malva silvestris*, and *Cerastium glomeratum* during Year 1, and for *Sonchus oleraceus* and *Erodium malacoides* during Year 2 (Figure 2). The diversity indices were greater in the inter-rows with cover crops in Years 1 and 2 (H'= 1.91 and 1.05) and in the intra-rows with no-tillage in Year 1 (H'= 1.59). It could be caused by a large number of weed species adapting to tillage, due to the repetitive use of this technique, as

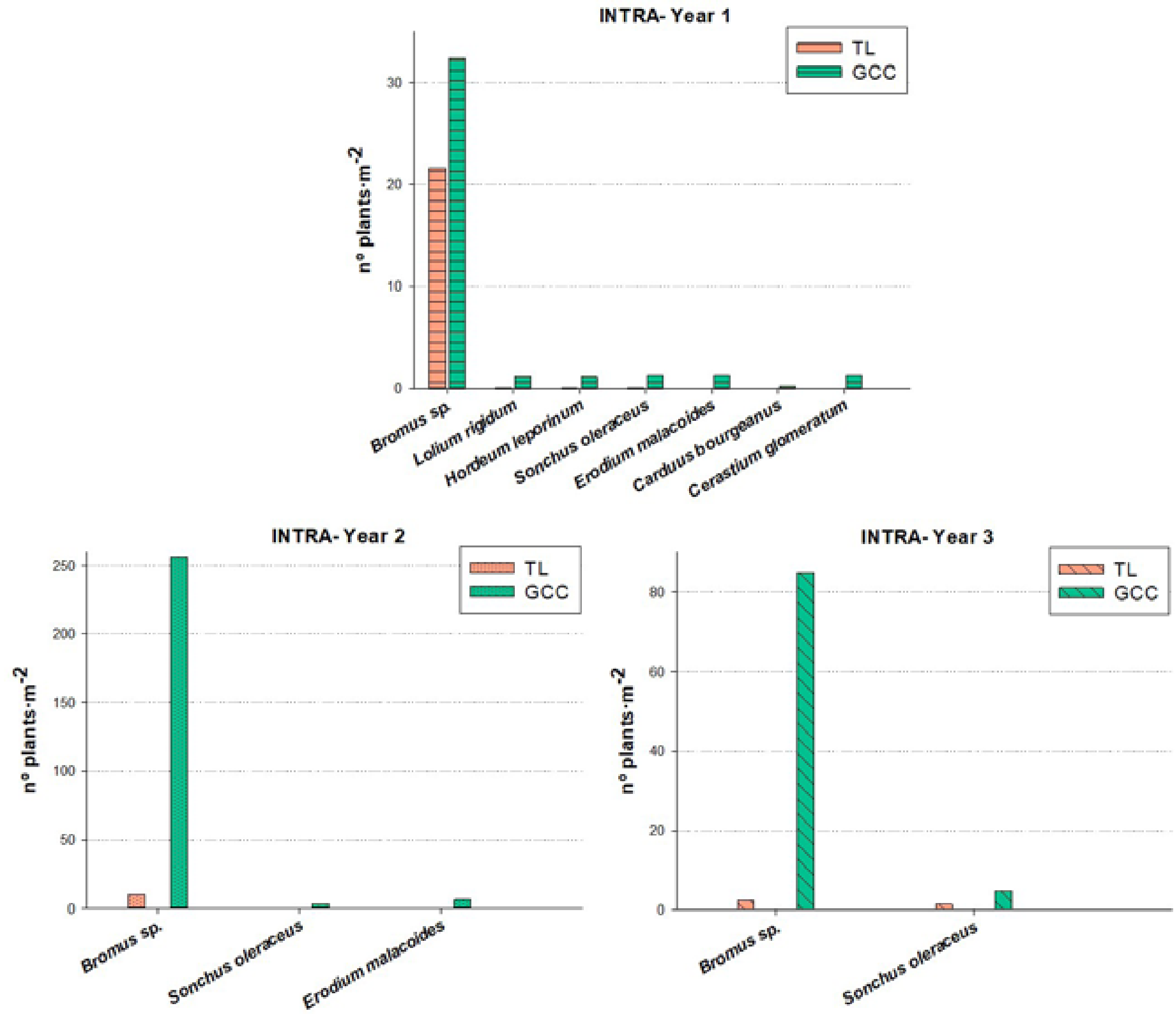


Figure 3 - Weed plant density (no. of plants·m^{-2}) showing significant differences between IWM strategies before weed-control methods were applied: grass and broadleaf weeds in the intra-rows during Years 1, 2 and 3. Different letters within each species indicate that the differences between treatments were statistically significant (Tukey test, $P < 0.05$) TL = Tillage + pruning wood residues; GCC INTER = Grass Cover Crops; GCC INTRA = No tillage + chemical control.

		Richness		Abundance		Diversity	
		INTER	INTRA	INTER	INTRA	INTER	INTRA
Year 1	**TL**	0.3 b[1]	0.3 b	0.3 b	0.4 b	0 b	0 b
	GCC	3 a	4 a	4 a	10 a	0.81 a	0.95 a
Year 2	**TL**	2 a	2 b	1 b	1 b	0.49 a	0.44 a
	GCC	4 a	4 a	20 a	14 a	0.88 a	0.94 a

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Tukey test, P < 0.05)

Table 2 - Richness (no. of species), abundance (no. of plants·m^{-2}) and diversity (Shannon index H') for each IWM strategy and sampling area in southern Spain after applying the weed-control methods. TL = Tillage + pruning wood residues; GCC INTER = Grass Cover Crops; GCC INTRA = No tillage + chemical control.

well as to chemical control, which ends up reducing weed diversity over the years. Finally, equity indices only showed significant differences between IWM strategies during Year 3, when greater equity between species was observed in both sampling areas of Strategy TL than in GCC areas (*J'*=0.92 and 0.77).

Weed control

Weeds were also evaluated after applying the control methods during Years 1 and 2 (weed samplings of Year 3 in progress). The results are presented individually for each year and sampling area due to the significant differences between them (Table 2). Richness values continued to be greater in both sampling areas of Strategy GCC (3-4 species) than in TL areas (0-2 species) in all the cases studied except in the inter-rows for Year 2 when there were no significant differences (Table 2). Abundance showed significant differences in all the study cases, giving the highest values in both sampling areas of the Strategy GCC during the two years of study (values ranging from 4 to 10 pl·m^{-2} for Year 1 and 14-20 pl·m^{-2} for Year 2). In fact, scarce or zero weed presence was observed in Strategy TL (0.3-1 pl·m^{-2}). Moreover, *Bromus madritensis* was the only species detected during Year 1, so the diversity indices were null in Strategy TL. However, the *Asteraceae* family had a high abundance in both sampling areas of Strategy TL during Year 2 (≈68%), and in spite of the low diversity indices, there were no significant differences with Strategy GCC. Strategy GCC showed similar diversity values in the inter-rows (H'= 0.81-0.88) and intra-rows (H'= 0.94-0.95) both years. Likewise, the *Poaceae* family was predominant in the GCC intra-rows (≈43% Year 1 and 69% Year 2), but *Bromus madritensis* was the only species showing a significantly greater plant density in Strategy GCC during Year 2 (Figure 4). This species was probably able to repeat its higher infestation rate despite the application of glyphosate + oxyfluorfen as it was

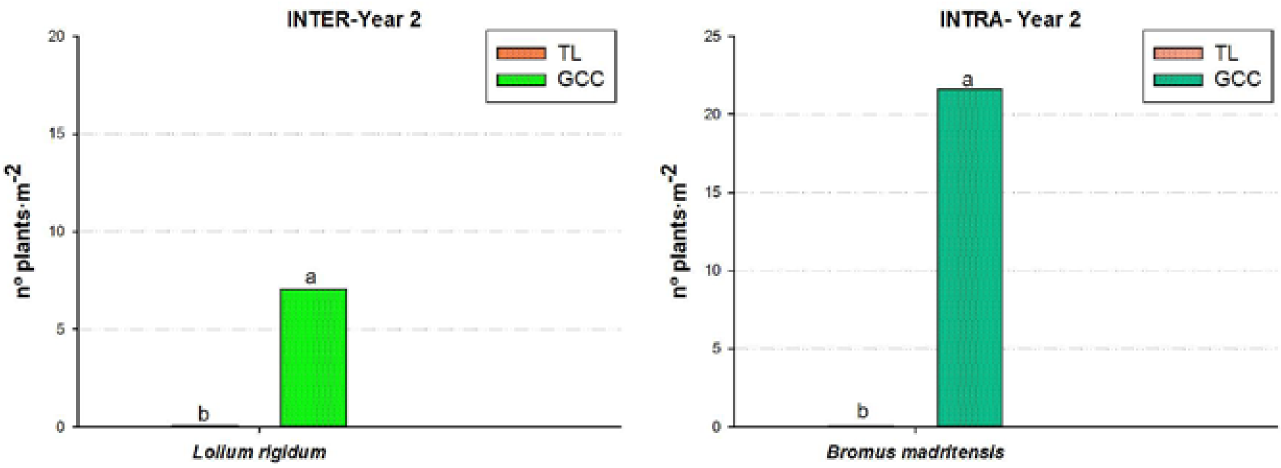


Figure 4 - Weed plant density (no. of plants·m^{-2}) showing significant differences between IWM strategies after the weed-control methods were applied in Year 2: grass weeds in the inter-rows and intra-rows. Different letters within each species indicate that the differences between treatments were statistically significant (Tukey test, P < 0.05).

present as the cover crop in the surrounding area (inter-rows).
In the GCC inter-rows in Year 2 (≈87%), there was a greater presence of *Lolium rigidum* in Strategy GCC than in TL (Figure 4). It was obviously due to the weed-control methods, taking into account that post-emergence broadleaf herbicides were the only ones applied in the GCC inter-rows, and grassweeds were allowed to coexist with the grass cover crop composed of *Bromus* spp. But these results could also be influenced by the weather conditions, since the accumulated mean monthly rainfall from January to March in Year 1 did not exceed 30 mm, and in Year 2 was 60 mm. Nevertheless, there was scarce biomass of troublesome weeds (< 82 kg/ha) (Figure 5).

Olive yield

Olive yield results showed that the 'IWM strategy' followed by farmers had no significant effect on the production any year of study (Figure 6).
The results were presented individually for each year, given the significant differences between them (Figure 6). During Year 1, the average yields were 5695 kg/ha for Strategy TL and 6293 kg/ha for GCC. During Year 2, yields reached 7648 kg/ha for TL and 8368 kg/ha for GCC; and during Year 3, 5016 and 5794 kg/ha respectively. These differences are due to various factors (olive nutrition, olive pruning, soil and weather conditions each year), one of the most important being the rainfall recorded during the critical phenological phases of flowering (May) and olive ripening (September-November). Therefore, Year 1 registered 18 and 168 mm respectively, and Year 2, 39 and 114 mm respectively. However, only 12 and 60 mm were accumulated in Year 3. Nevertheless, no significant differences were observed between the GCC and TL strategies.

Olive quality

Olive quality analysis did not induce differences in any of the measured parameters in any year of study (Table 3). Fruit oil content is taken into account in the calculation of the payment to the grower, and values were quite similar in both IWM strategies each year (≈21 % Year 1, ≈17 % Year 2 and ≈19 % Year 3). Fruit moisture showed water content ranging

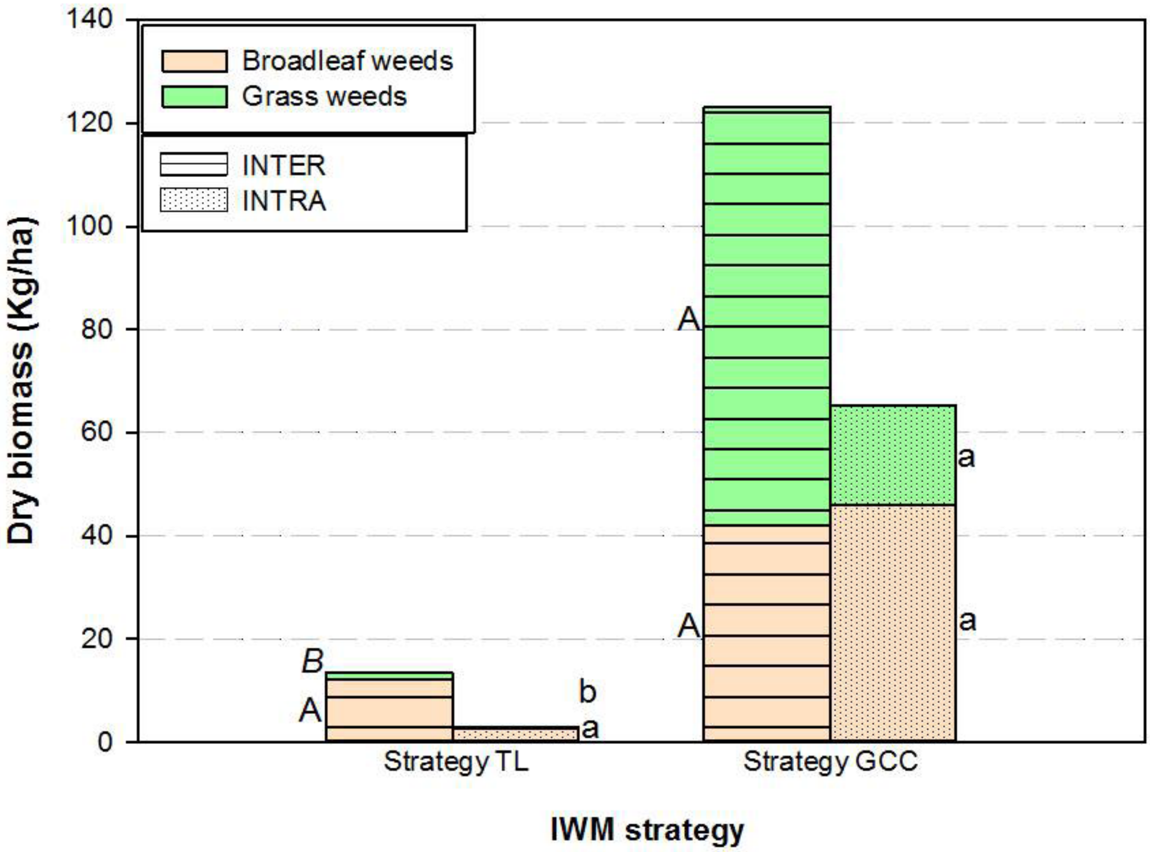


Figure 5 - Weed dry biomass (kg/ha) in each sampling area of the IWM strategies after the weed-control methods were applied in Year 2. Different letters within each year indicate that the differences between treatments were statistically significant (Tukey test, $P < 0.05$). TL = Tillage + pruning wood residues; GCC INTER = Grass Cover Crops; GCC INTRA = No tillage + chemical control.

from 47-48.5% (Year 1), 51-55% (Year 2) and 44-48% (Year 3). Fat content, which is vital to determining fruit ripening, since it is not influenced by water content, was around 39.5%, 37% and 36.5% in Years 1, 2 and 3 respectively. Finally, acidity value is also a key parameter that provides a reference of the oil quality. Results ranged from 0.39-0.43% (year 1), 0.36-0.47% (Year 2) and 0.22-0.29% (Year 3).

Soil fertility

Soil management techniques can also influence soil fertility, and our results showed that the 'IWM strategy' followed by farmers had some significant effects on fertility values (Table 4). Results were presented individually for each sampling area and year of study, given the significant differences between them.

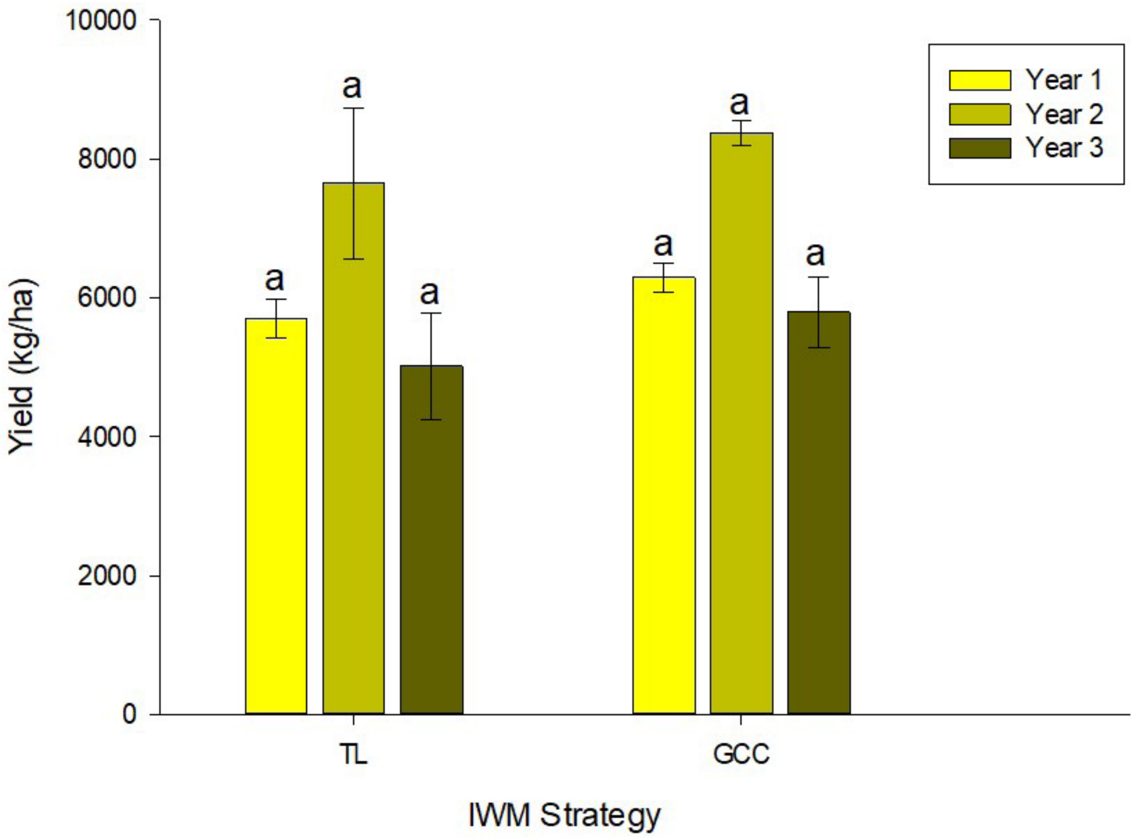


Figure 6 - Olive yield (kg/ha) in the different IWM strategies. Different letters within each year indicate that the differences between treatments were statistically significant (Tukey test, P < 0.05). Vertical bars represent standard errors.

		Fruit oil content	Fruit moisture	Fat content	Acidity
Year 1	**TL**	21.0 a[1]	47.0 a	39.2 a	0.39 a
	GCC	20.5 a	48.5 a	39.8 a	0.43 a
Year 2	**TL**	18.0 a	51.3 a	37.1 a	0.47 a
	GCC	16.8 a	54.8 a	37.2 a	0.36 a
Year 3	**TL**	19.3 a	44.1 a	34.6 a	0.22 a
	GCC	19.6 a	48.4 a	38.4 a	0.29 a

[1] Different small letters within each year indicate that the differences between treatments were statistically significant (Tukey test, P < 0.05)

Table 3 - Olive fruit quality parameters evaluated: fruit oil content (%), fruit moisture (%), fat content (%) and acidity (%) for the different IWM strategies and years in southern Spain. TL = Tillage + pruning wood residues; GCC INTER = Grass Cover Crops; GCC INTRA = No tillage + chemical control.

		N		OM		K		P	
		INTER	INTRA	INTER	INTRA	INTER	INTRA	INTER	INTRA
Year 1	TL	0.08 b[1]	0.08 b	1.13 b	1.28 b	361 b	366 a	5.13 a	5.56 a
	GCC	0.11 a	0.09 a	1.79 a	1.50 a	433 a	396 a	6.73 a	5.13 a
Year 2	TL	0.08 b	0.10 a	1.03 a	1.18 a	429 a	431 a	6.70 a	6.58 a
	GCC	0.10 a	0.11 a	1.22 a	1.28 a	428 a	428 a	4.63 a	4.73 a
Year 3	TL	0.08 b	0.08 a	0.99 b	1.04 a	377 b	382 a	6.95 a	6.99 a
	GCC	0.12 a	0.10 a	2.03 a	1.38 a	443 a	433 a	6.11 a	6.79 a

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Tukey test, $P < 0.05$)

Table 4 - Soil fertility parameters evaluated in each sampling area at a depth of 0-15 cm: organic nitrogen content 'N' (%), organic matter 'OM' (%), potassium 'K' (ppm) and phosphorus 'P' (ppm) for each IWM strategy and year in southern Spain.

Strategy GCC displayed higher organic N content than Strategy TL in the inter-rows every year and in the intra-rows in Year 1 (Table 4). The inter-rows of Strategy GCC also displayed higher values of OM and K content than Strategy TL in Years 1 and 3. It is important to note that in Years 1 and 3 there were a significantly greater N and OM content in the inter-rows where cover crops were installed than in the intra-rows. Furthermore, during Year 2 greater N and OM content was observed in the intra-rows of Strategy TL than in its inter-rows, due to the fact that pruning residues had been incorporated into the intra-row spacing the previous year. However, P content was not affected by the 'IWM strategy' followed by farmers.

Conclusions

This study showed that the different IWM strategies had an effect on the weed community. Three-year results before weed-control methods were applied showed greater richness, abundance and diversity in the GCC intra-rows than in TL ones, as well as greater richness and diversity in the GCC inter-rows, with a more diverse flora existing in Strategy GCC than in Strategy TL. Moreover, an association with specific weed species such as *S. oleraceus* and *Bromus* spp. seems to exist with the cover crop and tillage treatments. After the weed-control methods were applied, richness and abundance continued to be greater in both sampling areas of Strategy GCC, but scarce biomass of troublesome weeds was observed during the completed study years. These results, together with the similar richness and diversity indices observed in the inter-rows and intra-rows of Strategy GCC, showed that both grass cover crops (cover crop plant density ≈577 pl·m^{-2} and soil cover crop level ≈78%) and the incorporation of wood pruning residues (soil cover level ≈50%) improved ecosystem biodiversity more than tillage, controlling weeds and keeping them at a low level of abundance, with much more diverse species. Moreover, yield and quality results were not affected by the IWM strategy in spite of the greater weed abundance in the intra-rows with no-tillage than in tilled ones; weed diversity was also higher in the cover crop inter-rows during the harvest period over the three years studied. Finally, an improvement in the soil fertility of the inter-rows where cover crops were installed was observed, with higher organic N contents in Strategy GCC than in Strategy TL over the three years studied, with significantly greater OM and K content during Years 1 and 3. However, GCC intra-rows showed higher N and OM content in Year 2 only, as pruning residues were also incorporated into the TL plots, with fertility values not showing significant differences between IWM strategies. This fact highlights the improvement that both soil cover methods could represent in the long-term. Soil conservation is crucial in semiarid regions where soil cover is not frequent but necessary for erosion control and fertility preservation. Although our study presented no data on soil erosion under the treatment conditions, soil protection was assumed to be based on the coverage values, and they provided effective ground cover with values ≥ 50%. Therefore, combining the use of these soil-improving non-chemical weed-control methods (cover crops and pruning wood residues) with herbicide applications could lead to reconciling crop production and beneficial weed flora at a manageable threshold in order to achieve a profitable and sustainable agricultural system in the long-term.

Nowadays, little is known about the IWM practices that could be associated with the weed community in olive orchards, and such information is crucial for further research on the optimisation of this system. Moreover, the weed-control results of this study also showed some tolerant or resistant weed species. This knowledge could be very useful for farmers, who could change their current herbicides and not repeatedly use the same active substances (especially glyphosate) every year, thus preventing a shift in the weed flora established. Therefore, a better understanding of the factors influencing the emergence and proliferation of species could improve weed-control efficacy, reducing the use of herbicides and moderating the intensity of soil operations. This could also mean favouring the use of cover crops and incorporating pruning residues into future olive orchards.

RESULTS IN NORTHERN SPAIN (INTIA)

Weed community

Results of the weed flora before application of the two weed-control methods are included in Table 5. The number of species showed significant differences during Year 2, with higher values in the no-tillage inter-rows than in those with cover crops (24 pl·m^{-2} vs. 14 pl·m^{-2}). It could be due to the sowing of the white mustard as a cover crop for two consecutive years, which reduced the presence of other species. Nevertheless, there was a poor installation of *Sinapis alba* (219 pl·m^{-2} in Year 1 and 128 pl·m^{-2} in Year 2). The *Asteraceae* family had predominance in both sampling areas and IWM strategies, followed by the *Poaceae* family in the three-year study.

Weed control

Weeds were evaluated for the first time 3-4 weeks after the control methods (late winter weed control) were applied and also in late spring (late spring weed control). An extra control was carried out in autumn for the *Conyza* spp. (autumn weed control).

Late winter weed control

Table 6 presents dry biomass before and after herbicide was applied to the inter-rows each year except for Year 3, when biomass was evaluated in the late spring weed control (Table 8). *Sinapis alba* is a very fast-growing species, with higher dry biomass being produced by Strategy CCC during the three years of study, even in Year 3 when it was not sown. However, in spite of the values observed, there were no significant differences between IWM strategies.

Late spring weed control

Weed-control results in late spring are shown in Table 7. Given the great development of weeds over this sampling date, weed presence was evaluated as the number of species and ground cover percentage. There were no significant differences between IWM strategies. However, Strategy NT displayed a lower ground coverage percentage than Strategy CCC in absolute terms during the three years of study, due to the control carried out with herbicide application. This weed flora corresponded to plants that emerged after the herbicide application since no residual herbicide was applied. A new herbicide application was essential to preventing weed competition with the olive orchards during the summer in Strategy NT, while no application was necessary for Strategy CCC. Once again, the *Asteraceae* family had predominance in both IWM strategies, followed by the *Poaceae* family. In relation to weed plant density, *Lolium rigidum*, *Bromus* spp. and *Anacyclus clavatus* were the most abundant species in Strategy CCC while *Conyza* spp., *Convolvulus arvensis* and *Ditrichia viscosa* showed the highest plant density values in Strategy NT. Moreover, the species A*nacyclus clavatus, Beta maritime, Cirsium arvense, Convolvulus arvensis, Conyza* spp., *Ditrichia viscosa*, *Hordeum murinum, Lolium rigidum, Picris echioides, Polygonum aviculare*, and *Scorzonera laciniata* were detected in both IWM strategies in all the samplings. However, *Cirsium arvense* was the only species that was observed in Strategy CCC over the three years, while it was not present in Strategy NT at any stage. Weed dry biomass was collected in the inter-rows during Years 2 and 3 (Table 8). During Year 2, there were no significant differences between IWM strategies. However, statistical analysis could not be done for Year 3 due to a technical failure when the biomass of Strategy NT was being evaluated.

Autumn weed control

Weed management in Strategy CCC favoured the germination of autumnal species that were later destroyed with cover-crop killing methods (mechanical mowing with a brushcutter). Furthermore, the cover crop residues and mulching created on the soil surface acted as a natural barrier for the germination of species in early summer. Therefore, weed flora was scarce in summer and autumn, preventing it from competing with olive orchards for water and nutrients in these critical periods. In contrast, weed management in Strategy NT did not control *Conyza* spp. Two different weed species were identified: *Conyza bonariensis* and *Conyza canadensis*. The presence of these species was scarce during Year 1, but the plant density in

		No. of species	No. of families	Abundance	Abundance without including Sinapis alba
Year 1	**NT**	19 a[1]	11 a	1684 a	1684 a
	CCC	16 a	9 a	2346 a	2127 a
Year 2	**NT**	24 a	12 a	1407 a	1407 a
	CCC	14 b	7 a	1552 a	1424 a
Year 3	**NT**	33 a	15 a	2422 a	2422 a
	CCC	25 a	12 a	2571 a	2571 a

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, P < 0.05)

Table 5 - Summary of weed presence in the inter-rows of each IWM strategy: number of species, number of families, abundance (no. of plants·m^{-2}) and abundance, without including *Sinapis alba* (no. of plants·m^{-2}) in northern Spain. NT = No tillage + chemical control; CCC: No tillage + chemical control + cover crops.

		Before applying herbicide	After applying herbicide
Year 1	**NT**	1760 a[1]	-
	CCC	3260 a	6270
Year 2	**NT**	958 a	948 a
	CCC	1300 a	1711 a
Year 3	**NT**	735 a	-
	CCC	945 a	-

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, P < 0.05)

Table 6 - Weed dry biomass (kg/ha) in the inter-rows of each IWM strategy before and after weed control methods were applied.

		Ground coverage	No. of species
Year 1	**NT**	73 a[1]	-
	CCC	88 a	-
Year 2	**NT**	47.2 a	36 a
	CCC	74.7 a	35 a
Year 3	**NT**	49.8 a	20 a
	CCC	100 a	36 a

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, P < 0.05)

Table 7 - Summary of weed presence in the inter-rows of each IWM strategy in late spring: ground coverage (%) and the number of species.

the inter-rows was significantly higher in Strategy NT than in Strategy CCC in Years 2 and 3 (Table 9). Dry biomass was also evaluated in Year 3, with significant differences found between IWM strategies. Herbicide application in winter and summer was not able to control these species, which become herbicide-resistant after stem elongation starts, supporting high application rates and re-emerging later.

		Dry biomass
Year 2	NT	838 a[1]
	CCC	2229 a
Year 3	NT	-
	CCC	4560

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, $P < 0.05$)

Table 8 - Weed dry biomass (kg/ha) in the inter-rows of each IWM strategy during late spring of Years 2 and 3. NT = No tillage + chemical control; CCC = No tillage + chemical control + cover crops.

		Abundance	Dry biomass
Year 2	NT	6.73 a[1]	-
	CCC	0.13 b	-
Year 3	NT	261.3 a	1482 a
	CCC	7.5 b	36 b

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, $P < 0.5$)

Table 9 - Summary of the presence of *Conyza* spp. in the inter-rows of each IWM strategy during the autumn of Years 2 and 3: abundance (no. of plants·m^{-2}) and dry biomass (kg/ha).

		Olive yield
Year 1	NT	1473 a[1]
	CCC	1404 a
Year 2	NT	2928 a
	CCC	2865 a
Year 3	NT	3636 a
	CCC	3415 a

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, $P < 0.05$)

Table 10 - Olive yield (kg/ha) in the different IWM strategies.

Olive yield

Olive yield results showed that the 'IWM strategy' followed by farmers had no significant effect on the production any year of study (Table 10). Despite high weed existence in the inter-rows of Strategy CCC, there was no significant reduction in olive yield when compared to Strategy NT. Moreover, olive yields increased as the olive trees grew. Therefore, the average yields were 1473 kg/ha for Strategy NT and 1404 kg/ha for Strategy CCC in Year 1. During Year 2, yields reached 2928 kg/ha for NT and 2865 kg/ha for CCC, and during Year 3, 3636 and 3415 kg/ha respectively.

Olive quality

Olive quality analysis did not show differences in any of the measured parameters during Years 2 and 3 (Table 11). Due to a technical failure, statistical analysis was not possible during Year 1. Fruit oil content was around 23.3% and 26.4% for the second and third years respectively. Fruit moisture showed water content of around 43.1% (Year 2) and 41.1% (Year 3). Finally, acidity values were in the range of 0.32-0.33% (Year 2) and 0.40-0.41% (Year 3).

		Fruit oil content	Fruit moisture	Acidity
Year 1	**NT**	24.73	40.27	0.35
	CCC			
Year 2	**NT**	23.41 a[1]	43.29 a	0.33 a
	CCC	23.10 a	42.93 a	0.32 a
Year 3	**NT**	26.2 a	41.2 a	0.40 a
	CCC	26.5 a	41.0 a	0.41 a

[1] Different small letters within each year indicate that the differences between treatments were statistically significant (Student's t test, P < 0.05)

Table 11 - Olive fruit quality parameters evaluated: fruit oil content (%), fruit moisture (%) and acidity (%) for the different IWM strategies and years in northern Spain. NT = No tillage + chemical control; CCC = No tillage + chemical control + cover crops.

		N		OM		K		P	
		INTER	INTRA	INTER	INTRA	INTER	INTRA	INTER	INTRA
Year 1	**NT**	0.14 a[1]	0.13 a	1.79 a	1.64 a	208 a	185 a	20.51 a	25.69 a
	CCC	0.15 a	0.14 a	1.94 a	1.89 a	239 a	208 a	19.53 a	33.84 a
Year 2	**NT**	0.14 a	0.14 a	1.67 a	1.46 a	158 a	155 a	14.23 a	23.80 a
	CCC	0.15 a	0.13 a	1.62 a	1.34 a	160 a	204 a	13.24 a	24.09 a
Year 3	**NT**	0.11 a	0.10 a	1.81 a	1.76 a	231 a	228 a	16.98 a	24.31 a
	CCC	0.12 a	0.11 a	2.00 a	1.87 a	251 a	236 a	14.71 a	27.66 a

[1] Different small letters within each year per column indicate that the differences between treatments were statistically significant (Student's t test, P < 0.05)

Table 12 - Soil fertility parameters evaluated in each sampling area at a depth of 0-15 cm: organic nitrogen content 'N' (%), organic matter 'OM' (%), potassium 'K' (ppm) and phosphorus 'P' (ppm) for each IWM strategy and year in northern Spain.

Soil fertility

Soil analysis showed that the 'IWM strategy' followed by farmers did not show significant effects on fertility values (Table 12).

Conclusions

Cover-crop implementation and management in olive orchards of northern Spain attract considerable public interest among farmers in the area. However, there are no previous experiences in the area, and it is believed that the installation of autumnal cover crops can lead to some difficulties in soil and weed management in northern Spain. For example, mechanical harvesting in rainy autumns can hinder the proper installation and development of cover crops, as occurred during the first year.

For these reasons, there are still many questions and doubts about the most appropriate cover-crop management needed to establish a balance between the possibility of re-sowing existing species (both white mustard and spontaneous species) and the competition they could establish with the main crop (olive orchards). Nevertheless, this three-year study showed that there was no effect on yield and quality results, nor on soil fertility parameters. Given the existing irrigated conditions, further verifications of these strategies are required in order to know the effects on yield and quality in the long-term.

It was remarkable to observe that there was a greater abundance of *Conyza* spp. in the inter-rows of Strategy NT than in those of Strategy CCC after weed-control methods were applied. It could be due to the fact that these species ended up adapting to this chemical control (glyphosate), with them potentially competing with the olive trees for water in summer and autumn, which are critical phenological phases of olive ripening and oil accumulation. These results showed that the use of IWM strategies is needed to control *Conyza* spp., alongside other alternative herbicides combined with agricultural practices such as the cover crops, which managed to keep these resistant weeds at an acceptable level.

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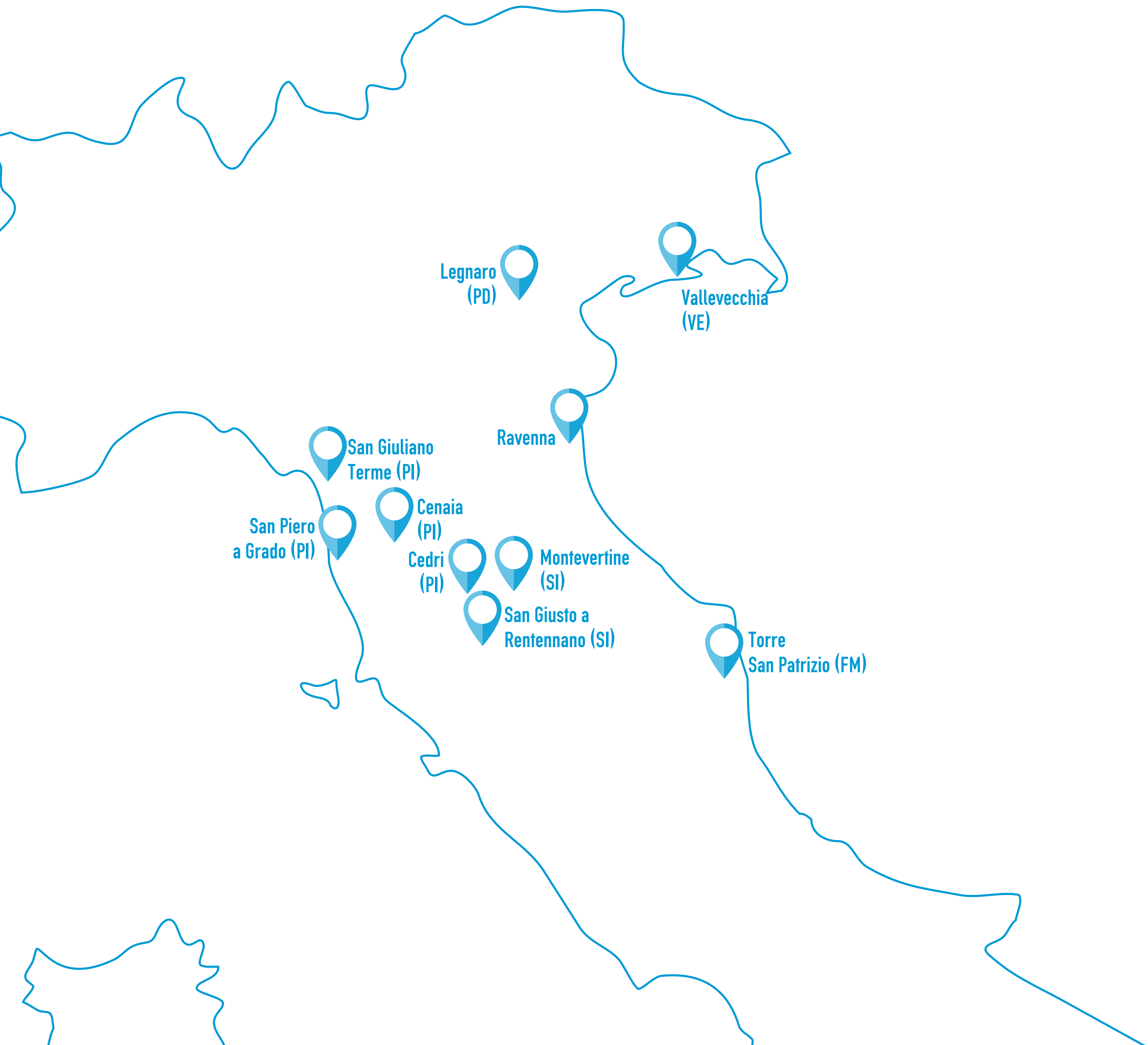
Legnaro
(PD)
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Terme (PI)
Cenaia
(PI)
San Piero
a Grado (PI)
Cedri
(PI)
Montevertine
(SI)
San Giusto a
Rentennano (SI)
Torre
San Patrizio (FM)

EXPERIMENTAL TRIALS AT VALLEVECCHIA FARM

Owned by the Veneto Region and managed by Veneto Agricoltura (the regional agency for innovation in the primary sector), Vallevecchia pilot farm is located between the beach towns of Caorle and Bibione, in the Province of Venice, and is the last non-urbanized coastal site in the northern Adriatic area.
Among the last land reclamations in Veneto, the area is characterized by important environmental sites: 63 hectares of coastal pine forest, 100 hectares of lowland forests, 24 km of hedges, and over 68 hectares of wetlands. Between the sandy shore and the pine forest lies one of the largest shoreline dune systems in the Veneto region; it is annexed to 377 hectares of farmland used for rotated crops (maize, winter-wheat, soybean, canola, sorghum, alfalfa, meadows and vegetables).
Vallevecchia was recognized as a Special Protected Area and Site of Community Importance within the European Union's Natura 2000 network.

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WP7 – WEED MANAGEMENT IN THE TRANSITION PHASE FROM CONVENTIONAL TO CONSERVATION AGRICULTURE

Conservation Agriculture (CA) is based on tillage reduction, continuous soil cover by crop residues and cover crops, and crop rotation. The adoption of CA produces major benefits, such as reduced fuel consumption, greenhouse-gas emissions and soil erosion, as well as improved soil fertility, but agronomic practices need to be adapted. Weed management, in particular for sod seeding, is more difficult because reduced soil tillage significantly limits the mechanical control of weeds. CA systems are consequently more dependent on herbicide use, including for cover crop termination.
Shifting to CA systems allows to interrupt recurrently burial and exhumation of weed seeds, caused by tillage operations. Seeds also accumulate on the top-soil layer where they have a higher probability of germinating. Minimising weed dissemination is therefore crucial for progressively reducing the soil seed bank and consequently weed infestation density, thus allowing future control strategies to use less herbicide. Weed management is particularly important during the transition phase, since transition results affect the future sustainability of CA systems. Poor weed control would lead to a rapid increase in superficial soil seed bank and consequently to increasingly problematic weed infestations. A rational chemical control strategy is necessary, but careful cover-crop management also contributes both to controlling weeds and reducing herbicide use. Cover-crop mixtures and sowing techniques should be adapted to local conditions, since good cover-crop establishment and rapid growth are crucial to controlling weeds. Furthermore, the adoption of effective no-chemical termination (e.g. mechanical) techniques may reduce the environmental impact of CA systems.

Objectives

This study focuses on establishing weed-control strategies for CA systems and, in particular, for the transition phase. A variety of chemical control options were compared, while various cover-crop species or mixtures were evaluated, and a range of sowing (i.e. undersowing in cereals) or termination techniques (i.e. roller crimper – Figure 1) were tested.
The specific objectives of this study were to:

- establish weed control strategies for cropping and intercropping periods to minimise dissemination;
- evaluate cover-crop mixtures and sowing techniques to achieve rapid establishment and high competition against weeds;
- decrease herbicide use for cover-crop termination by adopting mechanical tools (e.g. roller crimpers), or selecting cover crops which are killed by winter frost.

Materials and methods

This experiment is designed to simulate the transition phase, i.e. the first three years, from arable management to a CA system, by adopting a three-year crop rotation (wheat-sorghum-soybean) with cover crops during the intercropping periods. Minimum tillage was performed in autumn 2017 to prepare the seedbed of the first crop (wheat), while no-till was adopted from the second year. The experiment compared three treatments, i.e. three different management strategies, characterised by various levels of herbicide use and cover-crop

Figure 1 - Cover crop termination with Roller crimper.

Figure 2 - Cover crop undersowing in wheat plots.

Figure 3 - Experimental scheme of the WP7 trial.

Figures 4 and 5 - Cover-crop (clover) size in May 2018 (left) and two months after the wheat harvest (right).

	Treatment 1	Treatment 2	Treatment 3
October 2017	Wheat sowing	Wheat sowing	Wheat sowing
March 2018			Cover crop undersowing
April 2018	Post-emergence herbicide	Post-emergence herbicide	Post-emergence herbicide (if necessary)
June 2018	Wheat harvest	Wheat harvest	Wheat harvest
July 2018		Summer cover crop sowing	
August 2018	Glyphosate on stubble		
October 2018	Autumn cover crop sowing	Summer cover crop termination Autumn cover crop sowing	
March 2019	Chemical cover crop termination	Chemical cover crop termination	Chemical cover crop termination (if necessary)
April-May 2019	Sorghum sowing	Sorghum sowing	Sorghum sowing
May-June 2019	Pre and Post-emergence herbicide	Post-emergence herbicide	Post-emergence herbicide
September 2019	Sorghum harvest	Sorghum harvest	Sorghum harvest
October 2019	Autumn cover crop sowing	Autumn cover crop sowing	Autumn cover crop sowing
April 2020	Chemical cover crop termination	Chemical cover crop termination	Cover crop termination with roller crimper (if necessary)
June 2020	Soybean sowing	Soybean sowing	Soybean sowing
June 2020	Pre and Post-emergence herbicide	Post-emergence herbicide	Post-emergence herbicide
October 2020	Soybean harvest	Soybean harvest	Soybean harvest
December 2020	Wheat sowing	Wheat sowing	Wheat sowing
April 2021	Post-emergence herbicide	Post-emergence herbicide	Post-emergence herbicide (if necessary)
July 2021	Wheat harvest	Wheat harvest	Wheat harvest

Table 1 - Main operations for the three treatments from 2017 to 2020.

management. Treatment T1 included high herbicide use, with pre- and post-emergence application for some crops, and use of glyphosate for cover-crop termination. The objective of T1 was to achieve the maximum weed-control level by minimising initial weed dissemination and consequently reducing the superficial soil seed bank in order to facilitate weed control and reduce environmental impact in the following years. Treatment T2 simulated standard local management for CA systems and relied on post-emergence herbicide application for weed control and glyphosate for cover-crop termination. Cover crops were always present during the intercropping periods. Treatment T3 aimed to reduce herbicide use by adopting techniques for sowing cover crops (i.e. undersowing in cereals) that increase their ability to compete against weeds by using non-chemical termination techniques, such as roller crimpers (Figure 1), or by selecting cover crops which are killed by winter frost. Detailed information about the different management types for the three treatments are presented in Figure 3 and Table 1.
The field experiment was arranged in three adjacent fields, each divided into 10 m x 500 m strips with a randomised block design and three replicates (replicate plot size: 10 m x 500 m = 5,000 m^2; total experiment size: about 4.5 ha).
After the previous crop (soybean) had been harvested in October 2017, minimum tillage was carried out on the whole experiment surface and initial fertilisation (150 kg/ha of diammonium phosphate 18-46 NP) was performed. Wheat (cv Altamira) was sown on 28/10/2017. The first weed assessment was made in March 2018 to evaluate whether herbicide was needed and to choose a suitable herbicide mixture. Given that weed presence was low, no herbicide was applied on T3 plots, while a post-emergence herbicide (clodinafop 30 g/L, pinoxaden 30 g/L, florasulam 7.5 g/L at 0.7 L/ha) was distributed on the other plots. Undersowing of red clover (*Trifolium pratense*, 20 kg/ha) + white clover (*Trifolium repens*, 5 kg/ha) was performed on 29/03/2018 in the cereal plots of Treatment T3 (Figure 2). A second assessment was made in May to evaluate the level of weed control achieved with the different treatments, as well as cover-crop establishment and growth (Figures 4 and 5). Weed density was very low in all plots; clover emerged but remained at the 2-3 leaf stage until crop harvest. No differences were observed between the wheat yield (6-6.5 t ha^{-1}) achieved with the three treatments (Figure 6). After the wheat had been harvested, a summer cover crop (sorghum) was sown in T2 plots on 12/07/2018 (Figure 7), while the clover mixture covered the soil surface among cereal stubble in T3 plots.

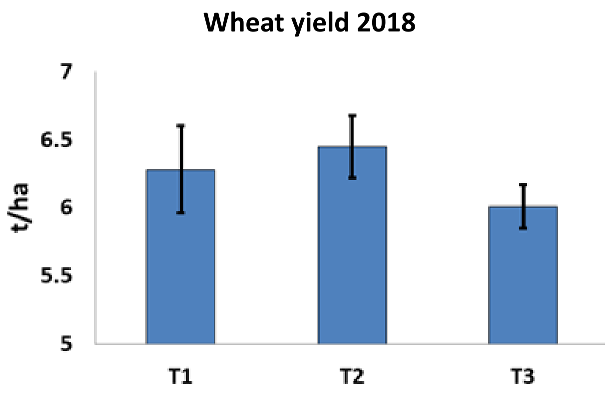

Figure 6 - Wheat yield obtained with the three treatments (T1, T2 and T3) in 2018. Vertical bars represent standard errors.

Figure 7 - Sowing summer cover crop in wheat stubble.

Figure 8 - Clover cover crop with high weed presence just before mulching in September 2018.

Figure 9 - Sorghum cover crop at harvest in September 2018.

Figure 10 - T3: clover cover crop completely covering the soil when glyphosate was applied before spring crop sowing.

Figure 11 - 15 July 2019. Poor crop emergence in the T3 plot (left side) and T1 plot (right side) due to drought. T3 plots: clover cover crop partially regrew after glyphosate application, with limited weed emergence.

Figure 12 - 10 October 2019. Sorghum harvest. Good yields (30 t/ha of fresh biomass), with no differences between treatments and few weeds.

However, the clover mixture was not able to prevent the growth of perennials, such as *Sorghum halepense*, *Cirsium arvense* and other species, so a mechanical operation (mulching) was required to control them (Figure 8). This operation did not terminate the cover crop, which continued to grow. No operations were conducted on the T3 plots until cover-crop termination in spring 2019 for all plots. Glyphosate was applied to T1 plots during the intercropping period in September and it controlled any emerged weeds. The summer cover crop sown in T2 plots grew very well, producing high amounts of biomass thanks to some summer rainfall (Figure 9). It was therefore decided to partially harvest the biomass as silage for livestock to avoid potential problems related to the excessive amount of residues during the subsequent sowing operations. Approximately 10 t ha^{-1} of fresh sorghum biomass were harvested at the end of September and removed from the field. The autumn cover crop (wheat for biomass) was supposed to be sown in early October, however the sowing was postponed until early December due to rainy weather and consequently biomass production was scarce. However, the clover cover crop managed to completely cover the soil during winter and produced significant biomass before termination (Figure 10). Cover crops were terminated in April 2019 in all plots by applying glyphosate. Sorghum for silage production, which is more tolerant to water stress than maize, was sown in June 2019. Different weed-management strategies were planned for the three treatments: application of pre-emergence followed by post-emergence herbicide for T1; and post-emergence for T2 and T3, but only when necessary for T3. However, an extremely dry period after sowing (almost no rain in June) hindered the utilisation of pre-emergence herbicides, only post-emergence herbicides (dicamba 150 g ha^{-1}, prosulfuron 15 g ha^{-1}) were therefore applied on T1 and T2 plots on 9 July. Lower weed emergence was observed in T3 plots, where the clover cover crop was able to produce good biomass and consequently good dead mulch was present on soil surface, and no herbicide was applied there (Figure 11). The drought conditions in the month after sorghum sowing also hindered its emergence, and the final crop density was not optimal.

No difference was observed between treatments. Sorghum was harvested for silage production on 10/10/2019, with yields being satisfactory (30 t ha^{-1} of fresh biomass with 70% RH) in spite of non-optimal crop density due to summer drought (Figure 12). Weed presence was low and localised in the gaps of crop canopy caused by failure of crop emergence. No differences could be detected between treatments regarding crop yield or weeds.

After sorghum harvest, red clover, which had maintained a small size under the crop canopy, again covered the soil surface in T3 plots (Figure 13). On 24/10/2019, autumn cover crops were sown with direct drilling in all plots: rye (*Secale cereale*, 160 kg ha^{-1}) for T1 and T2 plots, and lopsided oat (*Avena strigosa*, 60 kg ha^{-1}) for T3 plots. Lopsided oat was direct drilled in the T3 plots without removing or destroying the red clover biomass in order to improve soil cover in the initial part of the autumn (Figure 14). Lopsided oat was selected because it is usually killed by winter frost and therefore no chemical or mechanical operations would be required for termination. Cover crops grew during the autumn-winter period; however, the late sowing date limited their biomass production before the winter growing pause. Consequently, lopsided oat was able to overwinter and restarted its growth in February 2020 (Figure 15).

Similarly white clover, which was initially sown in February 2018, survived its second winter. Given the significant amount of biomass produced, the cover crops were then terminated by mulching in May 2020. Glyphosate was then applied when the next cash crop, soybean, was sown. The white clover was initially controlled by glyphosate, but it grew back three weeks after the treatment.

Due to a prolonged dry period in April and May 2020, soybean sowing was postponed until 2 June, after which some precipitation occurred, increasing soil moisture sufficiently. Crop emergence and establishment were good (Figure 16A), however some patches of white clover in T3 plots caused early competition with soybean (Figure 16B). Weed emergence was lower in plots with higher amounts

Figure 13 - 24 October 2019. After sorghum harvest, clover covered the entire soil surface of the T3 plots (right).

Figure 14 - 24 October 2019. Direct drilling: rye (*Secale cereale*, 160 kg/ha) for T1 and T2 plots, and lopsided oat (*Avena strigosa*, 60 kg/ha) for T3 plots.

Figure 15 - 18 February 2022. Cover crop conditions at the end of winter: rye (*Secale cereale*) for T1 and T2 plots (right), and lopsided oat (*Avena strigosa*) for T3 plots (left).

Figures 16A and 16B - End of June 2020. Crop emergence in plots with high presence of residues on soil surface (left) and within patches of white clover (right).

Figures 17A and 17B - End of September 2020. Soybean plots with low weed presence (left) and with patches of white clover (right).

of residue, which acted as dead mulch. Different weed-management strategies in the soybean crop were adopted for the three treatments: application of early post-emergence herbicides (bentazone + imazamox + thifensulfuron-methyl, on 24/06/2020) followed by a second post-emergence application (cycloxydim + imazamox + thifensulfuron-methyl, on 30/06/2020) for T1; and a single post-emergence application (cycloxydim + imazamox + thifensulfuron-methyl, on 24 June) for T2 and T3.
Good weed control was obtained with all treatments (Figure 17A), apart from limited areas where soybean plants were absent or small. The patches of white clover remained until harvest, reducing soybean growth and production (Figure 17B). The soybean was harvested on 10/10/2020 with average yields around 2.6 - 3.2 t ha^{-1} (Figure 18). Given the large variability between fields, no significant differences were detected between treatments.

After the soybean harvest, glyphosate was applied to all plots.
Direct-drilling of wheat was planned immediately after the soybean harvest; however, weather conditions in October and November 2020 were rather wet. The damp soybean residues on the soil surface obstructed the farm's direct-drilling seeder, so trials were necessary to find the right calibration and settings. Wheat was sown in December 2020. Heavy rainstorms in January and February 2021 caused prolonged stagnation and water logging conditions in some parts of the fields, leading to plant death and extended gaps in the crop stand. Weed density in March was average (about 20-30 plants m^{-2}) without differences among treatments. To prevent excessive weed growth in the gaps without crop, post-emergence herbicides (a mixture of clodinafop 21 g ha^{-1}, pinoxaden 21 g ha^{-1} and florasulam 5.25 g ha^{-1}) were applied to all

plots on April 2021, including Treatment T3. Weed control was good but in late spring dense patches of *Conyza canadensis* emerged in the crop gaps at the wheat milk-maturity stage (Figure 19). These weed plants were only partially damaged during the wheat harvest and were able to grow back over the following weeks. The wheat was harvested in July 2021, with yields ranging between 4.1 and 5.2 t ha^{-1} for treatments T1 and T3 respectively (Figure 20). These values were lower than the local average due to the gaps in crop stand caused by water stagnation. Given that these gaps were not uniformly distributed across the three fields, with some treatment plots significantly more affected than others, unfortunately we could not ascribe the differences observed between treatments to management.

This field experiment ended after the wheat harvest in July 2021. Given the results and observations achieved in this four-year trial, the following conclusions can be drawn:

- After four years, weed density was rather similar in the plots managed with the different treatments. The low-herbicide management (Treatment T3) did not cause a significant increase in weed populations in comparison with the high-herbicide management (Treatment T1).
- A partial shift in the composition of weed communities was observed, with a progressive and significant increase in wind-dispersed species, such as *Conyza canadensis*.
- All the different crops (wheat, soybean, silage sorghum) performed quite well, apart from the last year (2021) due to late wheat sowing. This underlines how important the correct timing of crop sowing is in conservation agriculture since seedbed conditions cannot be improved with soil tillage.
- Cover crops performed rather well, with the relay cropping of clovers during winter wheat achieving good results in terms of cover crop density and growth after the cereal harvest. White clover has proven to be very effective in covering the soil, even when established as relay cropping within cereal fields. However its termination before crop sowing was difficult in the following years, even when glyphosate was applied. The management of this clover species as a cover crop therefore seems rather challenging in no-till conservation agriculture.
- Sorghum also proved to be a competitive and fast-growing cover crop, adequate for summer sowing after winter cereal harvest. However, this species is able to produce high biomass under good environmental conditions; consequently, once

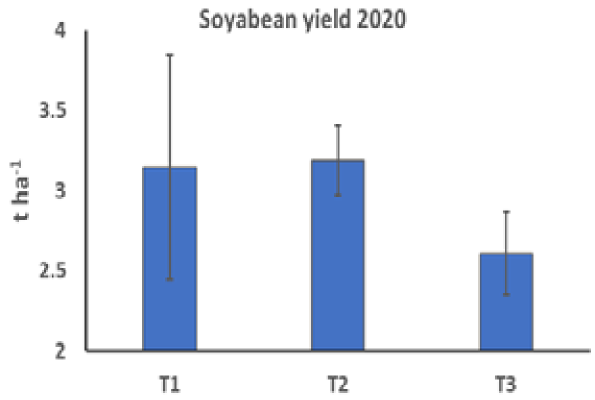

Figure 18 - Soybean yield (14% RH) for the different treatments. Values are means of three replicates; bars represent standard error.

Figure 19 - June 2021: Patches of *Conyza canadensis* growing in crop gaps within wheat fields.

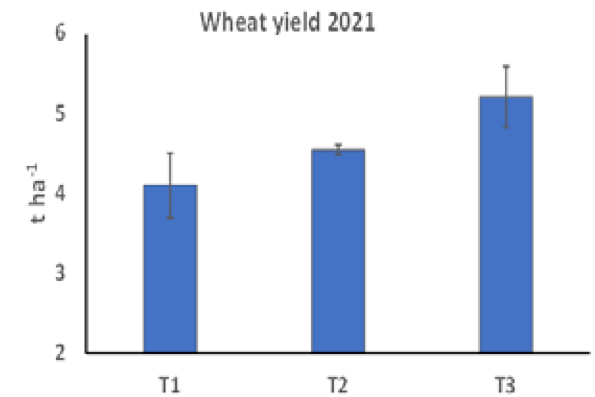

Figure 20 - Wheat yield (14% RH) for the different treatments. Values are means of three replicates; bars represent standard error.

sorghum is terminated, high amounts of residues remain on the soil and can hinder direct drilling of the subsequent cash-crop. The adoption of sorghum hybrids with medium productivity or the partial removal of the produced biomass, which can be used as silage or forage, can reduce this drawback.
- Lopsided oat (*Avena strigosa*) was supposed to be killed by winter frost and therefore no chemical or mechanical operations should have been required for termination. However, in this trial lopsided oat was able to overwinter due to the late sowing date in the previous autumn and restarted its growth in February, requiring it to be mechanically terminated. The use of this species in regions with mild winters, such as Southern European countries, is recommended only when early sowing, e.g. mid-September, is feasible.
- Mowing-tolerant cover crops, such as clovers, can allow weeds to be controlled during their cycle, thus preventing their dissemination.
- Weed control strategies with low herbicide-use can therefore be sustainable and effective, even during the transition phase towards conservation agriculture. It is crucial, however, to manage the different cash and cover crops correctly and to time all of the control operations correctly.

WP4 – WEED MANAGEMENT ON MAIZE USING PRECISION AGRICULTURE TO MINIMISE HERBICIDES

Reducing herbicide use and introducing alternative control methods is a key priority in Europe. Mechanical weed-control is usually adopted in the inter-row of wide-row crops such as maize via soil cultivation operations that also aim to incorporate fertiliser. However, common weed management in maize is based on the broadcast application of pre- or post-emergence herbicides, so herbicides are also applied in inter-rows where mechanical control is performed. Reducing herbicide use is feasible under these conditions as farmers can switch from a broadcast application to a localised (band) application along the crop row where mechanical control is not performed. The extent of reduced herbicide use would be related to the size of the treated area, which can be narrowed using precision agriculture technologies (semi-automatic deriving systems in tractors with RTK correction). This approach requires the various farming procedures to be carried out with great care. However, precision positioning and auto-steering systems based on RTK/GPS technology are now available for tractors. The currently available systems for herbicide band application are based on sowing machines equipped with nozzles that spray along the crop row (Figure 21). This operation is fairly quick and easy, but herbicides may only be applied during crop sowing. Only pre-emergence herbicides, whose efficacy is related to environmental conditions after the application date, can therefore be used, with a subsequent operation being required to perform

Figure 21 - Sowing machine equipped with nozzles for herbicide band application.

Figure 22 - The Maschio-Gaspardo prototype, which combines inter-row soil cultivation and herbicide band application along crop rows.

inter-row soil cultivation. Combining herbicide band application along the crop row with inter-row soil cultivation in a single operation would be a significant logistical improvement. Furthermore, this operation could be performed in a wide range of crop stages (from 2 to 6 leaves). This would also allow the use of post-emergence herbicides, thus increasing the range of potentially active ingredients. Herbicide application in this approach, however, could be performed only when soil conditions allow soil cultivation. Precision is also necessary since the operating machine has to maintain a precise course in relation to the crop rows; therefore this option requires precision tractor positioning and auto-steering systems to be combined with a crop-row detection system.

Objectives

Given that environmental conditions can strongly affect the feasibility and efficacy of mechanical and chemical weed control tools, developing alternative solutions for low-herbicide input strategies is crucial for guaranteeing flexibility when dealing with weather trends. This study aims to evaluate the feasibility and efficacy of weed control strategy in maize based on herbicide band application along crop rows combined with mechanical control in the inter-row. Its specific objectives are to:

- evaluate the efficacy of an existing system for herbicide band application (herbicide application with the sowing machine followed by inter-row soil cultivation);
- evaluate the efficacy of an innovative system for herbicide band application (with a prototype that simultaneously performs herbicide application along the crop rows and inter-row soil cultivation);
- assess the accuracy and efficacy of this prototype with different application timings or different sprayed-band widths along the crop row;
- compare the control efficacy of herbicide band application strategies with traditional herbicide broadcast application strategies (both pre- and post-emergence applications).

A prototype of an inter-row cultivator equipped with nozzles for herbicide band application (Figure 22) has been developed by Maschio Gaspardo by integrating three technologies:

1) a semi-automatic driving system in tractors with RTK correction that enables high precision and repeatability, i.e. the ability to return precisely (± 2.5 cm) to the same run-lines at any later date;

2) an imaging camera (Figure 23) that identifies crop rows and enables the equipment's position to be adjusted with a hydraulic side shift, thus allowing the mechanically cultivated inter-row area to be maximised;

3) herbicide band application along the crop rows by nozzles positioned on the cultivator structure (Figure 24) and managed by a control unit in order to adjust the volume applied according to tractor speed and the band size being treated.

Figure 23 - Imaging camera that identifies crop rows and enables equipment position to be adjusted.

Figure 24 - Nozzles for herbicide band application along crop rows positioned on the cultivator structure.

2018/2019 experiment results

The trial was conducted at "La Fagiana", a commercial farm at Eraclea, Venice, North-eastern Italy. The experiment was set up in one field and included four treatments: T1) broadcast application of pre-emergence herbicides (control standard management 1); T2) pre-emergence herbicide band application with the sowing machine (traditional band application management); T3) broadcast application of post-emergence herbicides (control standard management 2); and T4) post-emergence herbicide band application with an innovative system (the Maschio Gaspardo prototype, which simultaneously performs herbicide application along the crop rows and inter-row soil cultivation). Inter-row cultivation was performed for all treatments to control weeds and incorporate fertiliser into the soil. A randomised block design with three replicates was adopted with plot size of 150 m x 9 m = 1350 m^2 and total experiment size around 2 ha. Maize was sown on 19/04/2019 using a tractor equipped with RTK/GPS positioning and an autosteering system to map crop rows. Pre-emergence herbicide band application (mesotrione 37.5 g ha^{-1}, S-metolachlor 312.5 g ha^{-1}, terbutilazina 187.5 g ha^{-1}, band width treated 25 cm, spray volume 100 L ha^{-1}) was performed on T2 plots using a sowing machine equipped with specific nozzles (Figure 25 and Figure 26). The following day, broadcast pre-emergence herbicide application (mesotrione 112.5 g ha^{-1}, S-metolachlor 937.5 g ha^{-1}, terbutilazina 562.5 g ha^{-1}, spray volume 300 L ha^{-1}) was carried out on T1 plots with a boom sprayer. The 5-6 weeks after maize sowing were characterised by continuously rainy weather with total precipitation of almost 350 mm. As a consequence, no operation could be done during that period, and the first post-emergence herbicide application and inter-row soil cultivation with the Maschio Gaspardo prototype was performed on 07/06/2019. Maize was already at BBCH 17-18 and weeds were larger than the optimal size. Post-emergence herbicide application (tembotrione 30 g ha^{-1}, dicamba 80 g ha^{-1}, treated band width 25 cm, spray volume 100 L ha^{-1}) with the simultaneous inter-row soil cultivation was done with the Maschio Gaspardo prototype on 07/06/2019 on T4 plots. On the same day, broadcast post-emergence herbicide application (tembotrione 90 g ha^{-1}, dicamba 240 g ha^{-1}, spray volume 300 L ha^{-1}) was performed on T3 plots with a boom sprayer, and the following day inter-row soil cultivation was performed on all plots apart from T4 plots. An initial weed assessment was undertaken on 30/05/2019 before interrow cultivation and post-emergence herbicide application to evaluate initial weed density in the untreated plots. Weed population included the usual spring and summer species (*Abutilon theophrasti*, *Chenopodium album*, *Echinocloa crus-galli, Polygonum aviculare, Polygonum persicaria, Solanum nigrum,* and *Sonchus asper*) with a total density of 15-20 plants m^{-2} (Figure 27). Weed assessments were repeated one

Figure 25 - Maize sowing with herbicide band application along crop rows.

Figure 26 - Nozzle for herbicide band application positioned on the sowing machine.

month after post-emergence control (26/06/2019) and before crop harvest (12/09/2019). Maize was harvested on 24/09/2019. Pre-emergence herbicide application, both banded and broadcast, was very effective. Even when timing of application of post-emergence herbicide and inter-row cultivation was not optimal, weed control was satisfactory. Some plants, however, were too large and survived the mechanical control on the T4 plots. Weed density at crop harvest was therefore higher in T4 plots, with a value of 4-5 plants m^{-2}, while the lowest values, below 2 plants m^{-2}, were observed for the two treatments with broadcast herbicide application (T1 and T3). These differences increased when fresh weed biomass was considered: the value detected for T4 treatment (115 g m^{-2}) was ten-fold higher than all the other treatments (Figure 28) and this result was related to the presence of a limited number of large weed plants that survived post-emergence control operations due to their size. However, no differences in maize yield could be detected between treatments, with means ranging from 9.7 to 10.4 t ha^{-1} of maize grain at 14% RH (Figure 29). Moreover, the highest yield, as absolute value, was observed for Treatment T4. We can therefore consider that the two treatments with herbicide band application (T2 and T4) obtained a sufficiently high weed control level to keep weed competition below the threshold of economic damage, although weather conditions during spring 2019 delayed post-emergence operations and hindered inter-row hoeing.

2019/2020 experiment

Given the positive results of the 2018/19 experiment, even when weather conditions were not optimal, the same experimental design was maintained for the 2019/20 experiment in order to confirm these positive indications.

Materials and methods

The field experiment was arranged in three adjacent fields, and included four treatments (Figure 30 and Table 2):
T1) broadcast application of pre-emergence herbicides (Control standard management 1);
T2) pre-emergence herbicide band application with the sowing machine (Traditional band application management);
T3) broadcast application of post-emergence herbicides (Control standard management 2);
T4) herbicide band application with an innovative system (the Maschio Gaspardo prototype, which simultaneously performs herbicide application along the crop rows and inter-row soil cultivation).
Inter-row cultivation was performed for all treatments to control weeds and incorporate fertiliser into the soil. A randomised block design with three replicates was adopted with plot sizes of 250 m x 14 m = 3500 m^2 and total experiment size around 4.5 ha. Maize was sown on 16/04/2020 using a tractor equipped with RTK/GPS positioning and an autosteering system to map crop rows. Pre-emergence herbicide band application (mesotrione 48.75 g ha^{-1}, S-metolachlor 406.25 g ha^{-1}, terbutilazina 243.75 g ha^{-1}, band width treated 25 cm, spray volume 100 L ha^{-1}) was performed on T2 plots using a sowing machine equipped with specific nozzles (Figure 26). The following day broadcast pre-emergence herbicide application (mesotrione 150 g ha^{-1}, S-metolachlor 1250 g ha^{-1}, terbutilazina 750 g ha^{-1}, spray volume 300 L ha^{-1}) was carried out on T1 plots with a boom sprayer.
Post-emergence herbicide application (nicosulfuron 20 g ha^{-1}, dicamba 64 g ha^{-1}, treated band width 25

Figure 22 - Weed population before inter-row cultivation.

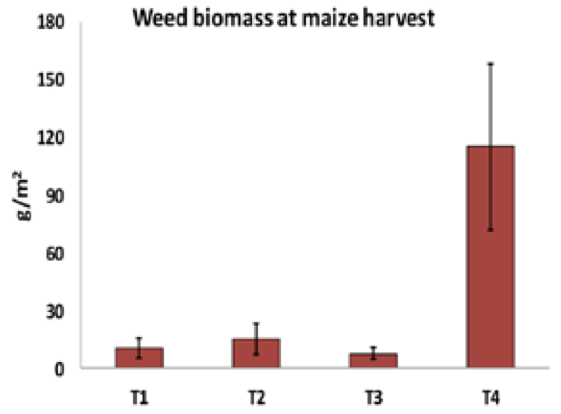

Figure 28 - Fresh weed biomass at crop harvest in 2019. Values are the means of three replicates and bars represent standard errors.

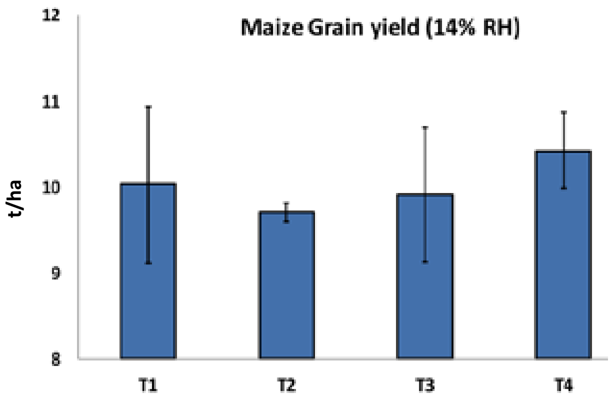

Figure 29 - Maize grain yield (at 14% RH) in 2019 for each treatment. Values are the means of three replicates and bars represent standard errors.

Margin	T 4	T 3	Margin	T 1	T 2	Margin	T 3	T 4
	T 2	T 1		T 3	T 4		T 1	T 2

Figure 30 and Table 2 - Experimental scheme of the WP4 trial.

Legend
T 1 Broadcast application of pre-emergence herbicides with boom sprayers
T 2 Band application of pre-emergence herbicides with a sowing machine
T 3 Broadcast application of post-emergence herbicides with boom sprayers
T 4 Band application of post-emergence herbicides with a Maschio-Gaspardo prototype

cm, spray volume 100 L ha^{-1}) with the simultaneous inter-row soil cultivation was performed on 22/05/2020 with the Maschio Gaspardo prototype on T4 plots. On the same day, broadcast post-emergence herbicide application (nicosulfuron 60 g ha^{-1}, dicamba 192 g ha^{-1}, spray volume 300 L ha^{-1}) was performed on T3 plots with a boom sprayer, and inter-row soil cultivation was performed on all plots apart from T4 plots. Weed assessment was conducted on 21/05/2020 before the post-emergence herbicide application. Weed density ranged from less than 10 plants m^{-2} in plots where pre-emergence herbicides were applied (T1 and T2) to above 50 plants m^{-2} in the other plots (T3 and T4). The main weed species were *Chenopodium album* and *Echinochloa crus-galli*, but the two perennials *Calystegia sepium* and *Sonchus arvenis* were also common.
Weed assessment was repeated one month after post-emergence application on 22/06/2020. Weed density ranged from less than 10 plants m^{-2} in plots where pre-emergence herbicides were broadcast applied (T1) to about 20-30 plants m^{-2} in the other plots (T2, T3 and T4). Many of these weed plants were seedlings after the rainstorm that occurred in the days following post-emergence control. A third weed assessment was conducted on 21/09/2020 just before maize harvest. In this assessment, weed biomass was also measured. At crop harvest, weed density ranged between 6.6 and 30.6 plants m^{-2} (for T1 and T4 respectively). Weed biomass at maize harvest reached the lowest value for T1 (around 70 g m^{-2}) and the highest for T4 (above 650 g m^{-2}), while T2 and T3 had intermediate values (Figure 31). The main weed species after post-emergence control operations were *Chenopodium album* and *Echinochloa crus-galli*, but the perennials *Calystegia sepium* and *Sonchus arvenis* were also common. Maize was harvested on 10/10/2020 and grain yields ranged between 12.2 and 13.0 t ha^{-1} (RH 14%) without differences between treatments (Figure 32). The higher density observed in T4 plots therefore had not resulted in significantly higher competition and yield loss.

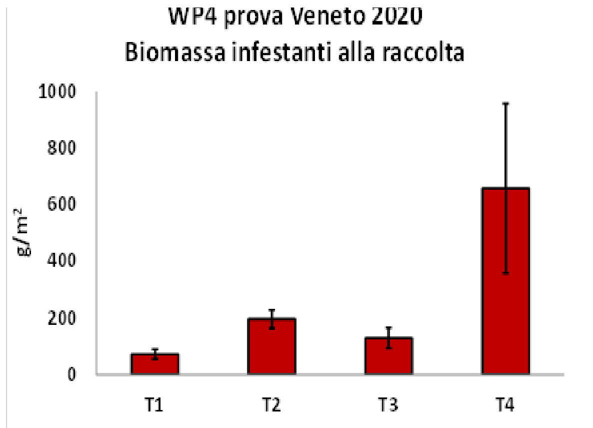

Figure 31 - Weed biomass (fresh weight) observed before crop harvest (21 September 2020). Values are means of three replicates; bars represent standard error.

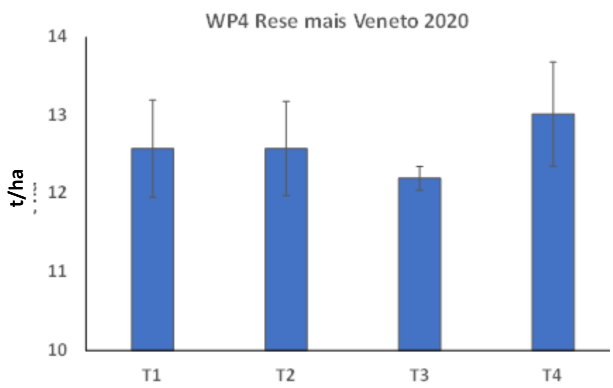

Figure 32 - Maize grain yield (14% RH) obtained for the different treatments. Values are means of three replicates; bars represent standard error.

General conclusions

Given the results and observations achieved in this three-year trial, the following conclusions can be drawn:

- Poor maize growth and yields were observed in 2018 due to water stress, and no differences could be detected between treatments. When water is scarce, no other agronomic operation can really guarantee satisfactory maize yield.
- Good maize yield and satisfactory weed control were on the whole achieved with all treatments in 2019 and 2020, even when higher weed densities were observed in the plots managed with post-emergence herbicide band application with an innovative system (T4). This could lead to a progressive increase in weed populations and therefore undermine the long-term sustainability of this management with low-herbicide use.
- The system of pre-emergence herbicide band application with the sowing machine (T2) has proven to be more reliable than the one with post-emergence band application (T4), but this efficacy is strongly reduced in the presence of perennial species.
- Weed control strategies with band herbicide application can therefore be sustainable and effective for maize production in Northern Italy, but it is crucial to integrate them with other cultural tactics (e.g. crop rotation, cover crops, tillage) to reduce weed presence.

EXPERIMENTAL TRIALS AT THE "LUCIO TONIOLO" FARM

Consiglio Nazionale delle Ricerche

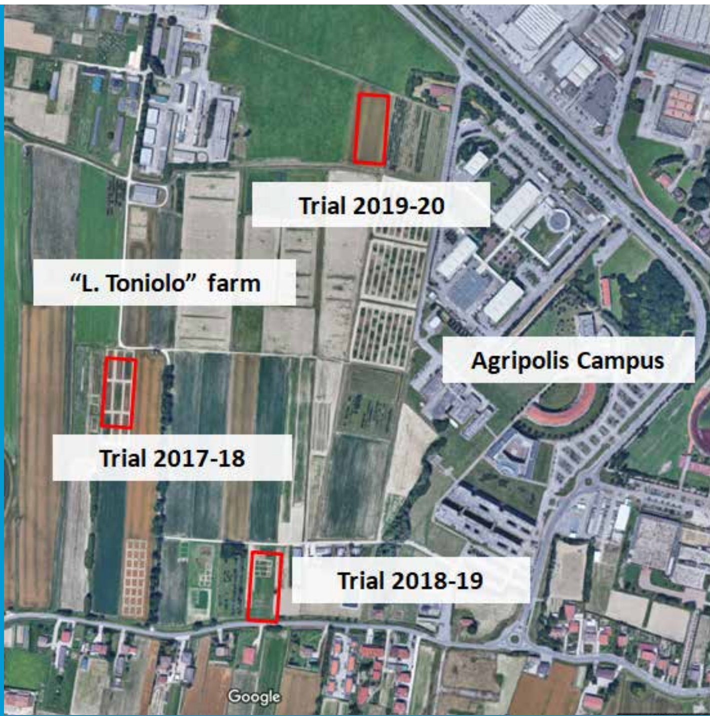

Figure 1 - Location of the trial at the "Lucio Toniolo" farm

The University of Padova's "Lucio Toniolo" experimental farm was founded in 1960 and has a main unit of about 65 ha of agricultural land at Legnaro (Padua), plus a second part of 15 ha at Pozzoveggiani (Padua) under organic agriculture management. This farm is both a research station and a commercial farm producing arable crops, dairy and animal products, and organic wine. Given its proximity to the Agripolis campus where the University of Padova's School of Agricultural Sciences and Veterinary Medicine is located, educational and demonstration activities are organized regularly. This farm is equipped with a range of research facilities, such as greenhouses and barns, and it is running several long-term experiments. It conducts field research on a variety of topics, such as the long-term effect of different cropping or management systems, mitigation measures (e.g. buffer strips, wetlands, biobeds) to reduce environmental contamination by pesticides or nutrients, turf grass management, crop protection and weed control, organic farming, cover crops, animal husbandry and food quality.

Address:
Azienda agraria sperimentale "Lucio Toniolo"
dell'Università degli studi Padova
Viale dell'Università, 4
35030 Legnaro (PD) - Italy
GPS coordinates: 45°20'48.9"N 11°57'00.3"E

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WP3 – INTEGRATED WEED MANAGEMENT IN WHEAT

Cropping systems in Northern Italy are usually based on spring crops (e.g. maize, soybean) and wheat is usually cultivated every three or four years. Wheat-yield potential (7-9 t ha^{-1}) is higher in this area than in Italy's traditional wheat-producing regions. Weed infestation can therefore cause economically relevant yield losses and weed-management strategies normally rely on post-emergence herbicide application in spring. However, since spring crops make up the majority of crop rotation, weed communities are not as specialised or as hard to manage as in wheat monoculture. Herbicide use can thus be reduced under these conditions by adopting a combination of mechanical and cultural control tools.
Mechanical tools, such as the false seedbed technique or flexible tine harrow, are very effective for weed management in wheat, but environmental conditions, such as soil moisture and weed size at the time of application, can strongly affect control efficacy. Low precipitation in autumn may decrease weed-seed germination and consequently make the false seedbed technique ineffective, while prolonged rainy periods in late winter/early spring may prevent the application of flexible tin harrowing.
Cover crops can both facilitate weed management throughout the rotation, e.g. by preventing weed growth during inter-cropping periods between wheat harvest and the sowing of the subsequent spring crop, and maintain soil fertility. However, soil and weather conditions after wheat harvest are not usually optimal for cover crop sowing and establishment due to low soil humidity, low precipitation and high temperatures. The relay cropping technique, i.e. seeding a cover crop early by undersowing it in wheat crop, has been proposed as a means of improving cover crop establishment and soil cover during summer months. However, limited information is available about its feasibility under Northern Italian conditions.

Objectives

This study evaluates the feasibility and efficacy of mechanical weed-control tools for wheat in both autumn and spring under the environmental conditions of Northern Italy. Since the 2018-2019 cropping season, the effect that relay cropping of a cover crop (clover) has on wheat has also been assessed. The control strategies compared are based on:
1) chemical control only (for the 2017-2018 season);
2) integration of chemical and mechanical control;
3) mechanical control only;
4) mechanical control plus relay cropping (2018-2019 and 2019-20 seasons).
The specific objectives of this study are to:
- design mechanical weed-control strategies for wheat according to both local environmental conditions and the limitations due to the timing of cropping operations and weather trends;
- reduce the environmental impact of weed control in wheat by decreasing or avoiding herbicide application thanks to the introduction of effective mechanical control;
- evaluate the effect of including relay cropping of clover in wheat in order to facilitate the adoption of cover crops.

2017/2018 results

Prolonged dry periods in October 2017 limited weed emergence and consequently the efficacy of the seedbed technique, while excessive soil moisture throughout February and March 2018 impeded the use of flexible tine harrow in M plots. Two different herbicide mixtures were applied on 28/03/2018 on both the C and CM plots. The lowest weed density (11.7 plants m^{-2}) and biomass (10.8 g m^{-2}) were observed in Treatment C (only chemical), while the highest values (101.8 plants m^{-2} and 122.5 g m^{-2}) were found in Treatment CM (chemical + mechanical), probably due to the very high initial density of *Veronica persica* (above 200 plants m^{-2}) on one of its plots. High yields were achieved for all treatments, ranging from 8.9 t ha^{-1} (14% RH) for Treatment C to 8.4 t ha^{-1} (14% RH) for Treatments CM and M (Figure 2). This result was probably partly due to the cropping system (rotation with spring crops), which reduced weed density; however, it underlined the feasibility of low herbicide weed management in wheat.

2018/2019 results

Given the positive results of the 2017/18 experiment, the experimental design was modified for 2018/19 season in order to test another IWM tool, i.e. relay cropping of clover, and to advance in the direction of low-herbicide use in weed management for wheat. Treatments CM (chemical and mechanical control) and M (mechanical control) were maintained, while Treatment C (chemical control) was replaced with Treatment MR (mechanical + relay) which included autumn false seedbed, flexible tine harrowing and relay cropping of red clover undersown in wheat. The false seedbed period (16 October - 14 November) was rather rainy and considerable weed seedling emergence was

observed, meaning that this technique was effective. However, prolonged high soil-humidity forced the wheat to be sown much later than in standard local management practices.
On 25/02/2019, a cover crop (red clover, 25 kg ha^{-1} of seed) was spread on the soil surface of MR plots and flexible tine harrowing was then performed on MR and M plots to control weeds and bury clover seeds. The lack of precipitation in March 2019 slowed clover germination and establishment, with the first emerged seedlings being observed three weeks after the sowing date. Herbicide was applied on 22/03/2019 to CM plots. Low weed density (less than 10 plants m^{-2}) and biomass (less than 20 g m^{-2}) were observed for all treatments. Good grain yields (6.8-7.3 t ha^{-1} at 14% RH) were achieved for all treatments without any significant differences (Figure 3). Cover crop growth was monitored after cereal harvest, but the hot, dry weather in June (less than 10 mm of precipitation) hindered clover growth, and its biomass was below 0.5 t ha^{-1} (fresh weight) in mid-July. Given the scarce growth of the cover crop, its ability to compete with weeds was limited, and a mechanical operation (mulching) was necessary in August to destroy all the weeds to prevent their dissemination.

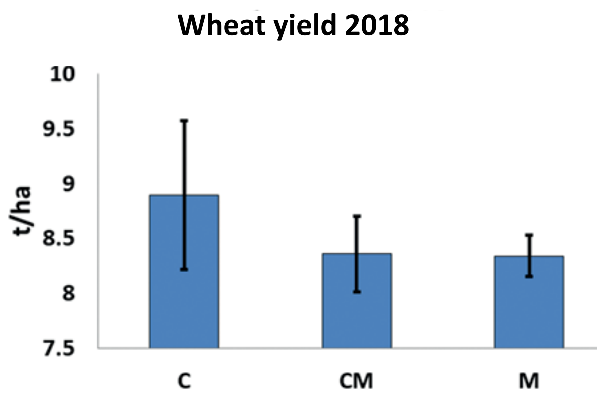

Figure 2 - Wheat yields (14% RH) obtained with the three control strategies (C: chemical control; CM: chemical and mechanical control; M: mechanical control). Vertical bars represent standard errors.

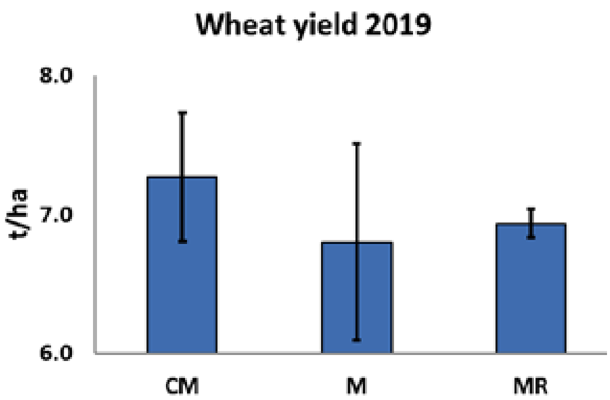

Figure 3 - Wheat yields (14% RH) obtained with the three control strategies (CM: chemical and mechanical control; M: mechanical control; MR: mechanical control + relay cropping). Vertical bars represent standard errors.

2019/2020 results

During the 2017/18 and 2018/19 experiments, satisfactory weed control and good yields were achieved for all treatments, including those with only mechanical weed control operations. Relay cropping of red clover tested in 2018/19 experiment was not successful due to the prolonged cold, rainy period in April and May, followed by a hot, dry period in June that strongly reduced clover density and growth. This technique was tested again in the 2019/20 experiment.
The experimental design adopted for the 2018/19 experiment was also used for the 2019/20 season, which was set up at the same site, the "L. Toniolo" farm in Legnaro (PD). Three treatments, corresponding to different weed-management strategies, were included:
1) integration of chemical and mechanical control with the false seedbed technique in autumn, plus spring post-emergence herbicide application only when necessary and attempts to minimise herbicide use (Treatment CM);
2) mechanical control only, with the false seedbed technique in autumn, plus flexible tine harrowing at the crop-tillering stage (Treatment M);
3) mechanical control, as in the previous treatment, plus relay cropping of red clover (Treatment MR).
The same strategy for fertiliser application and crop protection (i.e. fungicide and insecticide application) was adopted for all treatments. A randomised block design with three replicates was set up (replicate plot size: 30 m x 10 m = 300 m^2, total experiment size: about 5000 m^2).
The experiment was set up in a field where sugarbeet and maize had been previously cultivated. Just after that, sugarbeet was harvested in mid-September 2019 using a cultivator to prepare the false seedbed. Soil cultivation for seedbed preparation was then performed with rotary harrowing on the whole field on 21/10/2019, and wheat was sown on 23/10/2019. The false seedbed period (15 September - 21 October) was rather rainy, with considerable weed seedling emergence being observed, meaning that this technique was effective.

Figure 4 - View of the field trial with lodged wheat in mid-June.

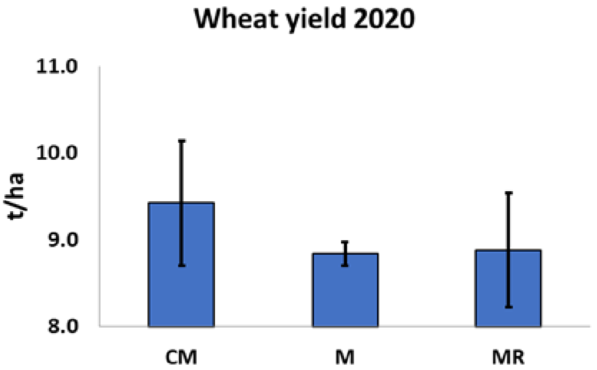

Figure 5 - Wheat grain yields (14% RH) obtained with the different treatments (CM integration of chemical and mechanical control; M only mechanical control; MR mechanical control + relay cropping). Values are means of three replicates and bars represent standard errors.

Weed assessment was conducted on 17/02/2020. Weed density was quite high, with mainly Dicot species such as *Lamium purpureum, Stellaria media* and *Veronica persica*, while *Poa annua* and *Lolium multiflorum* were the most common grasses.
On 18/02/2020, a cover crop (red clover, 25 kg ha^{-1} of seed) was spread on the soil surface of MR plots and flexible tine harrowing was performed on 20/02/2020 on MR and M plots to control weeds and bury clover seeds. Herbicide application (mesosulfuron-methyl 15 g ha^{-1} + iodosulfuron-methyl-sodium 3 g ha^{-1}) was performed on 18/03/2020 for CM plots. A second weed assessment was conducted on 12/05/2020 at wheat flowering. Due to the presence of many large *L. multiflorum* plants when flexible tine harrowing was performed, control efficacy was not satisfactory in one plot of Treatment MR (weed density 50 plants m^{-2} and biomass 566 g m^{-2}). Control efficacy on the other MR plots (mean weed density 35 plants m^{-2} and biomass 70 g m^{-2}), as well as on all M and CM plots was acceptable, given the high initial weed density. Prolonged dry periods in April and May hindered the emergence and growth of the red clover, whose establishment was not optimal. Heavy rainstorms during the first days of June caused the wheat to lodge completely, with it remaining in this condition till harvest (Figure 4). This caused a prolonged mulching effect and suffocated the red clover plants. Cereal harvest took place on 30/06/2020. High grain yield (8.8-9.4 t/ha at 14% RH) was achieved for all treatments without any significant differences (Figure 5). The higher weed presence in MR plots did not therefore cause higher competition with the crop, and yield losses were negligible. No red clover plants were present in the field after the wheat harvest because of the prolonged lodging.

General conclusions

Any proposed strategy based on a progressive reduction in herbicide use and substitution with mechanical control should be calibrated according to local environmental conditions and farming practices. Furthermore, both testing innovative or uncommon tools, such as relay cropping of clover in cereals, under real field conditions and contrasting weather trends are particularly important.
Considering the results and observations achieved in this three-year trial, the following conclusions can be drawn:

- Good wheat yield and satisfactory weed control were on the whole achieved with all treatments, even when higher weed densities were observed in managements based on mechanical control alone, particularly in plots with high initial weed presence. This could lead to a progressive increase in weed populations and therefore undermine the long-term sustainability of these managements.
- Weed control strategies with low or no herbicide-use can therefore be sustainable and effective for wheat production in Northern Italy, but it is crucial to integrate mechanical control with other cultural tactics (e.g. crop rotation, cover crops, tillage) to prevent serious weed dissemination.
- Relay cropping of clovers during winter wheat achieved poor results in terms of cover crop density and growth after the cereal harvest. The sowing technique adopted in this trial (broadcast distribution of clover seeds followed by flexible tine harrowing) did not guarantee the uniformity and density of clover emergence, so other techniques, such as direct-drilling, should be

preferred. The increasing occurrence of summer storms, probably related to climate change, raises the risk of cereal lodging and consequent failure of clover relay cropping. This technique probably still needs further adjustments to guarantee satisfactory results in Northern Italy conditions.

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EXPERIMENTAL TRIALS AT THE "ENRICO AVANZI" CENTRE FOR AGRI-ENVIRONMENTAL RESEARCH (CIRAA)


Figures 1 and 2 - Aerial views of the experimental sites at the "E. Avanzi" Centre.

The University of Pisa's CiRAA is the largest agricultural experimental centre in Italy and one of the largest in Europe (> 500 ha of agricultural land). CiRAA conducts on-farm research and regularly organizes demonstration activities to involve local stakeholders in new practices and product development. At CiRAA, plot-scale experiments are usually included in the layout of larger scale trials, with fields being used as experimental units. The main research topics at CiRAA are low-external input cropping systems, soil tillage, cover crops, crop protection and weed control, organic farming, agricultural mechanization, animal husbandry, food quality, biomass and bioenergy, plus economic and environmental impact. Due to its acreage, CiRAA is both a research station and a commercial farm.

A considerable portion of its agricultural land is managed for marketable production of arable crops and field vegetables. Due to these features, CiRAA has been formally included among the Centres for Innovation Transfer in Agriculture by the Tuscany Regional Government. CiRAA is located in the Regional Park of "Migliarino - San Rossore - Massaciuccoli" and within the "Selva Pisana" *biosphere reserve. It was founded in 1963 after the Italian Republic donated land to the University of Pisa with the aim of supporting research and teaching in veterinary and agricultural science. The research centre is named in memory of Enrico Avanzi, professor of agronomy and rector of the University of Pisa from 1947 to 1959.*

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LTE – LONG-TERM EXPERIMENT IN COVER CROPS

This long-term experiment started in 1993 to study alternatives to maize monoculture, a widespread cropping system in the Pisa area at that time. The starting-point experiment tested the introduction of cover crops in monoculture as a practice for reducing weed pressure on maize crops and for optimising the use of external inputs. Two tillage systems were included in the experiment.
In 1998, durum wheat (as an autumn-sown reference crop) was introduced into the system, leading to a two-year rotation. This change was made in order to mirror changes in the local cropping system. For the same reason, sunflower was introduced in 2007 as an additional spring-sown cash-crop. This raised the crop rotation to four years (durum wheat, maize, durum wheat, sunflower), with the cover crop being grown before each spring-sown cash-crop. The experiment takes place in strictly rainfed conditions. No irrigation is allowed, even in the event of an extreme drought emergency.

Objectives

The aim of this long-term experiment is to determine the combined effect on soil quality, crop yield and weed community dynamics of:

(i) two management systems (conventional vs. low-input system);
(ii) four N fertilization levels of the main crop;
(iii) four soil cover types (*Brassica juncea, Trifolium squarrosum, Vicia villosa* and a control).

Materials and methods

The three constant factors studied in the trials are tillage, nitrogen fertilisation and cover-crop type (Table 1). The experiment is arranged in a split-strip/split-plot design with four replicates (blocks). All factors are crossed.
Tillage comparison is based on two systems: a Conventional System (CS) based on annual ploughing at 30 cm depth and a Low Input System (LIS) based on no soil-inversion operations: chiselling at 30 cm depth for summer crops and direct sowing for durum wheat.
The four levels of fertilisation are arranged as a strip plot. The four levels are always constant in the ranking, but the amount of nitrogen changes according to the need of each cash crop: 0, 60, 120 and 180 kg of nitrogen per hectare for durum wheat; 0, 100, 200 and 300 kg for maize; and 0, 50, 100 and 150 kg for sunflower.
The four cover-crop plots are nested in each fertilisation strip: C, control (weedy); BJ, *Brassica juncea L.*; TS, *Trifolium squarrosum* L.; and Vv, *Vicia villosa* Roth. Cover crops are grown in winter before maize and sunflower, and terminated at the end of April. Disk harrowing or herbicide is used in CS and a crusher in LIS. Weed control is differentiated in the two tillage systems. In CS,

Figure 3 - Experimental site for the LTE trial.

FIELD 1		FIELD 2		FIELD 3		FIELD 4		FIELD 5		FIELD 6		FIELD 7		FIELD 8	
36 BJ	37 C	44 TS	45 Vv	52 C	53 BJ	60 TS	61 Vv	68 Vv	69 BJ	76 C	77 TS	84 BJ	85 Vv	92 Vv	93 C
35 C	38 BJ	43 BJ	46 TS	51 TS	54 C	59 Vv	62 BJ	67 C	70 TS	75 BJ	78 Vv	83 TS	86 BJ	91 C	94 TS
34 Vv	39 TS	42 Vv	47 C	50 BJ	55 Vv	58 C	63 TS	66 BJ	71 Vv	74 TS	79 C	82 Vv	87 C	90 TS	95 BJ
33 TS	40 Vv	41 C	48 BJ	49 Vv	56 TS	57 BJ	64 C	65 TS	72 C	73 Vv	80 BJ	81 C	88 TS	89 BJ	96 Vv
4 Vv	5 TS	12 C	13 Vv	20 BJ	21 C	28 TS	29 BJ	97 C	104 BJ	105 BJ	112 Vv	113 Vv	120 BJ	121 C	128 TS
3 BJ	6 C	11 Vv	14 BJ	19 TS	22 Vv	27 C	30 TS	98 Vv	103 TS	106 TS	111 C	114 BJ	119 Vv	122 Vv	127 BJ
2 TS	7 BJ	10 TS	15 C	18 C	23 TS	26 BJ	31 Vv	99 BJ	102 C	107 Vv	110 BJ	115 C	118 TS	123 TS	126 C
1 C	8 Vv	9 BJ	16 TS	17 Vv	24 BJ	25 Vv	32 C	100 TS	101 Vv	108 C	109 TS	116 TS	117 C	124 BJ	125 Vv
N0	N1	N2	N3	N2	N1	N0	N3	N0	N1	N2	N3	N2	N1	N0	N3
CS				LIS				CS				LIS			

DURUM WHEAT		MAIZE		SUNFLOWER	
N0=	0 Kg/ha	N0=	0 Kg/ha	N0=	0 Kg/ha
N1=	60 Kg/ha	N1=	100 Kg/ha	N1=	50 Kg/ha
N2=	120 Kg/ha	N2=	200 Kg/ha	N2=	100 Kg/ha
N3=	180 Kg/ha	N3=	300 Kg/ha	N3=	150 Kg/ha

C = Control (no cover crop)
Bj = *Brassica juncea*
Ts = *Trifolium squarrosum*
Vv = *Vicia villosa*

I Block
II Block
III Block
IV Block

Table 1 - The experimental layout of the Long-Term Experiment on Cover Crops.

post-emergence (for maize and wheat) and pre-emergence (for sunflower) herbicides are used; hoeing is usually applied to spring crops. In LIS, hoeing is used for spring crops and herbicides are applied in pre-sowing and early post-emergence for wheat. Active ingredients are chosen considering the dominant weed species.
Based on the availability of personnel, different intensities of sampling were performed from 1993 until the current growing season. The data collected in most seasons include the aboveground biomass of cash crop at harvest, the aboveground biomass of cover crops and weeds at the devitalisation phase and weed density at the early stage of a cash crop/cash crops. From 2008, weed cover at the full development of the cash crop/cash crops was included in the sampling calendar.

Results

Soil fertility

The two main parameters assessed to estimate soil fertility (soil organic carbon and total nitrogen) measured in the 0-30 cm layer from 1993 to 2008 clearly show a positive accumulation trend when reduced tillage is applied (+17.3% and +10.4% respectively in the first 15 years). Similarly, a significant increase was recorded when fixing nitrogen cover crops were applied (the mean for the two-nitrogen fixing cover crop type is a 13.3% and 4.4% increase for organic carbon and total nitrogen respectively in 15 years). The no-nitrogen fixing cover crop does not show any difference from the control (no cover crop applied) (Mazzoncini et al., 2011). Regarding soil biological fertility, the positive effect of reduced tillage on soil respiration and microbial biomass increased by 44% and 71% respectively when compared with conventional tillage systems. The abundance and diversity of micro-arthropods was another of the soil-health indicators used. Both indicators had higher values when tillage was reduced when compared with conventional tillage systems (Sapkota et al., 2012).

Weed control

According to weed-composition measurements from 2012 to 2015, cover-crop type strongly influences weed-community composition during the cover-crop growth cycle. This effect was not


Figures 2 and 3 - Sorghum grown in spring 2018 showing the effects of the previous cover-crop plots (photos by Lorenzo Tramacere and Massimo Sbrana).

clearly detectable in summer and winter cash crops. A low-input system mainly favoured the presence of perennial weeds. In this system, weed total biomass increased when compared with the conventional tillage system. This suggests that some adjustments to cover-crop management under a low-input system may be needed to prevent potentially troublesome weed shifts, which might offset the benefits attained by reduced tillage systems on other production-related agroecosystem services (Carlesi et al. 2015).

List of publications for further reading:

- Adeux, G., Cordeau, S., Antichi, D., Carlesi, S., Mazzoncini, M., Munier-Jolain, N., and Bàrberi, P. (2021). Cover crops promote crop productivity but do not enhance weed management in tillage-based cropping systems. European Journal of Agronomy, 123: 126221. doi: 10.1016/j.eja.2020.126221.
- Bàrberi, P., & Mazzoncini, M. (2001). Changes in weed community composition as influenced by cover crop and management system in continuous corn. Weed Science, 49(4), 491-499.
- Carlesi S., Antichi D., Bigongiali F., Mazzoncini M., Bàrberi P. Long term effects of cover crops on weeds in Mediterranean low input arable management systems. 17th European Weed Research Society Symposium “Weed management in changing environments”, 23-26 June 2015, Montpellier, France (Oral presentation)
- Iocola, I., Bassu, S., Farina, R., Antichi, D., Basso, B., Bindi, M., ... & Giglio, L. (2017). Can conservation tillage mitigate climate change impacts in Mediterranean cereal systems? A soil organic carbon assessment using long term experiments. European Journal of Agronomy, 90, 96-107.
- Lechenet, M., Deytieux, V., Antichi, D., Aubertot, J. N., Bàrberi, P., Bertrand, M., ... & Debaeke, P. (2017). Diversity of methodologies to experiment Integrated Pest Management in arable cropping systems: Analysis and reflections based on a European network. European journal of agronomy, 83, 86-99.
- Mazzoncini, M., Sapkota, T. B., Barberi, P., Antichi, D., & Risaliti, R. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil and Tillage Research, 114(2), 165-174.
- Moonen, A. C., & Barberi, P. (2004). Size and composition of the weed seedbank after 7 years of different cover-crop-maize management systems. Weed Research, 44(3), 163-177.
- Sapkota, T. B., Mazzoncini, M., Bàrberi, P., Antichi, D., & Silvestri, N. (2012). Fifteen years of no till increase soil organic matter, microbial biomass and arthropod diversity in cover crop-based arable cropping systems. Agronomy for Sustainable Development, 32(4), 853-863.

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Figure 4 - Evaluation of self-reseeding capacity in September 2018 (photo by Federico Leoni).

PERMANENT LEGUME LIVING MULCH FOR ORGANIC AND CONSERVATIVE VEGETABLE AGRO-ECOSYSTEMS

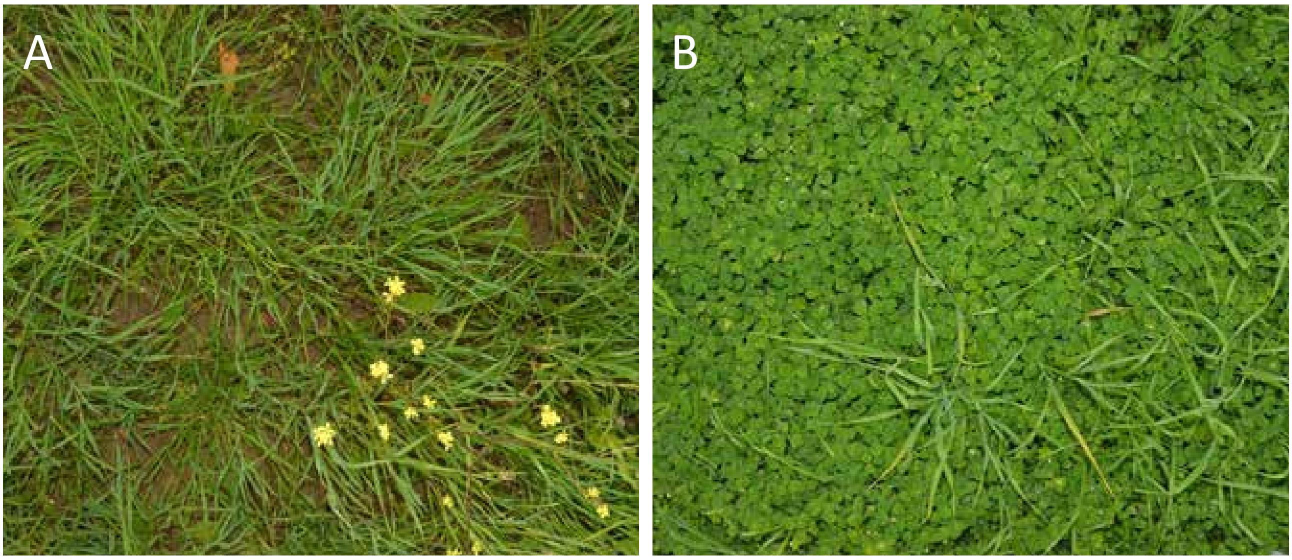
Vegetable crops are highly susceptible to weed competition. Crop rotation, mechanical control and transplanting are the main strategies for weed control in organic vegetable systems, but often these techniques are not enough to contrast weeds properly. In this experiment we focus on whether legume cover crops can be used as permanent living mulches (pLM) to improve weed control in organic vegetable cropping systems. We conducted a field experiment to screen several perennial and annual self-seeding commercial legume cultivars belonging to five legume species. The aim was to investigate the viability of their morphological and physiological characteristics for potential use as permanent living mulch, with particular respect to their weed suppression capacity. An additional experiment was conducted to screen local ecotypes of *Medicago polymorpha*. The screening of ecotypes is expected to better identify legumes that are well-adapted to the local environmental conditions in comparison with commercial cultivars. Ecotypes may have morphological and physiological characteristics that better fit with the legume ideotype required for the successful establishment of permanent living mulch. More generally, the selection of a legume characterised by the specific traits needed for this purpose may increase the practical application of this practice. In particular, a legume with prostrate growth habit, moderate biomass growth and low water

Legume species	Cultivars
Lotus corniculatus L.	Giada
Lotus corniculatus L.	Leo
Trifolium repens L.	Huia
Trifolium repens L.	Haifaa
Trifolium repens L.	RD84
Medicago polymorpha L.	Scimitar
Medicago polymorpha L.	Anglona
Medicago polymorpha L.	Mauguio
Trifolium subterraneum L.	Fontanabona
Trifolium subterraneum L.	Antas
Trifolium subterraneum L.	Dalkeith
Trifolium subterraneum L.	Campeda

Table 2 - List of legume cultivars used in Experiment 1.

Legume species	Cultivars
Ecotypes	
Medicago polymorpha L.	Pitigliano (SI)
Medicago polymorpha L.	Manciano (GR)
Medicago polymorpha L.	Talamone (GR)
Medicago polymorpha L.	Principina (GR)
Medicago polymorpha L.	VIlla Salto (SS)
Medicago polymorpha L.	San Felice Circeo (LT)
Medicago polymorpha L.	Tarquinia (VT)
Commercial	
Medicago polymorpha L.	Scimitar
Medicago polymorpha L.	Anglona
Medicago polymorpha L.	Mauguio

Table 3 - List of *M. polymorpha* ecotypes and commercial cultivars used in Experiment 2.



Figures 5A and 5B - A) weed infestation in the control plot in spring 2018, and B) weed infestation with living mulch of *T. subterraneum* subsp. brackycalicinum cv. Antas in spring 2018 (photo by Federico Leoni).

requirement could be a good candidate for this cropping system.

Materials and methods

The experiment was carried out in Pisa within an organic certified area of the "Enrico Avanzi" Centre for Agri-Environmental Research (CiRAA). Nineteen commercial legume cultivars and ecotypes (perennial and annual self-reseeding) were tested in plots (4.5 m^2). Each legume type was repeated in four randomised blocks. Within the legume self-reseeding group, a collection of seven ecotypes of *Medicago polymorpha* L. was tested. The legumes were sown in November 2017 on a field previously plowed at 25 cm depth and refined with a rotative harrow. No herbicides, fertilisers and fungicides were used. Legumes and weed growth were constantly monitored for two years, and three key biomass samplings were performed in spring and autumn 2018 and in spring 2019 in order to simulate what would be the most common practice at farm level in this system (before the hypothetical transplantation of summer and/or winter vegetable crops). The germination capacity and seed hardness of both the *M. polymorpha* ecotype and commercial cultivars were also evaluated during autumn 2018 (Figure 4). In accordance with the experiment objectives, legumes were divided into two sub-sets and analysed separately as follows:

- *Experiment 1*: treatments consisted in 12 legume commercial cultivars belonging to five legume types and spontaneous vegetation as a control (Table 2).
- *Experiment 2*: treatments consisted in seven ecotypes and three commercial cultivars of *M. polymorpha* (in common with Experiment 1) (Table 3). Bare soil was used as a control plot (Figure 5A). The ecotypes were collected in Central Italy and provided by the Germplasm Bank of the Institute of Genetic Improvement of the University of Perugia and by Pasture Research Centre or the National Research Council (CNR) of Sassari.

Results

The successful use of permanent living mulch (pLM) is largely determined by the choice of appropriate legumes that combine adequate weed control with a marginal competitive effect on the cash crop(s). However, the availability of legumes for such systems is limited and their characterisation based on growth traits can support the selection of suitable legumes for organic-vegetable conservation systems. The current study investigated weed-control capacity and variability in morphological and phenological traits relevant in inter-plant competition among a range of twelve commercial cultivars of legumes and seven ecotypes of *Medicago polymorpha* (burr medic). For commercial cultivars, *Lotus corniculatus* (bird's-foot trefoil) and *Trifolium repens* (white clover) showed the best weed-control capacity, while *Trifolium subterraneum* (subterranean clover) and *Medicago polymopha* had more suitable characteristics for a rapid and complete establishment of pLM.
Overall, legume mulches appear more effective in

dicotyledonous than in monocotyledonous weed control. *Trifolium subterraneum* cv. Antas and *T. repens* cv. Haifa were identified as the potentially most suitable legumes for use as pLM, and their use in mixtures could be a promising solution. In addition, the ecotypes of *Medicago polymorpha* Manciano and Talamone proved to be well-adapted to local environmental conditions, and they showed better weed suppression than the commercial cultivars of *Medicago polymorpha*. All the results are available and further discussed in the open-access research paper “Legume Ecotypes and Commercial Cultivars Differ in Performance and Potential Suitability for Use as Permanent Living Mulch in Mediterranean Vegetable Systems” (www.mdpi.com/2073-4395/10/11/1836).

Experimental site: “Enrico Avanzi” Centre for Agro-Environmental Research of the University of Pisa (CIRAA), in San Piero a Grado (Pisa, Italy).
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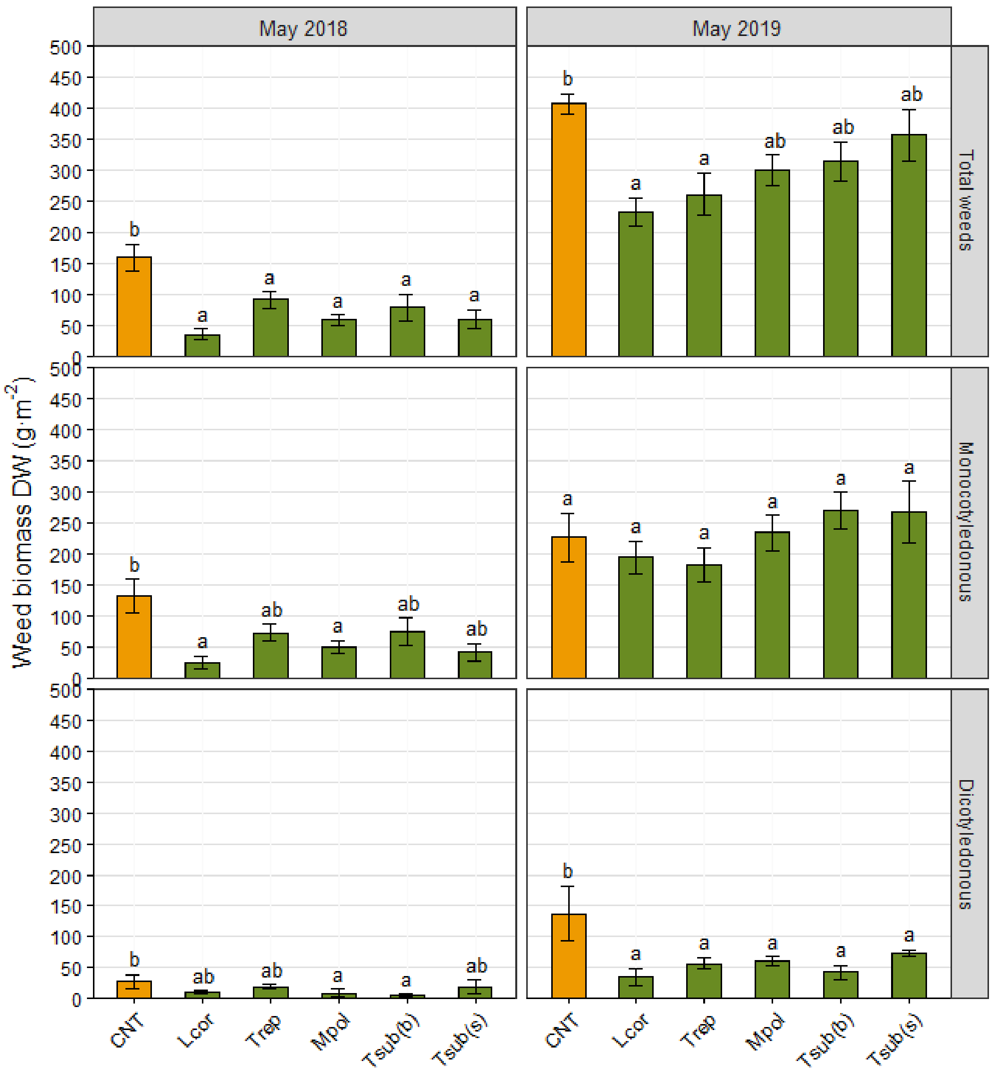

Figure 6 - Total above ground weed biomass (DW g/m^2) and specific biomass of monocotyledonous and dicotyledonous species in May 2018 and May 2019. CNT, control; Lcor, *Lotus cornicutaus*; Trep, *Trifolium repens* all cultivars together; Mpol, *Medicago polymorpha* all cultivars together; Tsub(b), *Trifolium subterraneum* all subsp. *brachycalycinum* together; and Tsub(s), *Trifolium subterraneum* all subsp. *subterraneum* together. Different letters within each sampling time indicate significant differences at the 0.05 level (Tukey post-hoc test). Error bars represent standard error (S.E.).

SELECTION OF SUITABLE LEGUMES FOR RELAY INTERCROPPING WITH DURUM WHEAT IN A LOW-INPUT CEREAL-BASED CROPPING SYSTEM

The relay intercropping of subsidiary legumes with durum wheat (living mulch) can be a sustainable and innovating tool for optimising nitrogen availability and weed control at rotation level in conventional low-input systems. Relay intercropping consists in growing two or more crops simultaneously during part of their life cycle. In Mediterranean cropping systems, cereal-legume relay intercropping involves broadcast-sowing or direct drilling of the legume in late winter, before the wheat steam elongation phase, in order to avoid damage on the main crop during the seeding operation. In such a system, legumes are supposed to persist in the field after the wheat harvest, maintaining the soil covered until the sowing of the subsequent cash crop. The choice of suitable legumes in relation to the co-cultivated crop determined the successful application of this agricultural practice and it needs to be fine-tuned to the local context.

The objective of this work was to identify suitable legumes for relay intercropping with durum wheat as an integrated weed management and diversification tool in a cereal-based cropping system located in Pisa plain. The study focused on the effects of wheat-legume intercrops at rotation level. Legume development, weed control, N uptake, crop production yield and grain quality were monitored in the co-cultivated wheat up to the harvest of the following cash-crop (forage sorghum).

It also addresses practical aspects related to the choice between contemporary and relay establishment of legumes with respect to the main crop, plus the choice of the most effective sowing method between broadcast and drill sowing.

The same experiment was carried out on the experimental farm of Horta located in Ravenna (see page 67). The performance of legumes

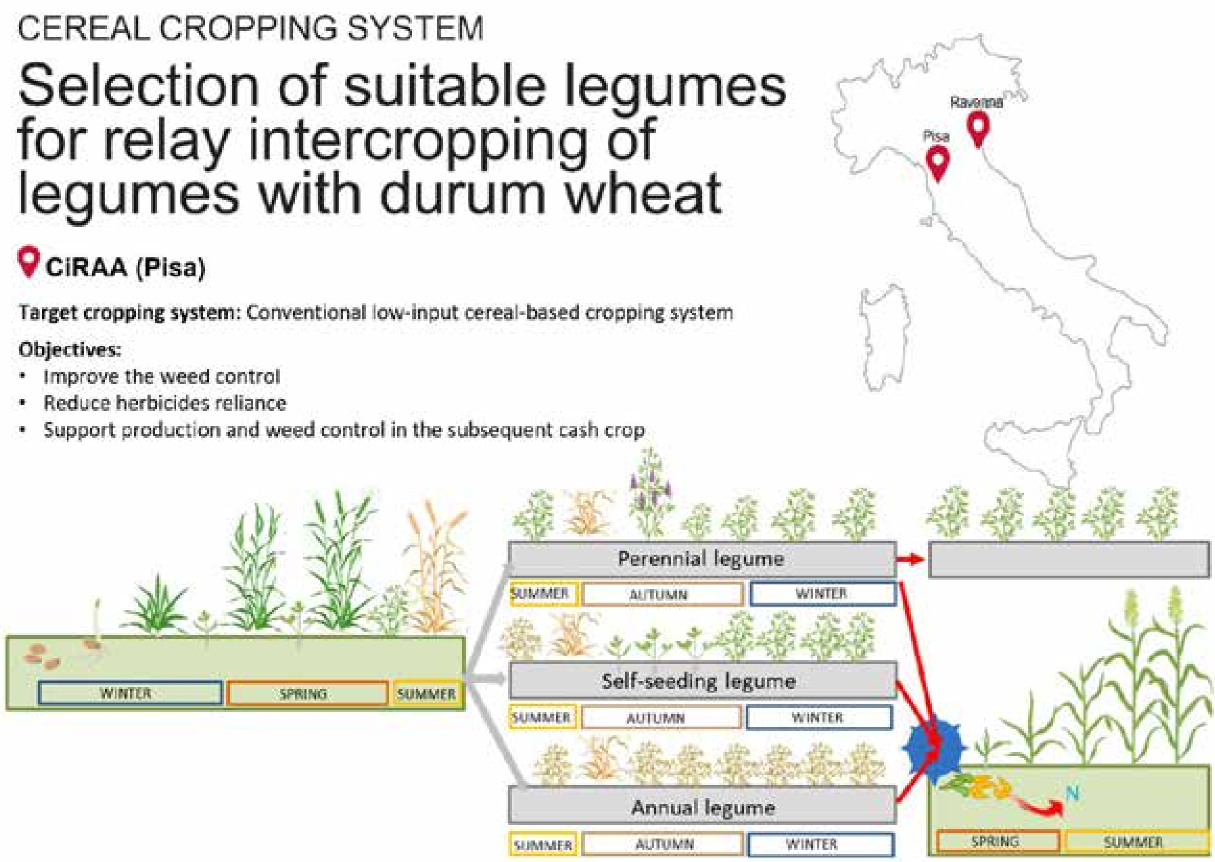

Figure 7 - Experiments on the selection of suitable legumes for relay intercropping of legumes with durum wheat as an integrated weed management and diversification tool in a Mediterranean cereal-based cropping system. The experiment was carried out in Pisa ("Enrico Avanzi"Centre for Agri-Environmental Research of the University of Pisa) and in Ravenna (Horta).

under these contrasting cropping system managements in Pisa and Ravenna were analysed and compared in the paper "Relay intercropping can efficiently support weed management in cereal-based cropping system when appropriate legume species are chosen". A video was produced about the experiment carried out in Pisa showing the performance of sorghum after legumes (https://www.youtube.com/watch?v=OoiSwaHMmrU&t=81s).

Materials and methods

This experiment was carried out in two locations in Italy (Pisa and Ravenna) over two consecutive crop seasons (2017/18, 2018/19). In Pisa, the field experiment was set up at CiRAA ("Enrico Avanzi" Centre for Agri-Environmental Research of the University of Pisa, Italy) and the experiment site was managed with a low-input system in which no herbicides and fungicides were used. Durum wheat (cv Minosse, provided by ISEA semences) was sown at the seed dose of 250 kg/ha in rows spaced 17.5 cm. Wheat sowing time ranged between October and November, whereas legumes were intersown in the already established wheat at the end of February (before the wheat elongation phase). The wheat was harvested in July and the legumes were maintained in the field until spring. In 2017/18, the tested legumes were reported in Table 4.
The number of undersown legumes were reduced in 2018/19 based on poor performance in both sites, with one annual legume (*Vicia villosa*) and three annual self-seeding legumes (*Trifolium michelianum, Medicago truncatula* and *Medicago scutellata*) being excluded. A control treatment with wheat grown as the sole crop was added to evaluate the incidence of undersown legumes on wheat yield performance. Pisa and Ravenna employed different standard sowing methods for the legumes. They were seeded by drill sowing in the Pisa experiments, and broadcast sowing in Ravenna. Three legumes (*Medicago sativa, Trifolium repens* and *Trifolium subterraneum*) were sown both with the drill and broadcast methods in Pisa and Ravenna to detect the influence of sowing technique on legume establishment.
Both contemporary and relay intercropping of *M. sativa* was performed for a comparison between the two intercropping systems. Legume biomass was incorporated into the soil in spring, and sorghum for forage production (cv. Sugar graze 2) was sown at a rate of 150 viable seeds per m^2 in 30 cm wide inter-rows following the legume plots. In the control, after the wheat harvest bare soil was maintained until the sorghum was sown.

Legume species	Cultivar	Seeding dose (kg/ha)	Biological cycle
Trifolium alexandrinum	Leila	30	Annual
Trifolium incarnatum	Kardinal	30	Annual
Trifolium resupinatum	Laser	10	Annual
Vicia villosa	Capello	80	Annual
Trifolium michelianum		15	Annual
Medicago polymorpha	Scimitar	40	Self-seeding
Medicago truncatula	Paraggio	40	Self-seeding
Medicago scutellata	Sava	40	Self-seeding
Trifolium subterraneum	Mintaro	35	Self-seeding
Medicago lupolina	-	40	Perennial
Medicago sativa	Gamma	40	Perennial
Trifolium repens	Companion	15	Perennial
Hedysarum coronarium	Carmen	30	Perennial

Table 4 - List of legumes used in the experiments.

Results

Effect of relay intercropping on wheat grain production was on average 3.2 t/ha, in line with the local production level. Undersown legumes had no negative effects on the potential durum wheat yield for any of the species used in this experiment. However, annual legumes such as *Trifolium resupinatum, Trifolium incarnatum* and *Vicia villosa* showed very vigorous growth during the final part of their life cycle when the competition with wheat for light and space decreased following grain ripening. The excessive growth and canopy height (>80 cm) of these legumes in respect to wheat canopy height (98 cm) can hinder mechanical harvest operations, resulting in grain yield losses and a serious post-harvest problem.
The other legumes grew in a complementary layer with respect to the harvestable wheat portion. The canopy height of these legumes was on average 16.5 cm and it was almost six times lower than the maximum canopy height of the wheat. Using these legumes, wheat can be easily harvested by setting the height of the combine harvester accordingly.
The results of this study showed that relay intercropping of legumes had no significant effect on wheat N uptake, but only on the subsequent cash crop. Legumes are sown in the already established wheat in late winter, before the wheat elongation phase, therefore the legumes are insufficiently developed to significantly support N uptake and increase grain protein content. Grain protein content was on average 14%.

Figure 8 - Relay intercropping of *M. lupolina* (left) and *T. incarnatum* (right) with durum wheat. In evidence the different suitability of these legumes for relay intercropping system. *M. lupolina* grew in a complementary layer with respect to the harvestable wheat portion, whereas the vigorous growth of *T. incarnatum* can hinder mechanical harvest operations, resulting in grain yield losses and a serious post-harvest problem.

Weed control

Under a low-input system, relay intercropping of legumes proved to be a suitable strategy to support weed control during the intercropping period. The weed control efficiency (WCE) of the legumes was correlated with legume dry biomass production in summer at wheat harvest time ($R2=0.35$, $P<0.05$), in autumn ($R2=0.50$, $P<0.001$), and the following spring ($R2=0.44$, $P<0.001$). The aboveground biomass of legumes at wheat harvest was sufficient to reduce weeds more than the sole crop.

The most effective legumes for controlling weeds during the intercropping period were *Medicago sativa, Hedysarum coronarium, Medicago lupulina, Trifolium incarnatum* and *Trifolium resupinatum*, with weed biomass being reduced by up to 70% when compared to the control. However, other legumes, such as *T. repens* and *T. subterraneum*, showed contrasting efficiency in controlling weeds between the two growing seasons. The low weed-control capacity of *T. repens* during the intercropping period was due to very slow growth during the early establishment stages, and for this reason it had a lower competitiveness against weeds. The legumes were maintained in the field after the wheat harvest. The following autumn, weed dry biomass in control plots was 112.11 g/m^2 and 361.20 g/m^2 respectively during the first and second repetition of the experiment.

In the first growing season, perennial legumes reduced weed dry biomass by 67% on average in comparison with the control, whereas in the second growing season perennial legumes reduced dry weed biomass by 72% in comparison with the control. During the second repetition of the experiment, *M. sativa* had a WCE of 97%, significantly higher than *H. coronarium* (53%) and *T. repens* (57%). In the spring following wheat harvest, weed dry biomass in control plots was 205.38 g/m^2 and 225.38 g/m^2 respectively during the first and second repetition of the experiment.

During the first growing season, the annual legumes used in this study, such as *T. resupinatum* and *T. incarnatum*, had negative values of WCE and increased the weed dry biomass by 78% and 18% respectively in comparison with the control.

During the second repetition of the experiment, *H. coronarium, T. Repens*, and *T. subterraneum* reached almost total weed control in comparison with the control (96%, 94%, 92% WCE respectively Figure 9).

Sowing method: drill or broadcast sowing?

In a low-input system, as in Pisa, direct seed drilling of legumes in the already established wheat can be the most appropriate sowing method. In this system, legume biomass production was on average 10 times higher when compared with high fertility systems due to the lower competition of wheat for space and light (wheat biomass -45% compared with Ravenna). In this condition, the optimised spatial arrangement of plants is fundamental to avoid competition issues with the main crop. Using direct drill sowing of legumes, seeds are placed in the wheat inter-row space and

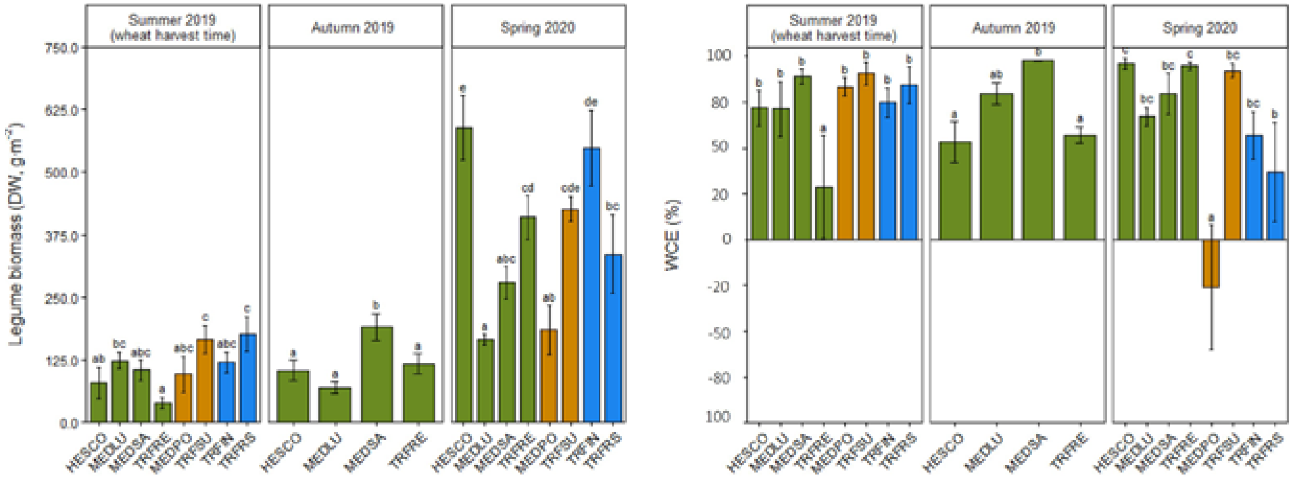

Figure 9 - Biomass (left, DW, g/m^2) and Weed Control efficiency (right, WCE, %) of legumes in summer (wheat harvest time), autumn and spring respectively during the second repetition of the experiment. CNTR: Control plot (wheat sole stand crop); MEDSA: *Medicago sativa*; TRFRE: *Trifolium repens*; HESCO: *Hedysarum coronarium*; MEDLU: *Medicago lupulina*; MEDPO: *Medicago polymorpha*; TRFSU: *Trifolium subterraneum*; TRFIN: *Trifolium incarnatum*; and TRFRS: *Trifolium resupinatum*. Different colours indicate the biological cycle of legumes (green: perennial, orange: annual self-seeding, blue: annual). Different letters (a-d) indicate significant differences at 0.05 level. Error bars represent standard error (S.E.).

the distance between wheat and legume rows is maximised. The drill sowing of legumes can be performed with mechanical seed drills.

Sowing time: relay or contemporary intercropping?

In a low-input system, the often-observed high biomass production of contemporary intercropped legumes can compete with wheat during cereal growth and hinder the mechanical harvest operation, with potential negative effects on grain production. In this case, providing wheat with a competitive advantage by relay intercropping legumes can limit the opportunity for competition with the undersown legume. In this study, we compared contemporary vs relay intercropping of *M. sativa* with wheat. Relay intercropping provided a competitive advantage to wheat and reduced the biomass production of *M. sativa* by 50% when compared with contemporary intercropping (Figure 10).

Notably, the weed control capacity of *M. sativa* was not significantly different between contemporary and relay intercropping. However, in a low-input cereal-based cropping system, as in Pisa, the delayed sowing of legumes can still cause competition with wheat when unsuitable legumes are used. In this experiment, annual legumes such as *T. resupinatum* and *V. villosa* overtopped wheat and showed very vigorous growth during the final part of their life cycle when the competition with wheat for light and space decreased following grain ripening. The late competition of these legumes did not affect wheat production because nutrient translocation to the grain had already occurred, although a significantly lower Harvest Index (HI) in comparison with the wheat sole crop was detected. The vigorous legume growth caused problems at harvest, though.

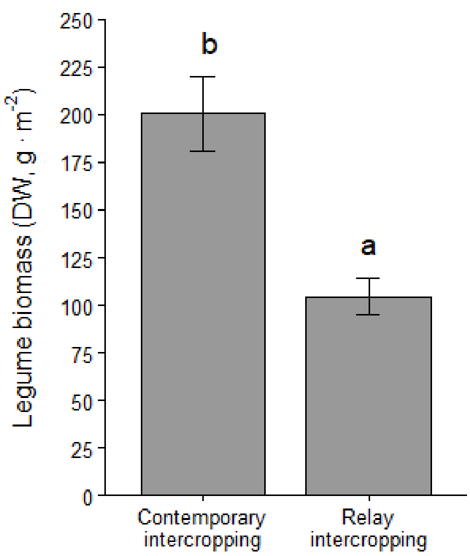

Figure 10 - Biomass production of *M. sativa* in contemporary and relay intercropping systems with durum wheat in a low-input cereal-based cropping system.

Destination of legumes

One of the most potential interests that relay intercropping presents to conventional low-input systems is the nitrogen enrichment of soil via symbiotic fixation on N_2 and N transfer to the subsequent cash crop. The N released from legume residues can significantly support productivity of the following crop and therefore reduce the use of external inputs. Overall, results from this experiment demonstrated that sorghum production was strongly correlated with the biomass accumulation of legumes in spring, and that legumes used in relay intercropping systems can significantly support both biomass production and N uptake in the subsequent sorghum (Figure 11).

During the first repetition of the experiment, sorghum preceded by *H. coronarium, T. subterraneum, T. repens* and *M. sativa* had a significantly higher dry biomass production (+457%, +437%, +363% and +291% respectively) when compared with the control (2.06 t/ha). A similar effect was observed during the second repetition of the experiment. A study on the agronomical performance of several cultivars of sorghum reported that dry biomass production of the same sorghum type used in the current experiment can range from 9 t/ha to 13 t/ha in conventional systems (fertilisation based on 50 unit of N/ha). In this study, sorghum preceded by *H. coronarium, T. subterraneum, T. repens* and *M. sativa* had biomass production of 11 t/ha on average without the use of mineral fertilisers, in line with the production level of the conventionally cultivated sorghum. We observed residual effects of legume residues on weeds in the subsequent sorghum during the second repetition of the experiment. Residual effects of *M. sativa* significantly reduced weeds biomass by 50% in sorghum when compared with the control. The residual effects of the legumes mainly affected dicotyledonous weeds, whereas residues of *T. resupinatum* and *T. incarnatum* promoted monocotyledonous weed growth.

Experimental site: “Enrico Avanzi” Centre for Agro-Environmental Research of the University of Pisa (CIRAA), in San Piero a Grado (Pisa, Italy).
GPS coordinates: 43°40’06.96’’N 10°18’31.49’’E

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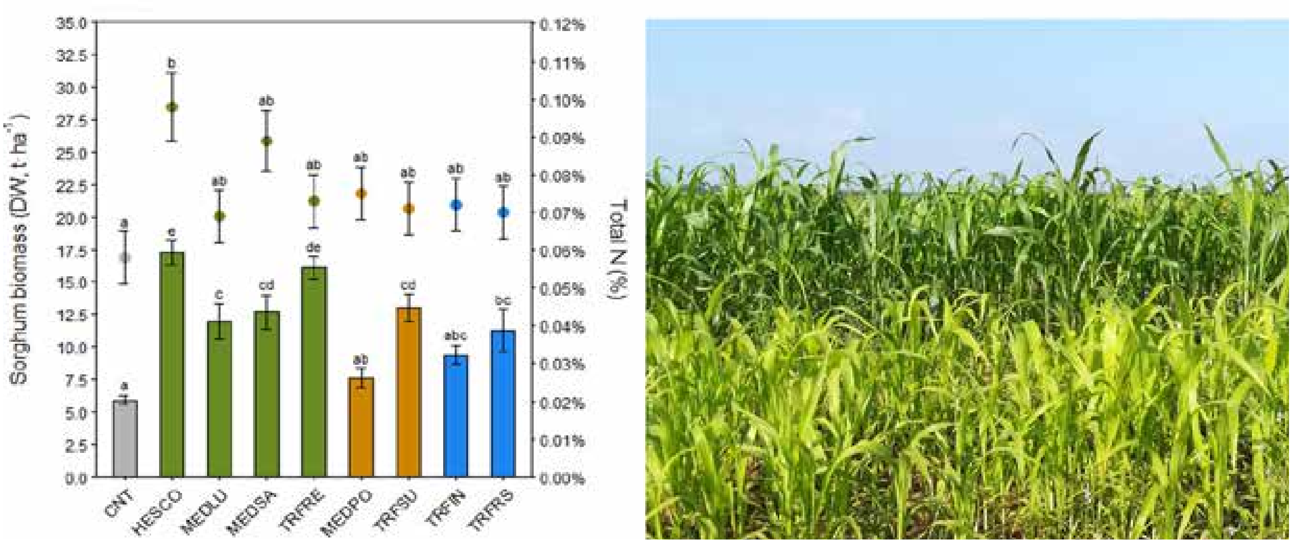

Figure 11 - Sorghum dry biomass (bars, DW t/ha) and total nitrogen content (dots, %), on the left, during the second repetition of the experiment. CNTR: Control plot (bare soil after the wheat harvest); MEDSA: *Medicago sativa*; TRFRE: *Trifolium repens*; HESCO: *Hedysarum coronarium*; MEDLU: *Medicago lupulina*; MEDPO: *Medicago polymorpha*; TRFSU: *Trifolium subterraneum*; TRFIN: *Trifolium incarnatum*; and TRFRS: *Trifolium resupinatum*. Different colours indicate the biological cycle of legumes (green: perennial, orange: annual self-seeding, blue: annual). Different letters (a-e) indicate significant differences at 0.05 level. Error bars represent standard error (SE). Sorghum preceded by legumes is shown in the photo on the right. This photo highlights the different effects of legumes as a previous crop on sorghum biomass and N content.

USE OF THE DONDI CUT-ROLLER AS A ROLLER CRIMPER

Objectives

To test the effectiveness of the "cut-roller" (produced by DONDI S.p.A. for crop residue management) when used as a roller-crimper for the mechanical termination of some of the most common winter cover crops for arable cropping systems. Besides fine-tuning working speed and blade typology, special focus is on weed suppression and soil compaction.

Materials and methods

An on-station field experiment has been carried out for three years (2018/19, 2019/20 and 2020/21) at the "Enrico Avanzi" Centre for Agri-Environmental Research of the University of Pisa (CiRAA), in San Piero a Grado (Pisa, Tuscany). Three different cover crop treatments (rye - *Secale cereale* L., hairy vetch – *Vicia villosa* Roth, and a rye-vetch mixture) were drilled in autumn 2018, 2019 and 2020 respectively on three different 30 m x 260 m fields. The sowing rates were 180, 120 and 90:60 kg ha^{-1} respectively for rye, vetch and the rye-vetch mixture. In sub-plots we tested the effect of different combinations of blade typology (i.e., sharpened vs not sharpened) and working speed (5, 10, 15 km hr^{-1}) on the killing rate of the three cover crops. In all the three years, we kept the same timing of cover crop termination as the first year, which happened when the phenological stage of rye was full milky ripening (BBCH 77) and the vetch was full flowering (BBCH 69) (Figure 12). Immediately after the termination of the cover crops, a grain sorghum cash crop (*Sorghum bicolor* (L.) Moench cv. Baggio) was directly sown into the dead mulch provided by the cover crops, with an inter-row space of 50 cm and a seed density of 40 seeds m^{-2}. The following parameters were assessed:

- Biomass and soil cover produced by cover crops at different stages, including the termination stage;
- Weed abundance and composition in cover crops at different stages, including the termination stage;
- Number of crimps per stem produced by the cut-roller on rye plants;
- Killing rate and dynamics of the cover crops (through image analysis);
- Weed suppression in the sorghum crop;
- Effect of the termination technique and cover crop species on sorghum emergence, growth, N accumulation and yield;
- Soil compaction;
- Energy consumption and economic issues.

Final results

Averaged over the three years, the mixture and the rye pure stand were the most productive **cover crop** treatments, accounting for an **aboveground dry matter of 6.31 t ha^{-1}**. This amount can be considered as satisfactory and in line with previous results obtained in the study area. The vetch pure stand, however, resulted in ~30% lower biomass production. The three cover crop treatments did not show any significant difference in terms of **weed biomass**, which was kept **far below 1 t d.m. ha^{-1}**. This result confirms that cover crops can reduce weed abundance not only by competitive interaction with weeds (i.e. proportionally to cover crop biomass production) but also by non-competitive mechanisms, such as allelopathy, which was documented in literature for both the cover crop species tested in this trial. In terms of nitrogen content, as expected, vetch and the rye-vetch mixture showed significantly higher results than the rye pure stand, which accumulated in its biomass less than 50% of the N contained in the other treatments. The calculation of the **LER (Land Equivalent Ratio)** revealed that the mixture was superior to the pure stands, both in terms of cover crop biomass **(LER 1.28)** and N uptake **(LER 1.45)**.

Figure 12 - Visual soil cover of rye (a), hairy vetch (b) and the mixture (c) at the cover crop termination stage in the three years.

Figure 13 - Greenness of rye, vetch and mixture of cover crops immediately after the pass of the cut roller (T0) and 7 days after (T7).

This means that, to achieve similar results to 1 ha of the mixture, the pure stands of the two cover crops would have had to occupy 1.28 ha and 1.45 ha of land respectively. From an agroecological perspective, these results support the effectiveness of the planned biodiversity at the level of cover crop species and show how biodiversity can help achieve good agronomic results by delivering a plethora of agroecosystem services.
In all three years, the cut-roller terminated the cover crops very effectively. This was expected because of the late phenological stages of rye and vetch. On average, the half-life of the cover crops was achieved around two days after the termination date, and a 90% termination rate was reached in just three to four days after termination (Figure 13).
These good results were partially explained by the advanced stages of the cover crops (full flowering for the vetch and milky dough for rye). Nevertheless, averaged over the three years, we observed some slight differences in the rate of green tissue decay in the three cover crops as a result of the different technical set-ups of the roller. For rye and the mixture, the sharpened blades in combination with the intermediate speed (i.e. 10 km h^{-1}) gave the quickest termination rate, whereas for vetch the combination of sharpened blades and 5 km h^{-1} showed the best performance. Overall, we can say that **all the tested combinations of roller set-up performed equally well** at the late cover crop stage, but further research can contribute to revealing the effect of the best performing combinations at earlier stages as well.
The roller's good level of termination rate was the result of a combination of crimping and cutting effects. Averaged over cover crop treatments, the cut biomass accounted for around one third of the total biomass, meaning that the roller was able to cause crimping on ~67% of the biomass. Rye was the cover crop with the highest proportion of crimped stems (~10%), whereas vetch showed the lowest, and the mixture was in between the two. Our results confirm that the use of roller crimpers is particularly effective with cover crops characterised by long, flexible and partly dry stems. Equipping the roller with sharpened blades resulted in a significant increase in the proportion of cut biomass, with variable results obtained in combination with cover crop species and work speed. Regarding the latter, we only observed a weak decreasing trend in the proportion of cut biomass at increasing speed, with a differential range of just 4% between the minimum and maximum levels.
Passing the cut-roller, despite producing up to 2.5 cm deep indentations, did not result in significant soil compaction. The values of cone index at 15 cm depth measured by the penetrometer showed

on average more soil penetration resistance after rolling than before rolling. This was particularly evident in the vetch plots. Nevertheless, the values did not reach the threshold of soil compaction (i.e. 2000 kPa). The effect of blade typology and working speed were less evident.
The grain sorghum directly seeded on the dead mulch provided by the cover crops was grown without any fertilisation and weed-control operations. Averaged over the three years, the mixture and hairy vetch alone gave five-fold the grain yield of rye plots, which gave unsatisfactory results (less than 2 t d.m. ha^{-1}). The poor performance of rye was likely due to the nitrogen drop effect caused by the high C:N ratio of the dead mulch provided by the rye, which led to reduced availability of mineral forms of N for sorghum roots.
We did not notice any significant effect on sorghum grain yield due to termination technique (i.e. the blades and the speed), but some interactions between this and cover crop type was revealed to be significant. Interestingly, grain yield of sorghum was significantly increased when the vetch and the mixture were terminated with the non-sharpened blades, suggesting that it was more beneficial to the resulting mulch. We argue that the lower level of cut biomass achieved with non-sharpened blades might have led in these treatments to longer-lasting dead mulch on the soil surface and thus to improved weed control and moister soil conditions, which helped crop development. The SPAD index (i.e. an index correlated to foliar chlorophyll and N content) determined at three different stages of sorghum development confirms this hypothesis as it showed, from the early stages (i.e. 4-6 leaves), higher values in vetch and mixture plots terminated by roller crimper equipped with non-sharpened blades.
Averaged over the treatments, weed biomass at sorghum harvest was kept very low by the three cover crops. Nevertheless, analysis of results from the three years showed significant differences among the treatments, with weed biomass being halved in the mixture plots when compared to rye and vetch pure stands. This result emphasises the value of the mixture in agroecological terms, and we believe this result was most likely due to its combination of complementary ecosystem services, which allowed the crop to over-grow the weeds and to out-compete them. We also observed that the roller's working speed had a significant effect, with the fastest pass (15 km h^{-1}) producing the lowest weed biomass, most likely due to a more intense cutting effect.

Besides excellent weed suppression, the dead mulch provided by the mixture and by the vetch pure stand supported the growth of sorghum by speeding up seed germination, vegetative growth and seed set thanks to higher humidity in the soil, no allelopathic effect and higher nitrogen availability in the soil. These effects resulted in very good grain N uptake levels for sorghum at harvest in all three years (around 237 kg N ha^{-1} on average for the three years for the two cover crops), whilst for rye we observed a significant 50% reduction in N uptake.

Further developments

The very good results of the cut-roller as a roller crimper over the three years were clearly down to the late termination date due to the wet conditions in spring of the experimental period. The key factor for boosting the spread of roller crimpers would be a high termination rate, even when used at the early stages of cover-crop development. Nevertheless, the good level of grain sorghum yield obtained in the first two years in vetch and mixture plots confirmed that the late sowing date did not negatively affect the establishment and growth of sorghum, even without irrigation.

GPS coordinates of 2020/21 fields: 43°39’31’’N 10°18’08’’E

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SMOCA LTE – CONSERVATIVE MANAGEMENT OF ORGANIC FIELD VEGETABLES

Objectives

The main objective of this on-station trial was to test the agro-environmental performance of combining conservation agriculture (i.e. no-till or strip tillage, permanent soil cover with living mulch) and organic farming practices (i.e. non-chemical weed control, organic fertilisation and crop protection) in the production of organic field vegetables. This involved comparing three different cropping systems based on the same three-year crop sequence (processing tomato-chicory-melon-faba bean-fennel), but with a decreasing level of soil disturbance, to assess crop performance, economic viability, soil fertility, plus weed abundance and composition.

Materials and methods

The experimental field was located at the University of Pisa's "Enrico Avanzi" Centre for Agri-Environmental Research (CiRAA) in San Piero a Grado (Pisa, Tuscany) (Figure 14). Three different cropping systems (ORG, RED, PER) were established there in winter 2017-18 and compared with a system approach for three years. ORG was mainly based on standard organic practices, such as annual soil tillage, green manures incorporated into the soil, organic NPK fertilisation (broadcast application in pre-transplanting, plus fertigation coupled with drip irrigation), as well as mechanical and thermal weed control. RED was based on permanent soil cover with a perennial cover crop (i.e. a dwarf variety of white clover, *Trifolium repens* L. var. Pipolina), strip-tillage performed along seed furrows, and organic NPK fertilisers applied as band application in pre-transplanting and fertigation). PER, which was established on plots managed under no-till for the previous three years, was based on permanent soil cover with white clover and no-till transplanting of vegetables, whilst only NK fertilisers were applied within the crop furrows or in fertigation treatments, with P fertiliser being completely replaced by an

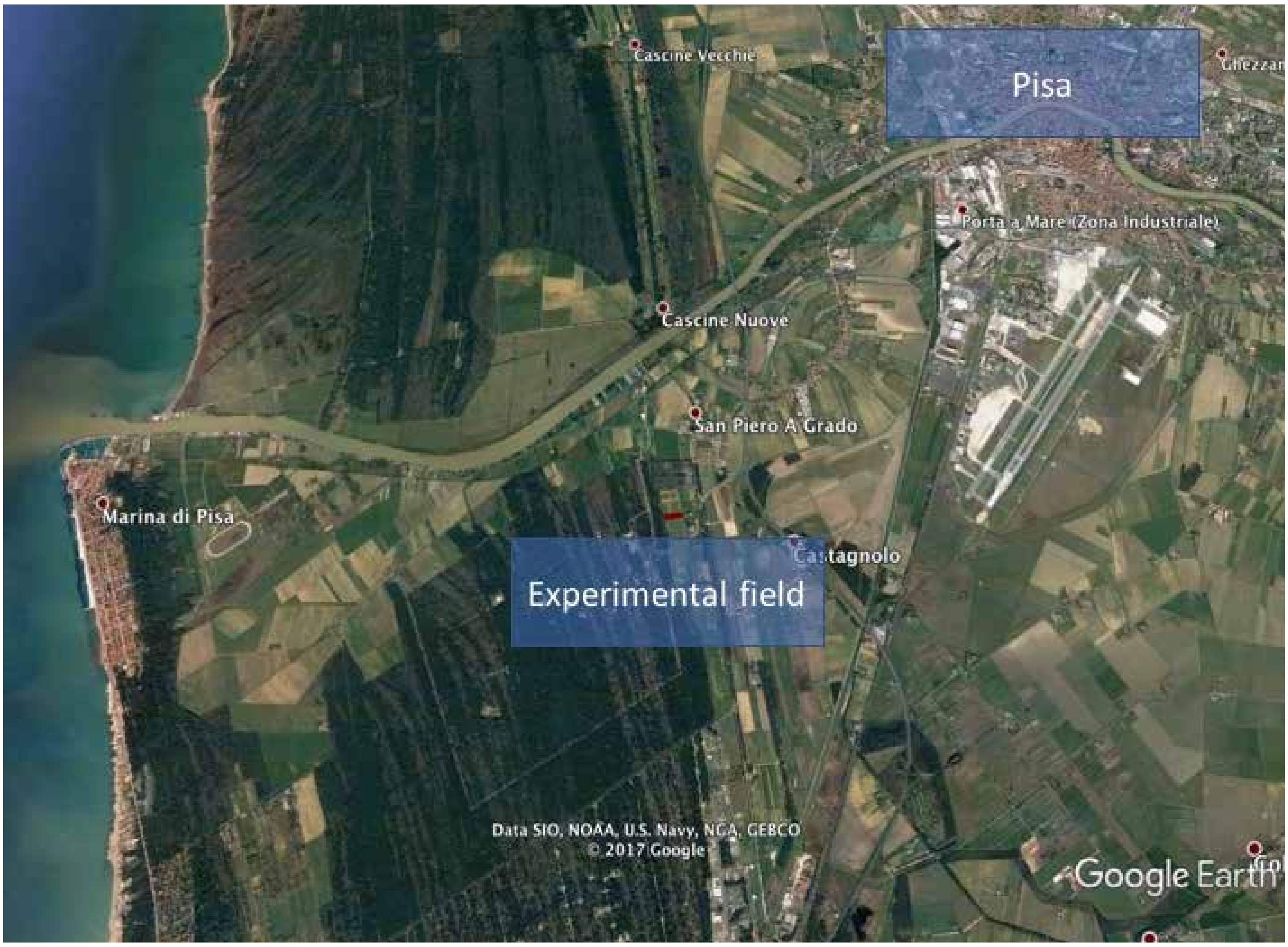

Figure 14 - 2019/20 field trial at CiRAA (43°40'18.47''N 10°20'40.25''E) (photo ©2017 Google).

arbuscolar mycorrhizal formulation.
The experimental design was a randomised complete block (RCB) with three replications for a total of 18 plots, each sized 3 m wide and 21 m long. The field was split into two parts (Field 1 and 2) hosting the two different segments of crop sequence in order to halve the time needed to replicate the crop sequence twice. Each year, the following parameters were assessed:

- Biomass and soil cover produced by cover crops and cash crops (i.e. yield and residues) at maturity;
- NP uptake of cash crops and cover crops;
- Crop root colonisation by AMF;
- Weed abundance and composition in cover crops and cash crops;
- Rheological quality of crop produce;
- Energy consumption and monetary cost of each field operation.

Final results

Field 1

The trial started with tomato (*Solanum lycopersicon* cv. Brixsol) in 2017/18, but the crop developed very poorly in all the treatments due to late transplanting, affected by harsh spring weather and huge competition from summer weeds. In 2018/19, after tomato, chicory (*Cichorium intybus* Pan di Zucchero cv. Uranus) was transplanted in early autumn and harvested in December 2018. For chicory we obtained good yield results in all the treatments, with PER showing the highest yield, still not statistically different from ORG and RED. The level of weed biomass at harvest time was very low (0.11 t d.m. ha^{-1}) on average, although the white clover living mulch was not well developed (~15% soil coverage) in PER and RED. After chicory, melon (*Cucumis melo* cv. Bacir) was transplanted in May 2019 and harvested in August 2019. The results confirmed those of tomato grown in the first year, with a very low level of fruit yield in all the three systems due to very high weed presence (~5, 7 and 8 t d.m. ha^{-1} for ORG, PER and RED respectively), especially aggressive summer species such as *Echinocloa crus-galli, Digitaria sanguinalis*, and *Setaria viridis, Cynodon dactylon*. The clover, although resown in spring 2019, did not survive the melon harvest.
Broad faba bean (*Vicia faba* var. major cv. Aguadulce Supersimonia) seeded on 21 January 2020 (late sowing due to harsh weather in winter 2019/2020) was harvested twice: on 26 May and 6 June 2020. The short growing period affected the marketable yield of the crop (expressed as fresh weight of pods), which was on average far lower than farmers' standards. The two conservative systems PER and RED resulted in significantly lower cumulative marketable yield than ORG, but no differences were observed between the two. The dry weight of weeds followed the same trend as faba bean biomass, with ORG giving the best performance (i.e. the lowest weed biomass). There were no differences between PER and RED, but their weed biomass was almost twice that observed in ORG. This result clearly demonstrates that clover living mulch did very little to improve competition with weeds, due to the very poor biomass observed in 2019/20.
After the faba bean harvest, the crop residues were mulched in all the plots. The ORG plots were tilled by rotary cultivator and then broadcast seeded with red cow pea (*Vigna unguiculata* (L.) Walp.), grown as summer green manure and soil incorporated on 3 September 2020 with another pass of the rotary cultivator. Four days later, fennel (*Foeniculum vulgare* L. cv. Montebianco) was transplanted in all the plots at 0.8 m inter-row distance x 0.3 m intra-row distance. The crop grew regularly, but was negatively affected by the harsh weather, characterised in autumn-winter 2020 by huge levels of rainfall (743 mm rainfall from September 2020 to January 2021) that caused waterlogging, poor root growth and activity, as well as low nutrient availability (Figure 2). The crop was harvested once on 22 December 2020. Statistical analysis resulted in no significant differences among treatments, with PER and RED showing still similarly higher (+30%) values than ORG. RED resulted in the best weed suppression (-43% weed biomass when compared to PER and ORG, on average), although it was not significantly different from the other treatments. Although the results were clearly affected by the low levels of biomass production, the poor performance of the ORG was most likely due to the negative behaviour of the tilled soil when compared to strip-tilled RED and no-tilled PER during what was a very wet year. We argue that wheeling tracks and soil compaction caused by the rotary cultivator might have enhanced the risk of waterlogging, leading to slower crop growth and poor nutrient uptake. Once again, the conservative management of the soil achieved the best results in winter vegetable crops, partly due to poor competition from the weeds (on average, less than 0.5 t d.m. weeds ha^{-1}).

Field 2

As in Field 1, the melon in Field 2, which started the crop sequence in 2018, gave extremely negative results in all the treatments due to

Figure 15 - Limited radial growth of the fennel heads in the PER treatment 2020.

poor establishment and highly competitive weed biomass.
The subsequent faba bean was late transplanted in 2019, after a very rainy autumn-winter season. In faba bean, we observed better results for ORG and then RED, whilst PER gave the lowest yield (87.5% less than ORG and 50% less than RED). This was most likely due to poor development of the root system and to low activity of root nodules (not investigated).
For fennel grown in autumn 2019 in Field 2 after faba bean, the head yield results obtained in PER were significantly lower than in RED and ORG (ca. -60%). The weed biomass at harvest was acceptable and very similar among the three systems (~1 t d.m. ha^{-1}), meaning that the main reason behind the difference in crop yield was not weeds.
The tomato transplanted on 7 May 2020 was harvested three times (21 July, 4 and 18 August). Mild temperatures and rainfall in June after a long dry period allowed the crop to grow better than in 2018 and, most importantly, reduced early emergence and growth of microthermal grass weeds, which were contained by mechanical weeding and hand weeding until late July (Figures 16A and 16B). Abundant rainfall occurred in August 2020 favoured the weeds much more in the last part of the growing season.
Nevertheless, the tomato was able to reach maturity in all the plots and its potential marketable yield (i.e. the sum of red, damaged and ripening fruits) was, on average, acceptable when compared to organic standards (~38 t f.m. ha^{-1} obtained vs ~ 50 t f.m. ha^{-1}). We observed a low fruit set in the ORG plants (close to the one observed in the PER plots and one third lower than the RED plots), most likely due to drought stress and slow early plant growth in the post-transplant period and exacerbated, when compared to the RED and PER plots, by the tillage effect. The plants were able to recover later in the season, as demonstrated by the comparable dry weight of the plants at harvest. We did not observe any statistical differences among the three treatments in terms of biomass production, fruit yield, fruit diameter and sugar content (°Brix). RED showed the best performance in terms of biomass production, potential yield and weed suppression (-18% weed biomass when compared to ORG and PER), but summer weeds contributed to unsatisfactorily high weed competition (~4 t d.m. ha^{-1}, averaged over the three treatments, despite intensive hand weeding).
After the tomato harvest and the mulching of tomato residues, the seedbed for chicory transplant in the ORG plots was prepared by rotary cultivator. The transplant of chicory was performed on 29 September with the same spatial arrangement as for tomato. On the PER and RED plots, only two mowing operations were done to control weeds and living mulch due to the poor development of plants and harsh weather conditions. Due to massive waterlogging in December 2020, the level of biomass and yield production at harvest date (i.e. 19 January 2021) was very low when compared to farmers' standards. No significant differences were observed among treatments for all the parameters assessed. Overall, the level of weed biomass at harvest was very low (0.1 t d.m. ha^{-1}).

General results on P uptake

Interestingly, none of the tested crops showed a significant reduction in P concentration in the biomass components in PER plots when compared

Figures 16A and 16B - Good development by tomato plants at the flowering stage in RED (left) and PER (right) plots in 2020.

to the RED plots. The observed differences in P2O5 uptake between the two treatments were always due to the biomass component rather than to P concentration. This observation, coupled with the one on the mycorrhization rate of crop roots, which showed very similar levels between the two treatments, allowed us to consider the replacement of P fertiliser with mycorrhizal preparation as a highly effective way to mobilie soil P and make it available for the crops. Nevertheless, due to similar mycorrhization levels between PER and RED, which was not supplemented with mycorrhizal preparation, we cannot exclude that native mycorrhizal strains might have played a role in supporting crop P uptake. Similarly, microbes other than mycorrhizal fungi (e.g. P-solubilising bacteria) might have been present in the microbial populations colonising crop roots, most likely also playing a role.

Further developments

Overall, conservative treatments based on the agroecological design of cropping systems led to variable results, normally showing better performance for winter crops such as chicory and fennel, where weed competition was low and did not challenge the living mulch. For summer crops, we observed satisfactory results only for tomato in 2020, but the weeds clearly overgrew the living mulch and the crop. The white clover used as living mulch did not provide satisfactory soil cover and did not establish well in the three years, most likely due to an untimely sowing date and no effective management (e.g. mowing was suspended at the latest stages of the companion vegetable crops due to inter-row coverage).

Further steps in this field will be to test alternative management options for living mulch, as well as alternative living mulch species with higher adaptability to Mediterranean conditions. Ensuring a good environment for crop growth was a challenging feature in conservative systems, where early weed competition can be very high, especially in warmer seasons. In most cases, we observed reduced vegetative growth in vegetable crops in the two conservative management plots, possibly affected by reduced soil aeration and slower mineralisation rate of organic matter and fertilisers. Subsoiling or baseline application of organic amendments at high rates, or treatment with biostimulant products might be promising options for improving soil conditions and allowing the crops to start growing quickly after transplanting.

GPS Coordinates: 43°40'18.47''N 10°20'40.25''E

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MANAGEMENT OF WHITE CLOVER LIVING MULCH IN FIELD VEGETABLES

Objectives

The main objective was to test alternative management options for a dwarf variety of white clover (*Trifolium repens* L. var. Pipolina) grown as living mulch for two field vegetables in sequence, i.e. cauliflower (*Brassica oleracea* L. var. botrytis) and eggplant (*Solanum melongena* L.).

Materials and methods

The experimental field was located at the University of Pisa's "Enrico Avanzi" Centre for Agri-Environmental Research (CIRAA) in San Piero a Grado (Pisa, Tuscany) (Figure 17). Three different treatments (i.e. control without cover crop and based on conventional tillage, living mulch system with white clover regularly managed by flaming and living mulch system with white clover regularly managed by mowing) were established here in winter 2018-19.

In October 2018, white clover was broadcast sown at a 100 kg ha^{-1} seeding rate. In spring 2019, the clover was regularly mowed or flamed before the transplanting of the field vegetables. Cauliflower was established with a wide inter-row (0.8x1 m) to allow for mowing and flaming. The living mulch and weeds were controlled in the two living mulch treatments by mowing (once a week) or flaming (three times a week) for the entire crop growing period (Figure 18).

In the control treatment, the weeds were controlled by inter-row cultivation (twice for the entire crop growing period). The same operations were carried out for eggplant (which was transplanted in May 2020). The cauliflower was harvested manually on 4/12/2019 and 10/12/2020 respectively in the two experimental years 2018/19 and 2019/20 (Figure 19). The eggplant was harvested multiple times: on 22/07, 30/07, 13/08, 31/08 and 20/10/2020; and on 13/07, 29/07, 29/08, 15/09 and 13/10/2021.

The experimental design was a randomised complete block (RCB) with three replications for a total of nine plots each sized 5.6 m wide and 20 m long. The field was split into two parts to achieve a one-year time offset of the crop rotations. In one half, cauliflower was grown in 2018/19 and eggplant was grown in 2019/20; in the other, a temporal replication of the trial was carried out from 2019/20. Each year, the following parameters were assessed:

- Biomass and soil cover produced by cover crops

Figure 17 - 2019/20 field trial at CiRAA 43°40'20.0''N 10°20'39.0''E (photo ©2020 Google).

Figure 18 - Living mulch of white clover well-established in cauliflower.

Figure 19 - Cauliflower at harvest time in the living mulch system.

and cash crops (i.e. yield and residues) at maturity;
- Energy consumption and monetary cost of each field operation.

Results

Over the two years, cauliflower marketable yield and plant residues of the tilled control were respectively 15% and 27% higher than the two living mulch-based systems. The system based on regular mowing of the living mulch performed better than flaming in terms of yield (+10%), crop residue biomass (+16%) and weed biomass reduction (-116%). Concerning weed biomass, the regularly mown living mulch system even outperformed the tilled control (-27% weed biomass). Moreover, regular mowing of the living mulch resulted in a higher living mulch biomass (+182%) in cauliflower fields.
Over the two years, eggplant showed higher marketable yields on conventional tilled plots when compared to the living mulch-based systems. Conventional tilled plots showed 141% higher fresh marketable yields when compared to the living mulch system managed by flaming, but only 13% higher yields when compared to the regularly mowed living mulch system. Eggplant residue biomass was only 0.3% higher in the conventional tilled and mowed living mulch-based systems. Conversely, the living mulch system managed by flaming had 77% lower plant residue biomass.
The living mulch systems managed by regular mowing achieved the best weed control effect. Weed biomass reduction was 400% lower when compared to conventional tilled plots and 531% lower when compared to living mulch-based systems managed with flaming. However, living mulch biomass in the flaming-managed system was up to 721% higher when compared to the periodic mowing treatment.
Taking into account energy requirements, the living mulch-based system managed with regular mowing provided the highest energy savings when compared to the living mulch managed by flaming (-835%) and the conventionally tilled system (-268%).

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For further reading:

Sportelli, M., Frasconi, C., Fontanelli, M., Pirchio, M., Gagliardi, L., Raffaelli, M., Peruzzi, A., Antichi, D. (2022). Innovative Living Mulch Management Strategies for Organic Conservation Field Vegetables: Evaluation of Continuous Mowing, Flaming, and Tillage Performances. Agronomy, 12 (3), art. no. 622. doi: 10.3390/agronomy12030622.

EXPERIMENTAL TRIALS AT HORTA SRL

Figure 1 - Aerial view of experimental plots.

Figure 2 - Main Horta building, Cà Bosco farm (Ravenna).

Horta is a spin-off company of University Cattolica of Sacro Cuore. It was founded in 2008 and its mission is to add value to research results by transferring technological innovation to practical agriculture. Horta provides agriculture services for crop production at both national and international level in a bid to improve the production of both farmers and agro-food industries in terms of quality, stability and sustainability. Horta conducts experimental trials on Cà Bosco farm, which covers 220 ha and is divided into three 70 ha blocks.
The farm has one area run under integrated management and one under organic management.

It applies 3-4-year rotations, with durum wheat, bread wheat, maize, sugar beet, pea and soy as its main crops. Soil texture is mainly loamy, with a tendency to silt-loam. The farm has a two-pivot irrigation system, with one pivot being set up as a hippodrome. It also has an underground drainage system. Horta manages about 20 ha of the farm and conducts its experimental trials there in plots. Its main experiments are on small-grain cereal, maize and tomato, with its small-grain cereal trials studying chiefly fungicide efficacy, crop fertilization and sowing density.

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SCREENING OF SUITABLE LEGUMES FOR RELAY INTERCROPPING WITH DURUM WHEAT

Durum wheat is the most-cultivated small grain cereal in Italy, and it is a major agricultural commodity because of the importance of the country's pasta industry. Weed competition and nitrogen deficiency are two of today's main factors behind yield and grain protein content losses in cereal production in conventional cropping systems, as there is a massive use of external inputs such as herbicides and synthetic nitrogen (N) fertilisers. Wheat-legume relay intercrops can be an effective alternative to chemical weed control, and it supports optimisation of nutrient cycling and resource conservation without negative impacts on crop productivity.
Relay intercropping consists in growing two or more crops simultaneously during part of their life cycle. In the current study, legume subsidiary crops are intersown in an already established durum wheat crop stand (living mulch). The objective of this work is to identify suitable legumes for relay intercropping with durum wheat as an integrated weed management and diversification tool in a conventional cereal-based cropping system located in the Ravenna area.
This study also addresses practical aspects related to the choice between contemporary and relay establishment of legumes and their effect on the main crop, and the choice of the most effective sowing method: broadcast or drill sowing. The same experiment was carried out in Pisa under low-input management (see page 52). Performance of legumes in the experiments conducted in Pisa and Ravenna were analysed and compared in the paper "Relay intercropping can efficiently support weed management in cereal-based cropping system when appropriate legume species are chosen".

Materials and methods

This experiment was carried out in two locations in Italy (Pisa and Ravenna) over two consecutive cropping seasons (2017/18, 2018/19). The Ravenna field experiment was set up at Horta (Horta, permanent platform for enhancing results from research in the agro-alimentary sector, Cà Bosco farm, Ravenna, Italy. The experiment was managed as an integrated system with optimised use of fertilisers, herbicides and pesticides (timing and

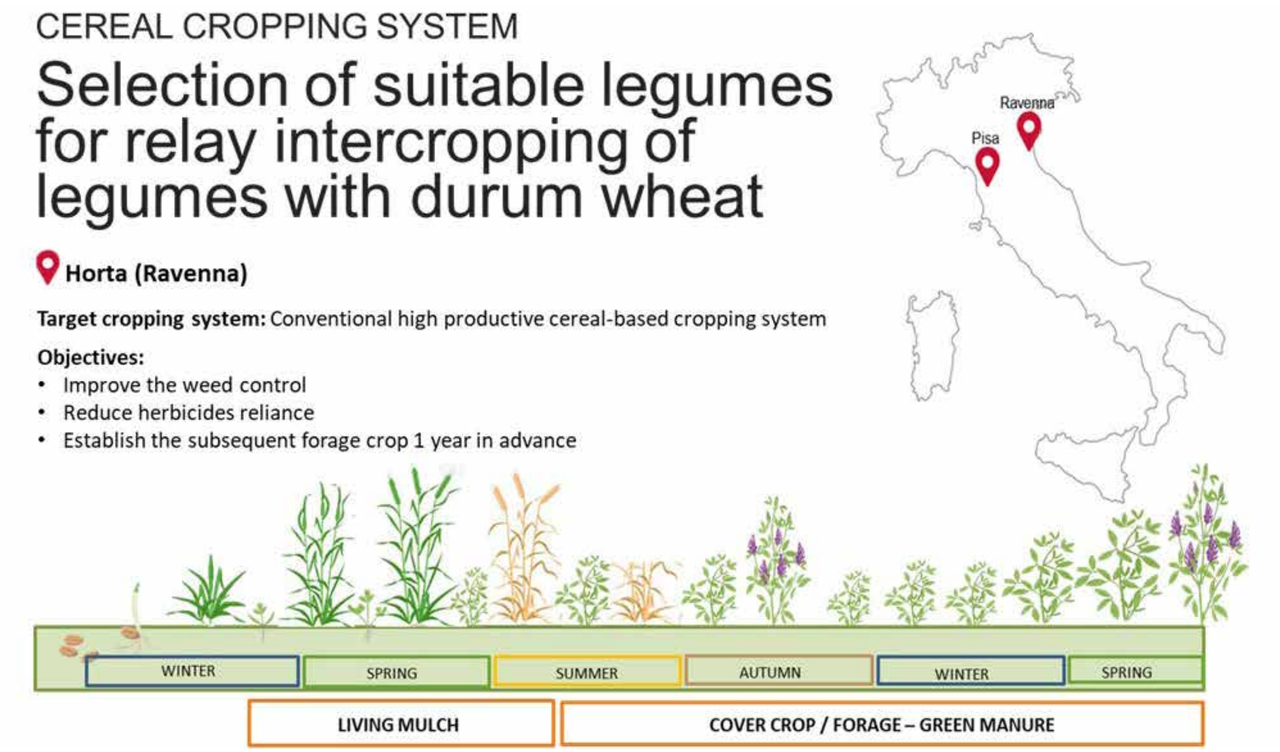

Figure 1 - Experiments on the selection of suitable legumes for relay intercropping of legumes with durum wheat as an integrated weed management and diversification tool in a Mediterranean cereal-based cropping system. The experiment was carried out in Pisa ("Enrico Avanzi" Centre for Agri-Environmental Research of the University of Pisa) and Ravenna (Horta).

doses of each application were optimised with the decision-support system grano.net®, developed by Horta S.r.l.). Durum wheat (cv Minosse) was sown at the seed dose of 250 kg/ha in rows spaced 17.5 cm. Wheat sowing time ranged between October and November, and legumes were intersown in the wheat established at the end of February (before the wheat elongation phase). The wheat was harvested in July, and legumes were maintained in the field until spring. In 2017/18, the tested legumes were i) four perennial legumes, *Medicago sativa* (40 kg/ha), *Trifolium repens* (15 kg/ha), *Hedysarum coronarium* (30 kg/ha) and *Medicago lupulina* (40 kg/ha); ii) three annual legumes, *Trifolium incarnatum* (30 kg/ha), *Trifolium resupinatum* (10 kg/ha) and *Vicia villosa* (90 kg/ha); and five annual self-seeding legumes, *Trifolium michelianum* (15 kg/ha), *Trifolium subterraneum* (35 kg/ha), *Medicago polymorpha* (40 kg/ha), *Medicago truncatula* (40 kg/ha) and *Medicago scutellate* (40 kg/ha).
The number of intersown legume species were reduced in 2018/19 based on poor performance in both sites, with one annual legume (*Vicia villosa*) and three annual self-seeding legumes (*Trifolium michelianum, Medicago truncatula* and *Medicago scutellata*) being excluded. A control treatment with wheat grown as the sole crop was added to evaluate the incidence of intersown legumes on wheat yield performance. Pisa and Ravenna employed different standard sowing methods for the legumes. They were seeded with drill sowing in Pisa and broadcast sowing in Ravenna. Three legumes (*M. sativa, T. repens* and *T. subterraneum*) were sown both with the drill and broadcast methods in Pisa and Ravenna to detect the influence of sowing techniques on legume establishment. Both contemporary and relay intercropping of *M. sativa* was performed for a comparison between the two intercropping systems.

Results

Effect of relay intercropping on wheat

Wheat grain production was on average 6.8 t/ha, in line with the local production level (Figure 2). Intersown legumes had no negative effects on the potential durum wheat yield for any of the species used in this experiment. The wheat growth was supported with fertilisers, increasing the competition of wheat on legumes for light and space. Due to the vigorous wheat growth, intercropped legume dry biomass was on average 8 g/m^2, almost 10 times lower when compared with the Pisa site where crops were managed under a low-input system. The wheat canopy height was on average 98 cm. The canopy height of all legumes ranged from 3.6 to 7.7 cm; therefore wheat harvest was never hindered and no differences in wheat performance were detected. There was no significant difference in wheat grain protein content, intercropped or not. Grain protein content was on average 13%.

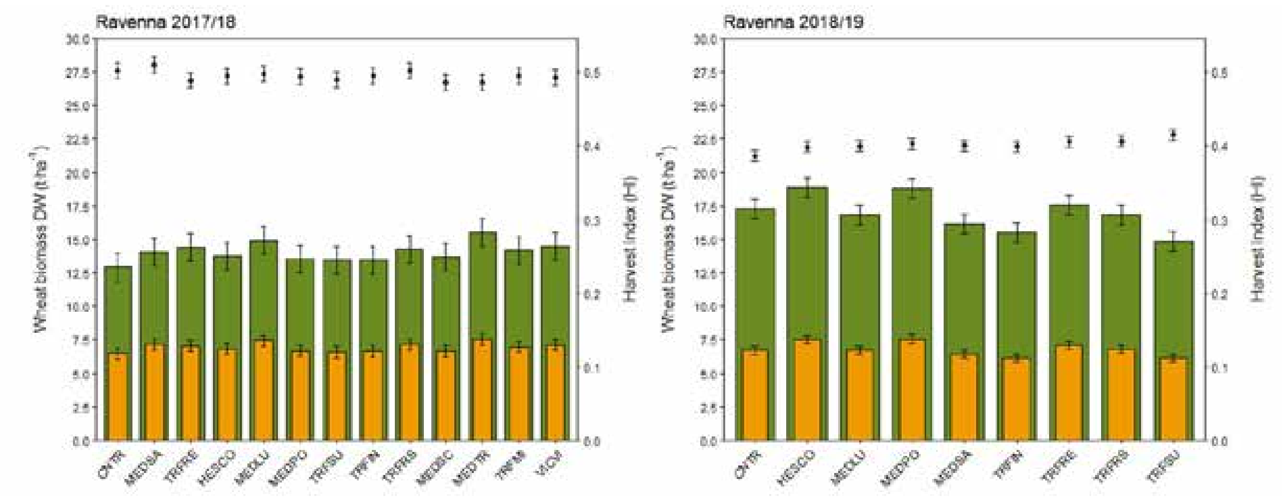

Figure 2 - Wheat grain production (orange bars), wheat straw (green bars) and Harvest Index (blue dots) in Ravenna. Significance referred to the contrast between control plot (CNTR) and each other level. Error bars represent standard error (SE). CNTR: Control plot (wheat sole stand crop); MEDSA: *Medicago sativa*; TRFRE: *Trifolium repens*; HESCO: *Hedysarum coronarium*; MEDLU: *Medicago lupulina*; MEDPO: *Medicago polymorpha*; TRFSU: *Trifolium subterraneum*; TRFIN: *Trifolium incarnatum*; TRFRS: *Trifolium resupinatum*; MEDSC: *Medicago scutellata*; MEDTR: *Medicago truncatula*, TRFMI: *Trifolium michelianum*; and VICVI: *Vicia villosa.*

Weed control

Legume biomass was not significantly related to the weed control capacity of the legume species used as living mulches (Figure 3). In this system, legume growth was strongly reduced by wheat competition, and weeds were already well-controlled by the preventive application of herbicides. Despite the low contribution of undersown legumes to weed control during the intercropping phase, the viability of legumes under the wheat canopy remains fundamental for the successful establishment of legumes after the wheat harvest and for weed control in the following seasons. In high-productive cropping systems, as in Ravenna, shade tolerance proved to be a fundamental characteristic for successful legume establishment under the dense wheat canopy. Shade tolerant species, such as *M. sativa* and *T. repens*, proved to be well-suited to co-cultivation with wheat and persisted after the wheat harvest, establishing dense, weed suppressive coverage (Figure 4). Biomass sampling performed in the subsequent spring revealed that *M. sativa* and *T. repens* reduced weed dry biomass by 83% when compared with the control (26 g/m^2 vs 154 g/m^2). In this time, there was no significant effect by other legumes on weed dry biomass when compared with the control.

Sowing method: drill or broadcast sowing?

In high-productive cereal-based cropping systems, the relay intercropping of legumes with broadcast sowing can be a suitable option. Results from this experiment showed that for *M. sativa*, *T. repens* and *T. subterraneum*, the sowing method did not affect wheat yield and legume biomass. In high-productive systems, as in Ravenna, the vigorous growth of wheat reduced the risk of competition from living mulches and the different spatial arrangement of legumes, as a consequence of the sowing method chosen, did not affect intercropping performance. In this condition, broadcast sowing can be a suitable option because it is less costly and more rapid, and these are important characteristics, especially during winter when time, daylight, favourable weather and soil condition are often limiting factors for timely sowing.

Broadcast seeding of legumes involves the use of a centrifugal seeder combined with a light harrow. When broadcast seeding is performed, light harrowing has a dual functionality: the

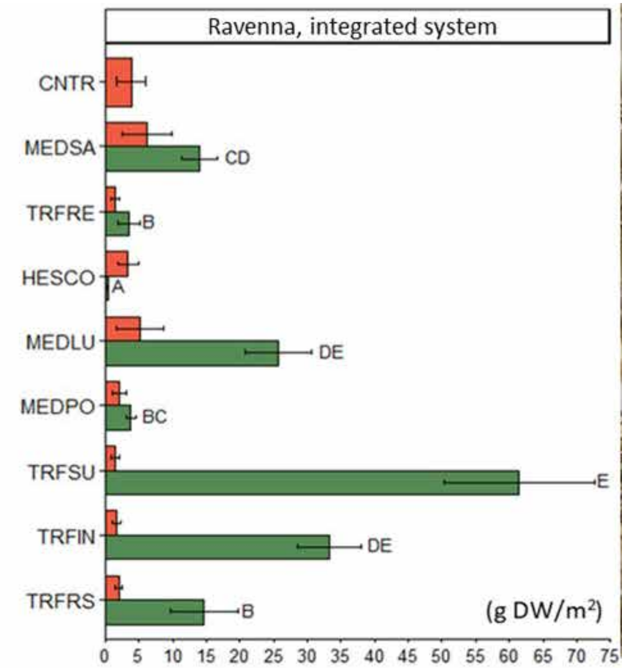

Figure 3 - Legume (green bars) and weed (red bars) aerial biomass (DW g/m^2) at wheat harvest time in Ravenna during the 2018/19 growing season. CNTR: Control plot (wheat sole stand crop); MEDSA: *Medicago sativa*; TRFRE: *Trifolium repens*; HESCO: *Hedysarum coronarium*; MEDLU: *Medicago lupulina*; MEDPO: *Medicago polymorpha*; TRFSU: *Trifolium subterraneum*; TRFIN: *Trifolium incarnatum*; and TRFRS: *Trifolium resupinatum*. Letters (A-E) indicate significant differences at 0.05 level. Error bars represent standard error (SE). Figure on the right shows relay intercropping of *M. sativa* with wheat.

Figure 4 - Control plot (left) and *Trifolium repens* (right) in the spring after the wheat harvest in Ravenna. In evidence the weed control capacity of *T. repens* the following spring.

incorporation of seeds into the soil; and mechanical control of smaller weeds. However, with broadcast sowing, seeds are incorporated into the soil only superficially, thus decreasing seed contact with the soil and increasing their susceptibility to unfavourable environmental conditions or seed predation. When unfavourable climatic events occur after legume sowing (e.g. drought), the germinability of legumes can significantly decrease when broadcast sowing is employed. For this reason, seeding rate should be increased by 20% to 50% when broadcast sowing is performed.

Sowing time: relay or contemporary intercropping?

Results from the sub-experiment comparing contemporary and relay intercropping of *M. sativa* with wheat revealed that legume biomass production and wheat yield were not affected by the sowing time of legumes (Figure 5). Therefore, the contemporary establishment of legumes with wheat can be a suitable solution in high-productive systems, as in Ravenna.

Destination of legumes

The establishment of forage crops in wheat can be one potential benefit that relay intercropping presents to farmers in integrated high-productive systems. The relay intercropping of legumes in wheat enables legume forage crops to be established nine months in advance in Mediterranean cropping systems, reducing costs for tillage and external input use. Moreover, the prompt establishment of legumes after wheat harvest allows the soil to remain constantly covered, preserving the soil from erosion and reducing weed growth and dissemination. In this experiment, we performed an assessment on the biomass production level of alfalfa (*Medicago*

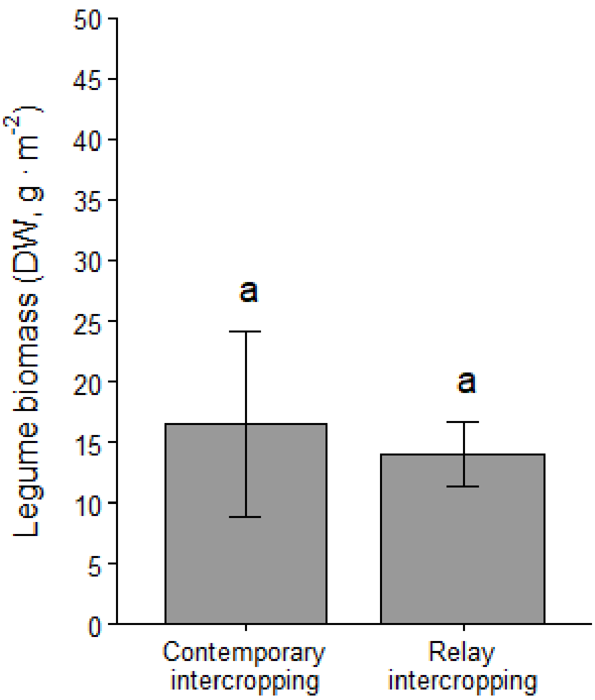

Figure 5 - Biomass production of *M. sativa* in contemporary and relay intercropping systems with durum wheat in a high-productive cereal-based cropping system.

sativa) in a relay intercropping system with wheat and as a pure forage crop. The assessment was performed in springtime on one year alfalfa. We observed that relay intercropping reduced dry biomass production of *M. sativa* by 30% in spring after wheat harvest when compared with a *M. sativa* pure stand crop (198 g/m^2 vs 287 g/m^2). As a consequence, when the main aim is to produce forage, the sowing rate of alfalfa in relay intercropping should be increased in order to compensate for lower biomass production.

Experimental site: Horta Srl - Spin Off Università Cattolica del Sacro Cuore, sede operativa c/o Az. Agr. Ca' Bosco, Via S. Alberto 327, 48123 Ravenna

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ON-FARM EXPERIMENTAL TRIALS

LA VIOLA FARM

La Viola (www.agrilaviola.com) is an organic arable farm located in Torre San Patrizio, Marche (Italy). The farm consists of 10 ha of arable land with sloped fields of loamy to clay soils. The main crops are cereals and pulses, cultivated in intercropping. The intercropping is performed between a cereal, which can be durum wheat, bread wheat, rye, barley or oat, and a grain legume such as chickpea, Indian pea, lentil and roveja (an edible cultivar of Pisum sativum ssp. arvense). All crops are broadcast sowed with a sowing machine composed of two hoppers, one for the cereal and the other for the legume seeds, which allows the two crops to be sown simultaneously and each at the desired seeding rate.
The two crops are harvested together and subsequently divided in the farm's processing laboratory. The seed types are divided using sifters on the basis of the different grain dimensions and/or density. After the separation process, the wheat is used for flour production with a farm-owned mill, and together with the other cereals and grain, the legumes are sold directly or to local organic stores.
A video was produced about the experiment carried out on La Viola farm: https://www.youtube.com/watch?v=rszca3WBGUE&t=70s

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LENTIL AND WHEAT INTERCROPPING

Lentil is an important crop at La Viola and intercropping with a winter cereal is the best way to grow this legume on the farm (Figure 1). Lentil is very susceptible to lodging and this often makes it impossible to use a combine-harvester. Lentil and wheat intercropping significantly reduces legume stem lodging because the cereal culms act as a mechanical support for the companion crop. A mixture of bread wheat landraces is used in intercropping with a mixture of one commercial cultivar and one landrace of lentil. The intercropping of wheat and lentil ensures, in comparison with the local production level, sufficient production of wheat (1.8 t/ha in average), good production of lentil (0.35 t/ha in average) and supports weed control. Although ensuring an acceptable level of production, intercropping can be optimised by increasing lentil density to maximise yield and weed control.

Figure 1 - Intercropping between bread wheat and lentil.

Objectives
The aim of this on-farm trial is to optimise wheat-lentil intercropping in the local conditions of La Viola cropland. The specific objectives are to:

- Maximise lentil production;
- Preserve acceptable wheat production;
- Minimise wheat to lentil competition;
- Maximise weed control.

Materials and methods

In 2018/2019, this experiment tested four seeding rates of lentil (75, 100, 125, 150 kg/ha) associated with a fixed seeding rate of wheat (185 kg/ha) (Figure 2). Additionally, lentil and wheat were grown as sole crops with the standard seeding rate applied by the farmer (185 kg/ha for wheat and 100 kg/ha for lentil), in order to evaluate the Land Equivalent Ratio (LER). LER is a value that describes the yield advantage obtained by growing two or more crops or varieties as an intercrop when compared to growing the same crops or varieties as a collection of separate monocultures. In 2019/2020, the experiment was slightly modified to allow a more detailed study of how wheat and lentil interacted when intercropped; farmers and scientists arranged the experimental plots to study the effect of increasing seeding rates of lentil (0, and from 75 to 150 kg/ha) sown in three different wheat-seeding arrangements and a control strip (0, 100,150, 200) (Figure 2). In 2019/2020, the experiment was organised in a randomised complete block design, with three replicates for each lentil-seeding rate. Each plot area was 500 m^2 (6 x 80 m). In 2020/2021, the

Figure 2 - Experimental fields of the three replicates of the experiment.

Figure 3 - Set-up of the seeder used for the intercropping (photos by Simone Marini and Stefano Carlesi).

experiment was organised in a randomised strip plot design, with three replicates for each wheat-seeding rate, and a gradient of lentil density (100, 150, 200 and 250 kg/ha) (Figure 2); at the beginning of each strip, a control plot with no lentil was established and the strip density gradient orientation was alternated. Each strip was 100 m long and 4 m wide, for 4800 m^2 of experimental area. Randomisation and block orientation were performed, taking into account the maximum gradient of variability in both experimental fields, which is the slope. After seedbed preparation, the wheat and lentil were broadcast sown using a seeding machine equipped with two hoppers, one for cereal and one for grain legume (Figure 3). The hoppers were set according to the seeding dose (Figure 3).
During the growing seasons, assessments were performed on both the lentil and wheat in order to collect data on:

i) Lentil and wheat emergence (Figure 4) and yield;
ii) Intercropping efficiency through LER estimation;
iii) Effects of intercropping on weeds.

Results

The main results during the first replicate of the experiment concern the failure of the lentil crop due to a pest (slugs) attack during the growing season, so the lentil was not harvested in 2019. As a direct consequence of lentil failure, no LER estimation was possible. Despite the loss of the lentil, figures for wheat yield, plus crop and weed biomass, were collected. Concerning crop investment, in February 2019 the wheat was 195 plants/m^2, representing between the 43% to 50% of the wheat seeded, while lentil seedling density was very low: 7 plants/m^2. Therefore, lentil was seeded again in spring. The spring-seeded lentils performed much better, showing a linear response in seedling density at increasingly sown lentil rates. Considering dry biomass, lentil biomass was also collected despite the slug attack, showing a very low total biomass (5.26 g/m^2) for all lentil seeding rates.

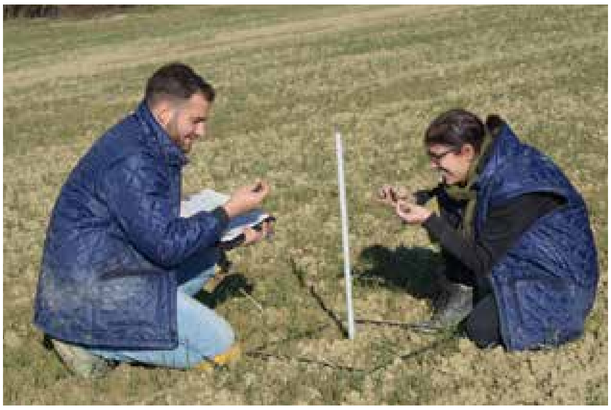

Figure 4 - Counting of wheat and lentil emerged (photo by Stefano Carlesi).

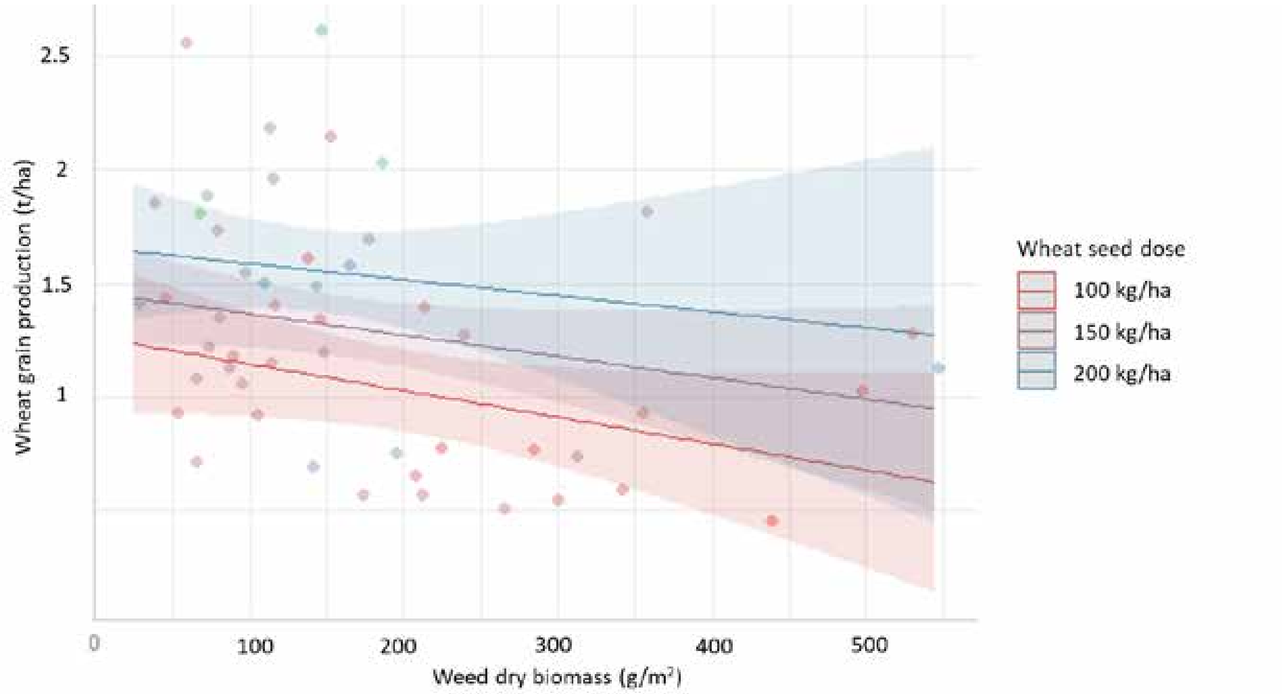

Figure 5 - Wheat grain yield in response to weed dry biomass (g/m^2) in the 2019/20 growing season. The three coloured zones indicate the trends and confidence intervals of the three different wheat plant densities as indicated in the legend.

Theoretical wheat seed dose (kg/ha)	Theoretical lentil seed dose (kg/ha)	Wheat yield (t/ha)	Lentil Yield (t/ha)	Weed dry biomass (g/m²)	Weed Control
0	0	-	10	257	-54%
	100	-	0.18	120	
	150	-	0.29		
	200	-	0.34		
	250	-	0.35		
100	0	0.95	0	123	-30%
	100	0.43	0.14	87	
	150	0.48	0.33		
	200	0.61	0.14		
	250	035	0.33		
150	0	0.58	0	133	-21%
	100	0.66	0.27	105	
	150	0.67	0.47		
	200	0.63	0.15		
	250	0.55	0.65		
200	0	0.89	0	131	-16%
	100	0.73	0.15	110	
	150	1.13	0.14		
	200	0.65	0.33		
	250	069	0.28		

Table 1 - Productive performances of wheat and lentil at different crop seed doses and their effects on weed biomass in the 2020/21 growing season. Weed control (%) was calculated as the ratio between the average amount of weed dry biomass of wheat-lentil intercrops and weed dry biomass of wheat as a sole crop at the four target seeding doses (0, 100, 150 and 200 kg/ha).

Wheat yield was not affected by lentil seeding rate and harvest was on average 2.16 t/ha. Weed dry biomass was also unaffected by lentil seeding rate (43.62 g/m^2 in mean), but strongly affected by wheat presence (Figure 5), with an 85% reduction in weed biomass when compared to the sole lentil plots.

In the 2019/20 growing season, lentil production was on average 0.17 t/ha, lower than the local production level (0.35 t/ha). The results of this experiment confirmed that lentil is a low competitive crop against weeds. Weed biomass in uncultivated plots (561 g/m^2) was not statistically different when compared with lentil grown as a sole stand crop (436 g/m^2) whatever lentil density. Intercropping with wheat proved to be an efficient tool for weed control. In the plots where lentil was cultivated with wheat, dry biomass of weeds was on average 158 g/m^2, significantly lower than lentil as a sole crop. Weed dry biomass in wheat as a sole crop was on average 278 g/m^2. Plant density significantly affected weed control capacity of wheat sole crop. Weed dry biomass in wheat at the seeding dose of 100, 150 and 200 kg/ha was 432, 242 and 161 g/m^2 respectively. The real plant density of lentil was significantly lower than the theoretical density. According to the seeding dose of 75, 100, 125 and 150 kg/ha, the expected plant density was 144, 192, 240, 288 plant/m^2. However, the real density of lentil was lower: 95, 104, 132, 208 plant/m^2 respectively. In order to compensate for the low establishment, we increased the seeding doses of lentils (0, 100, 150, 200, 250 kg/ha) in the 2020/21 growing season. However, the average success of settlement was still low (only 33% of the target density). Lentil production was on average 0.28 t/ha. Due to the low crop emergence, lentil production was not significantly affected by plant density (Table 1). A general trend highlighted that wheat-lentil intercrops can reduce weed biomass. Wheat-lentil intercropping significantly reduced weed biomass when compared with uncultivated plots; however, we were not able to detect significant differences between treatments due to low crop emergence (Table 1).

During both the 2019/20 and 2020/21 growing seasons, the test failed to capture the full range of interactions between the development of the two crops due to the low emergence of lentil and wheat. The saturation limit of available resources was therefore not reached, nor was the peak productivity of the two crops, which would have made it possible to identify the optimal yield ratio of lentil and wheat. Therefore, the results of this study must be read with caution and need to be supplemented by further experimentation in order to produce reliable indications.

FLORIDDIA FARM

Floriddia (www.ilmulinoapietra.com) is an organic farm located in Peccioli, Tuscany (Italy). It cultivates cereals (bread wheat, durum wheat, emmer, spelt, oats, and barley), grain legumes (chickpea, lentil, chickling vetch) and forage crops. In the last few years, Floriddia was a strong promotor of the cultivation of wheat landraces and composite cross populations for the production of high quality bread and pasta in Tuscany. This process involves researchers (University of Florence geneticists), other farms, advisors and Rete Semi Rurali *(Rural Seed Network). It is an example of a collaborative approach that aims to set up landrace cultivation techniques in order to optimize yields in an organic production system.*

Every year, the farms, supported by Rete Semi Rurali, *arrange a demonstrative field with over 200 types of cereals on display. Floriddia manages a mill with state-of-the-art tools for grain cleaning and a laboratory for pasta and bread production. Floriddia's work can be considered radical, social innovation within the bread supply chain because it takes a collaborative approach and creates a network among various actors, including farmers, researchers, extensionists, consumers and associations, who work along the same sustainability principles. The products of this farm are sold directly at the farm shop and online in Italy only, as well as through community-supported agriculture groups and local markets.*

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56030 Località Cedri - Peccioli (PI) - Italy
GPS coordinates: 43°29'11.18''N 10°47'54.06''E

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Rosario Floriddia
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CHICKLING VETCH AND EMMER INTERCROPPING

Chickling vetch (*Lathyrus sativus L.*) is traditionally cultivated in Tuscany, and it is among the legumes produced by Floriddia farm. This crop grows very well locally, but its high lodging susceptibility makes mechanized harvesting difficult. Intercropping chickling vetch with a cereal may reduce lodging problems significantly and prevent yield loss.
The hypothesis is that intercropping may reduce lodging problems because the associated cereal culms work as a mechanical support for the chickling vetch. Intercropping may also provide benefits in terms of weed control.

Objectives

In this on-farm experiment, we are studying intercropping between chickling vetch and emmer (*Triticum dicoccum*). The objective is to maximize chickling vetch production and to prevent lodging-related yield loss. Additionally, intercropping with cereal may support weed control in this legume, which is not highly suppressive.

Materials and methods

In this experiment, we studied the intercropping of chickling vetch and emmer (Figure 1). After seed bed preparation, chickling vetch and emmer were sown in February 2019. Seeding rate of chickling vetch was 100 kg/ha, and emmer-seeding rate was 40 kg/ha (1/3 of the optimum dose). We used a reduced dose of emmer to prevent interspecific competition with the chickling vetch.
In addition to the main intercropped field, chickling vetch and emmer were sown as sole crops to evaluate Land Equivalent Ratio (LER). LER is a value that measures the yield advantage obtained by growing two or more crops or varieties as an intercrop compared to growing the same crops or varieties as a collection of separate monocultures.
During the growing season, we performed assessments both on the chickling vetch and emmer in order to collect data on:

iv) Chickling vetch and emmer emergence and yield;
v) Intercropping efficiency by calculating LER;
vi) Effects of intercropping on weeds.

Results

The results of this experiment confirmed that intercropping between emmer and chickling vetch is an interesting solution for improving weed control and land-use efficiency.

Figure 1 - Intercropping between emmer and chickling vetch (photo by Federico Leoni).

The intercropping of chickling vetch with emmer significantly improved weed control when compared with chickling vetch stand as sole crop. Emmer efficiently filled the empty space left by chickling vetch and otherwise occupied by weeds, reducing weed biomass by 40% when compared with chickling monoculture.
The LER value was calculated to measure the yield advantage obtained in this intercropping system. As reported in Figures 2A and 2B, the production of both chickling vetch and emmer decreased significantly when grown together. However, this intercropping system was overall more efficient than the respective monocropping systems, with LER value being 1.48. The interpretation of this value is that 1.48 ha of sole cropping area is required to produce the same yields as 1 ha of the intercropped system.

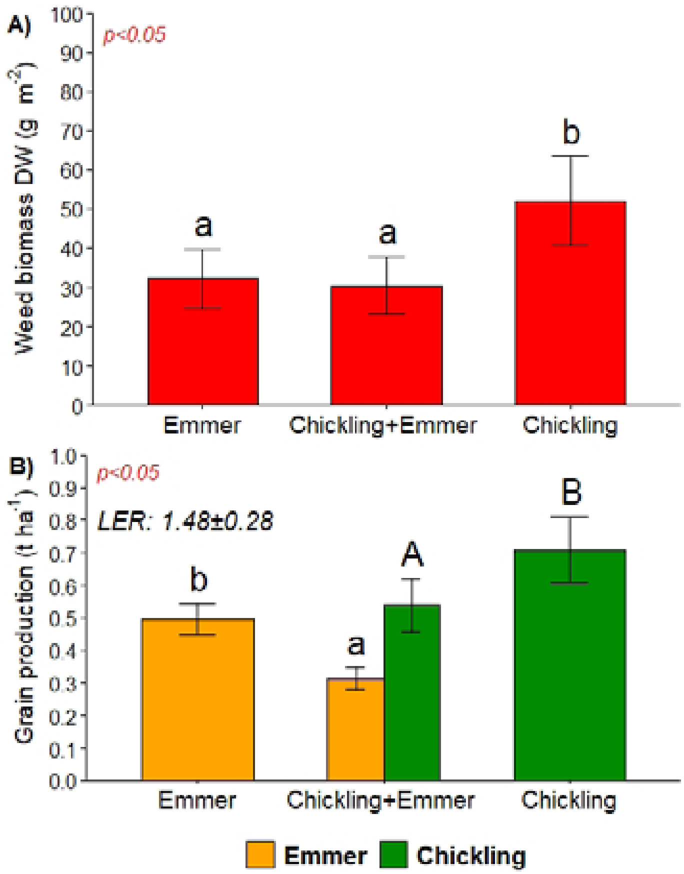

Figure 2 - A) Weed biomass (DW g m^{-2}) and B) Grain production (t ha^{-1}).

MARTELLO NADIA FARM

Figure 1 - Field trial at Martello Nadia farm 43°34’51.46’’N 10°32’02.63’’E (photo ©2017 Google).

These on-farm field experiments are being carried out at the Martello Nadia commercial farm (Cenaia, Pisa, Tuscany) in collaboration with the University of Pisa’s “Enrico Avanzi” Centre for Agri-Environmental Research (CiRAA).

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PARTICIPATORY FIELD TRIAL ON CONVENTIONAL VS CONSERVATIVE MANAGEMENT TO MANAGE RESISTANT RYEGRASS POPULATION IN ARABLE CROPS

Objectives

Long-term implementation of reduced tillage (i.e. minimum tillage or no-till) combined with glyphosate application can lead to a selection of weed populations that are resistant to herbicides. This is the case of the flatland close to Pisa (Tuscany, Central Italy), where reduced tillage has been a standard practice among farmers since the 1980s. Short crop rotations dominated by winter cereals and frequent use of glyphosate (up to eight times in just three years) in the intercrop period at sub-optimal rates have led to a selection of ryegrass (*Lolium* spp.) with triple resistance to ACC-ase, ALS and glyphosate. This also happened in the no-till plots of a long-term trial started in 2008 and terminated in 2017 comparing on-farm continuous no-till vs annual ploughing. The presence of resistant populations of ryegrass became so severe that the farmer decided to revert to ploughing at 25-30 cm in order to devitalise *Lolium* seeds and be able to yield again. A new system trial was then set up under WP7 on a four-year crop rotation (durum wheat-grain sorghum-durum wheat-chickpea) in order to compare two management options on the two fields formerly managed under no-till:

i) annual ploughing with different types of herbicides but not glyphosate;
ii) integrated management combining reduced tillage (minimum tillage and no-till), cover crops and limited herbicide application (excluding glyphosate). With the farmer, we aimed to test whether continuous disturbance of ryegrass (either mechanically, chemically or agronomically) in the periods of its peak emergence would result in conservation agriculture still being an option to preserve soil fertility without significant yield losses due to resistant weed populations.

Materials and methods

This on-farm field experiment was carried out at the Martello Nadia commercial farm (Cenaia, Pisa, Tuscany) in collaboration with the “Enrico Avanzi” Centre for Agro-Environmental Research of the University of Pisa (CiRAA). Two different management treatments (CONVENTIONAL vs INTEGRATED) were compared on two plots sizing 2.5 ha each (Figure 1). Each treatment was replicated on five pseudo-replicates (sub-samples in the same unique big plot).

The crop sequence included:

- Sunflower (*Helianthus annuus* L.) 2019/20;
- Durum wheat *(Triticum turgidum subsp. durum* (Desf.) 2020/21;
- Chickpea (*Cicer arietinum* L.) 2021/22.

In the conservative system, a cover crop of radish (*Raphanus sativus* L.) was grown between wheat and chickpea. Originally, a different crop rotation was planned, with durum wheat to be used instead of sunflower and hairy vetch (*Vicia villosa* Roth.) as cover crops between wheat and sunflower. Unfortunately, the harsh weather conditions in autumn 2019 impeded timely sowing of wheat, and the farmer decided to shift directly to sunflower in spring 2020. A red clover (*Trifolium pratense* L.) cover crop was also proposed to the farmer to be interseeded in wheat 2020/21 and left to grow until the pre-sowing period of chickpea when it was to be incorporated by harrowing as green manure. The poor establishment of the red clover in parallel experiments of intercropping in wheat led the farmer to change strategy and try with radish. The choice of radish was motivated by its quick establishment and growth, potentially enabling it to tackle early ryegrass infestation and to leave the soil soon, making way for chickpea seedbed preparation.
Herbicide application was managed as the main IWM tool in the CONVENTIONAL system, whilst in the INTEGRATED one it was minimised and tailored to the specific conditions.
We assessed the following parameters:

- Biomass and soil cover produced by cover crops and cash crops at the termination/harvest stage;
- Weed abundance and composition in each crop at harvest/termination and possibly also at earlier stages (e.g. after crop emergence);
- Evolution of the soil seedbank from t0 (early spring 2019) and t1 (end of crop sequence cycle);
- Economic and energy costs.

Results

Sunflower (cv. Excellio) was harvested on 5/09/2020, and the grain yield was found to be very similar in the two systems (4.2 vs 4.4 t ha^{-1} in the standard and the conservative systems respectively). After the sunflower harvest, the soil was tilled for the planned winter wheat (cv. Platone), which was sown on 11/11/2020 on tilled soil in the two systems. In the conservative system, the soil was tilled by shallow harrowing, whereas in the standard system the main tillage was performed by chiselling at 30 cm depth. Weed control, crop protection and fertilisation were performed identically in the two systems according to the farmer’s willingness. Durum wheat was harvested on 15/07/2021 and the grain yield was once again comparable in the two systems (4.5 vs 4.2 t ha^{-1} in the standard and the conservative systems respectively). The preliminary results of the trial indicated that a reduction in tillage intensity would not necessarily mean a reduction in crop yield in a system where herbicide-resistant weed populations occur. The farmer, originally sceptical about reintroducing reduced tillage on those fields, showed increasing interest in diversifying cropping systems, with special emphasis on cover cropping, a practice that he has been experimenting for many years.

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UNDERSOWING RED CLOVER IN DURUM WHEAT TO ENHANCE WEED SUPPRESSION AND N NUTRITION

Objectives

Weed control in organic wheat is mainly performed by flex tine harrowing. In soils with high clay and silt content, a flex tine pass at the end of the winter is not always easy to perform due to wet conditions. In Mediterranean climates, the ever-increasing frequency of mild winters without freezing temperatures is reducing the structuration of the soil by weather agents. If the soil remains too cloddy or is too dry at the end of the winter, harrowing is dramatically less effective for detaching weed plants. Furthermore, keeping the soil covered in the intercrop period between wheat harvest and the following spring crop sowing is crucial to maintaining weed populations below damage thresholds. Autumn-sown cover crops can be an effective solution for covering the soil in this period. This might be challenging, however, when the following cash crop is sown in early spring (e.g. chickpea, sunflower), as it reduces the length of the cover crop growing season and thus its potential biomass production. To maximise soil cover and reduce weed competition in the wheat crop, a legume cover crop can be interseeded in early spring before the cereal's stem elongation stage and kept growing until the next spring. This is possible when the legume cover crop is a self-reseeding crop, a perennial one, or a biannual species, e.g. red clover (*Trifolium pratense* L.).
In this on-farm trial, we performed a two-year assessment on intersowing red clover in organic durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) and letting it grow until the sowing date of the following chickpea (*Cicer arietinum* L.), when the clover was incorporated as green manure.

Materials and methods

This on-farm field experiment was carried out at the Martello Nadia commercial farm (Cenaia, Pisa, Tuscany) in collaboration with the "Enrico Avanzi" Centre for Agro-Environmental Research of the University of Pisa (CiRAA). Two management treatments (INTERSOWING vs WHEAT SOLE CROP) were compared on two plots sizing 1 ha each. Each treatment was replicated on five pseudo-replicates (i.e. spatial replicates identified within a strip where only one treatment was not randomly applied). The crop sequence also included chickpea the following year.
We assessed the following parameters:

- Biomass and soil cover produced by wheat and

Figure 2 - Field trial at Martello Nadia farm 43°35’55.15’’N 10°31’48.43’’E (photo ©2017 Google).

clover at harvest stage and before termination of the clover;
- Weed abundance and composition in each crop at harvest/termination and possibly also at earlier stages (e.g. after crop emergence);
- Economic and energy costs.

Results
Harsh weather conditions in late winter in both years prevented good cover crop being established. The clover did not reach sufficient biomass in both years. New tests are needed, including on different species and undersowing techniques.

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Figure 3 - Red clover interseeded in durum wheat in March 2019 after emergence.

USE OF THE DONDI CUT-ROLLER AS A ROLLER CRIMPER: EFFECT OF TERMINATION DATE AND NUMBER OF PASSES

Objectives

To test the effectiveness of the "cut-roller" RT-300 (produced by DONDI S.p.A. and marketed as a tool for crop residue management) when used as a roller-crimper for the mechanical termination of some of the most common winter cover crops for arable cropping systems at different termination dates. It is well-known that roller crimpers are quite effective at killing grass and legume cover crops (e.g. rye, vetch) at late phenological stages (i.e. milky ripening for grasses and full flowering for legumes). Nevertheless, timely sowing dates of spring crops is essential in Mediterranean climates to avoid severe drought conditions and achieve satisfactory yield results. Improving the efficiency of roller crimpers at the early phenological stages of cover crops could pave the way for a wider adoption of cover crops as a IWM tool.

Materials and methods

An on-farm field experiment was carried out for two years (2018/19 and 2020/21) at the Martello Nadia commercial farm (Cenaia, Pisa, Tuscany) in collaboration with the "Enrico Avanzi" Centre for Agro-Environmental Research of the University of Pisa (CiRAA). Two different cover crop treatments (a grass species, i.e. rye - *Secale cereale* L. - in 2018/19 and barley - *Hordeum vulgare* L. - in 2020/21, and a legume, i.e. hairy vetch - *Vicia villosa* Roth) were drilled in September 2018 and 2020 on two separate fields sizing ~1 ha each (Figure 4).
The sowing rates were 180 and 40 kg ha^{-1} for rye/barley and vetch respectively. In sub-plots, we tested the effect of three different termination dates (full vegetation stage vs early earing/flower set vs milky ripening/full flowering) and one or two passes of a cut-roller used as a roller crimper (with the second one performed one week after the first one in order to emphasise the stress on the plants as soon as they start recovering from the first pass) on the termination dynamics of each cover crop species (Figure 5). Each treatment (i.e. samples taken from the same experimental unit that can therefore not be considered independent from a statistical point of view). Was replicated on five pseudo-replicates (i.e. spatial replicates identified within a strip where only one treatment was not randomly applied). The cut-roller was equipped with non-sharpened blades and operated at a working speed of 10 km hr^{-1}. To maximise roller weight and action, the cut-roller was

Figure 4 - Field trial at Martello Nadia farm 43°67'08.51''N 10°31'19.57''E (photo ©2017 Google).

filled with water up to a weight of 2.7 tonnes. We assessed the following parameters:

- Biomass and soil cover produced by cover crops at the termination stage;
- Weed abundance and composition in cover crops at the termination stage;
- Killing rate and dynamics of the cover crops (with image analysis);
- Soil compaction before and after the pass of the roller.

Results

In the first year, the biomass of the cover crops was very good, especially for rye, which yielded 11 t d.m. ha^{-1}, averaged over the three termination dates, whereas vetch yielded 5 t d.m. ha^{-1} on average. The cut-roller terminated the vetch very efficiently from the second termination date and with only one pass, a result that was very valuable given the experimental conditions. In previous experiments conducted on the same farm with a classic Rhodale V-shape design roller crimper, we did not achieve significant vetch termination until the full flowering stage. Nevertheless, it is worth mentioning that in these experimental conditions the weather was very wet during spring, and soil humidity was very high especially in the vetch plots. This facilitated roller action, which resulted in a high percentage of cut vetch biomass. Due to very high rye biomass, the roller was less effective, and two passes were needed to achieve an acceptable termination rate, even at the later termination date.

In 2020/2021, the biomass of the barley was very good, reaching a maximum of ~8 t d.m. ha^{-1} at the latest termination date. The biomass produced by vetch was a little lower than in the first year, reaching a maximum of ~4.6 t d.m. ha^{-1}. The results of the termination dynamics confirmed the good results for the vetch obtained in the first year, whereas for barley, which produced more tillers than rye, the percentage of plants recovering after rolling was pretty high. These results require further experimentation on different cut-roller operational parameters (e.g. higher operating speed or sharpened blades) and sowing rates.

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For further reading:

Antichi, D., Tramacere, L.G., Sbrana, M., Bendinelli, S., Mazzoncini, M., Frasconi, C., (2021). Agronomic aspects of cover crops termination with roller crimper. In: Preceedings of the 50th Conference of the Italian Society of Agronomy. Udine, Italy, 15-17 September, 2021.

Figure 5 - Termination of rye by the cut-roller in 2018 at the full vegetation stage (first pass on 28 March).

SAN GIUSTO A RENTENNANO FARM

SAN GIUSTO A RENTENNANO
Fratelli Martini di Cigala

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MONTEVERTINE FARM

MONTEVERTINE

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COVER CROPPING TO IMPROVE SOILS IN CHIANTI CLASSICO'S VINEYARDS

Viticulture is a critical component of agriculture in Southern Europe. Here, vineyards have been historically planted on poor-developed soils (e.g. course texture, high stoniness, low soil organic matter). The combination of (i) poor inherent soil characteristics, (ii) the steep topography which characterises the majority of Europe's wine-producing regions, and (iii) the typical Mediterranean climatic pattern, make these soils highly susceptible to degradation. In this scenario, intensive soil management practices, such as the very common inter-row tillage, has escalated soil degradation and about 9 tonnes of soil per hectare are lost from vineyards every year. In other words, vineyards are, to date, the land use with the highest soil loss rate in Europe.
Cover cropping could play a critical role in reducing soil loss, advancing soil physical, chemical and biological fertility and thus improving the sustainability of the European wine sector. Nevertheless, farmers are often reluctant to apply soil cover practices due to the potential competition between cover crops and vines for water and nutrients. This calls for on-farm experimentations in order to test and discuss with farmers strategies that can improve soils while guaranteeing grape production and quality.

Objectives

A group of innovative farmers in Chianti Classico have applied mixtures of cereal and leguminous cover crops, or left spontaneous vegetation to grow, combining them with non-inversion tillage to restore and protect their soils. However, these innovations were not supported by local studies and local growers are concerned about the outstanding sugar accumulation in grapes due to temperature increases associated with climate change.
Our on-farm study aims to identify the most promising cover cropping strategies to manage soil sustainably and ensure grape yield and quality. To this end, we are exploring the effects of different cover cropping practices on: soil (chemical, physical and biological parameters), spontaneous vegetation communities, vine stress, grape production and quality in Chianti Classico. Results will then be discussed with farmers and local technicians.

Materials and methods

The experiment is being carried out on two commercial organic farms in Chianti Classico:
(i) Fattoria San Giusto a Rentennano (SG) (Gaiole in Chianti, Siena); average annual rainfall 801 mm; average annual temperature 14.4°C; elevation 233 m.a.s.l., slope 10%;
(ii) Montevertine (MT) (Radda in Chianti, Siena); average annual rainfall 824 mm; average annual temperature 12.6°C; elevation 425 m.a.s.l., slope 8%.

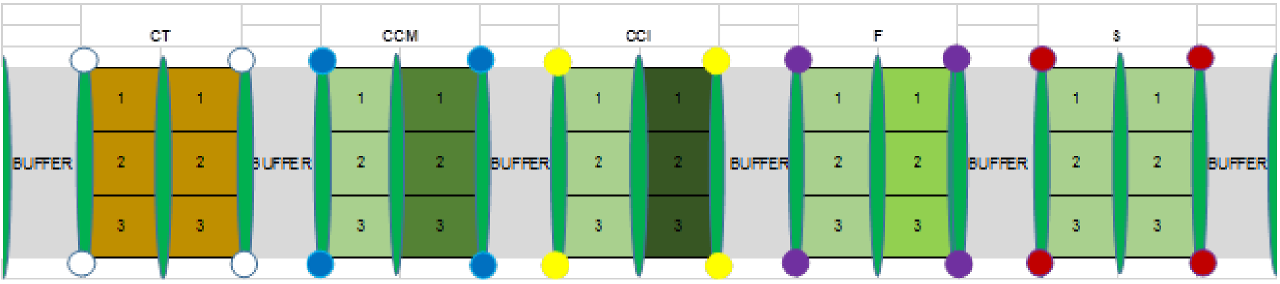

Figure 1 - Experimental design of the experimental plot on each farm. CT = Conventional Tillage; CCM = Mulched cover crop of barley + squarrose clover; CCI = Cover crop of barley + squarrose clover incorporated in the soil; F = Faba bean cover crop incorporated in the soil; and S = Spontaneous grassing.

Figures 2A, 2B, 2C and 2D - Appearance of the four soil cover types tested in this trial: A) conventional tillage; B) cover crop of faba bean (*Vicia faba minor* L.) incorporated in late spring; C) cover crop of barley (*Hordeum vulgare* L.) and squarrose clover (*Trifolium squarrosum* L.); and D) spontaneous.

The vines (*Vitis vinifera*, L. var. Sangiovese R10, rootstock 420A) had been planted in rows (2.50 x 0.8 m, 5.000 vines/ha). The vineyards' years of establishment are comparable (1995 and 1991 in SG and MT respectively). The training system is in transition from spurred cordon to the guyot trellis in SG, and spurred cordon in MT. Five soil management practices are being studied on both farms (Figure 1):

1. Conventional tillage (CT), performed once in autumn, spring and summer with a rigid tine cultivator at 15 cm depth (Figure 2A);
2. Cover crop of faba bean (*Vicia faba minor* L.) sown at 90 kg/ha, incorporated in late spring (F) (Figure 2B);
3. Cover crop of barley (*Hordeum vulgare* L.) and squarrose clover (*Trifolium squarrosum* L.) sown at 85 and 25 kg/ha respectively, mown in late spring and left as mulch (CCM) (Figure 2C);
4. Cover crop of barley and squarrose clover sown at 85 and 25 kg/ha respectively, incorporated in late spring (CCI) (Figure 2C);
5. Spontaneous vegetation mown in late spring and left as mulch (S) (Figure 2D).

An in-row ventral plough is used to control weeds under the trellis during the season. Each experimental plot consists of three rows and two inter-rows (about 5x100 m). Treatments are displayed in alternate rows as this is common practice in the area. Each experimental plot is divided in three pseudo-replicates (i.e. samples taken from the same experimental unit that can therefore not be considered independent from a statistical point of view). According to the slope of the vineyard.

Parameters measured

- **Soil:** N, P, K, Soil Biological Quality Index (QBS-ar), Aggregate stability (following grape harvest);
- **Vine stress:** SPAD, stem water potential (from June to September);
- **Grape production:** yield/plant, number of clusters/plant, cluster weight, berries weight (at harvest);
- **Must quality:** total acidity, pH, malic acid, °Brix (at harvest);
- **Spontaneous vegetation:** biomass and soil cover per species (before cover crop termination and at harvest);
- **Cover crop:** biomass and soil cover per species (before cover crop termination and at harvest).

Results

The period between bud break and veraison means high nutrient and water requirements for the vines. For instance, it has been estimated that between fruit-set and veraison, vines need about 50% of

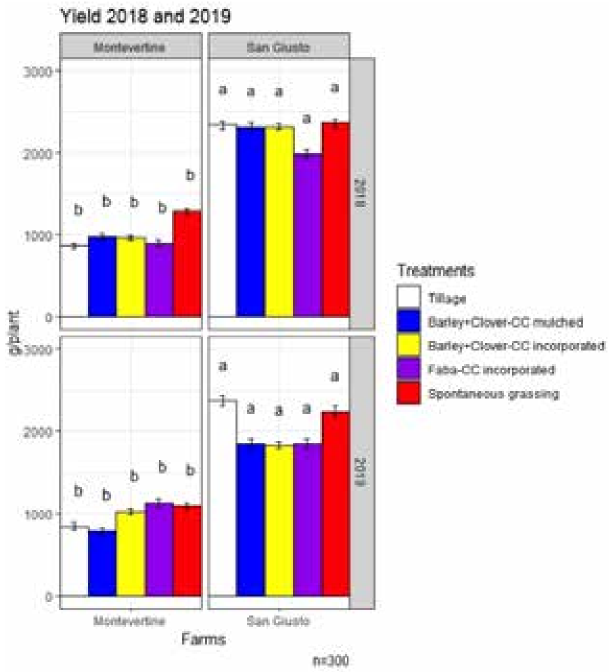

Figure 3 - Yield per plant (g/plant) in Montevertine (MT) and San Giusto a Rentennano (SG) in 2018 and 2019 (n=300).

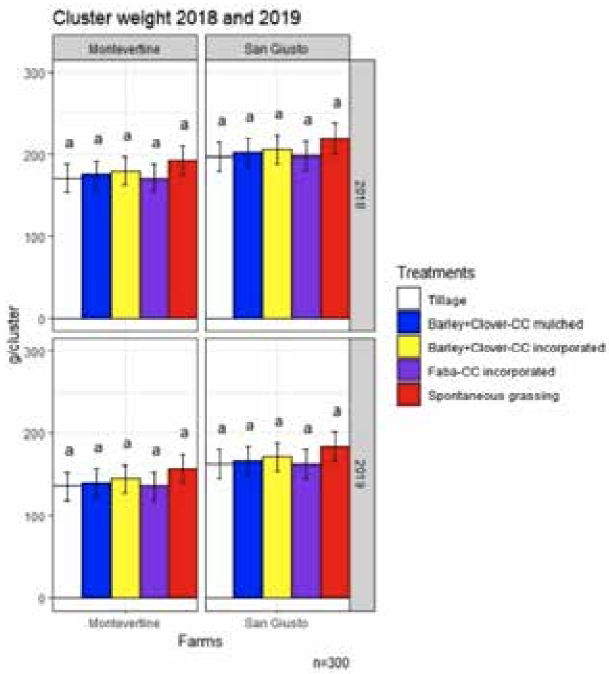

Figure 4 - Cluster weight (g/cluster) in Montevertine (MT) and San Giusto a Rentennano (SG) in 2018 and 2019 (n=300).

their annual water requirements. In this study, cover crops were sown in October and terminated in June between fruit set and veraison, meaning that cover crops were growing during these delicate vine stages. Differences in weed composition/biomass and soil management can therefore trigger different stress patterns, which in turn may affect yields. Nevertheless, spontaneous vegetation and cover cropping did not affect grape yield, as we did not find any significant effect of the treatment on yield and yield composition, namely cluster weight and number of clusters (Figures 3, 4 and 5). “Farm” was the only significant parameter in the yield dataset, mainly due to the various training systems. The reason behind the non-significant effect of soil treatments on yield and yield composition could be due to:
(a) complementary resource uptake between the vines and the cover crop/weeds;
(b) rainy vintages that “diluted” the effect of the treatments, especially in Montevertine;
(c) importance of in-row management when compared to the inter-row treatments.
These findings will be discussed with farmers in order to design more sustainable soil management practices in the Chianti Classico region.

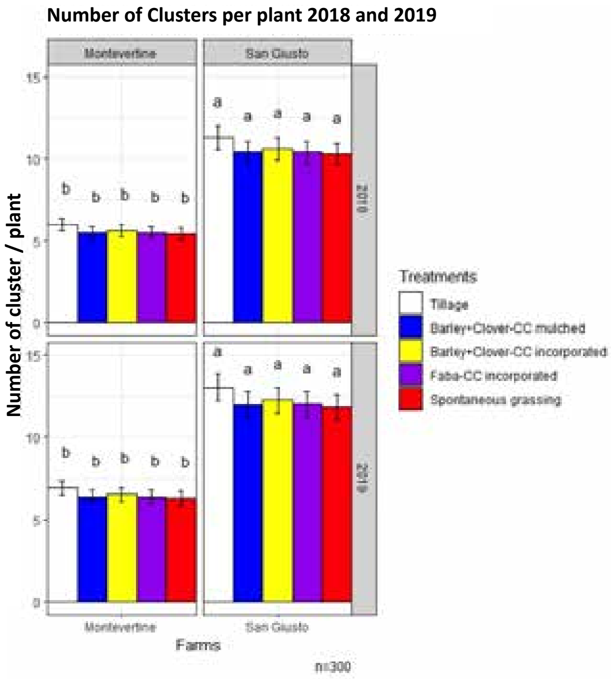

Figure 5 - Number of clusters per plant in Montevertine (MT) and San Giusto a Rentennano (SG) in 2018 and 2019 (n=300).

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DEL SARTO GRAZIANO FARM

Figure 1 - Location of the trial at Graziano Del Sarto Farm.

Del Sarto Graziano is a typical Pisa plain farm that produces cereals and protein crops, on a total area of about 160 ha, 13 ha of which are property. The rotation follows the classic sequence of winter cereals, summer crops such as maize, soybean, sorghum and sunflower, alternated with lucerne. It also participates in the INNOVA SOIA (http://www.sonotoscano.it/) and LIFE-Agrestic (https://www.agrestic.eu/) projects. "INNOVATIVE Systems for the Cultivation and Transformation of GMO-free Tuscany SOY" (INNOVA SOIA) is a co-financed by the Tuscany Region - PSR 2014-2022, which aims to transfer innovative techniques with reduced inputs for soybean production in Tuscany; it also focuses on the application of innovative technologies for the processing of soybean for livestock. "LIFE AGRESTIC - Reduction of Agricultural GReenhouse gases EmiSsions Through Innovative Cropping Systems" is part of the broader climate change mitigation objective of the EU-funded "LIFE Program for the Environment and Climate Change 2014-2022" and will promote the adoption of innovative, efficient cultivation systems with high potential to mitigate climate change. It will also contribute to the dissemination of innovative visions and tools for more efficient, climate-aware agriculture.

Address:
Azienda Agricola Del Sarto Graziano
Via Ferrucci, 8
56017 San Giuliano Terme (Pisa)
Italy

GPS coordinates: 43°74'55''N 10°35'95''E
For more information, please contact:
Graziano del Sarto
e-mail: graziano.delsarto@libero.it

RELAY INTERCROPPING OF LEGUMES IN WINTER WHEAT IN AN ON-FARM TRIAL NEAR PISA

A catalogue field experiment was carried out at CIRAA and at HORTA for two consecutive years to describe and test the most successful legumes for relay intercropping with winter wheat (see relay intercropping experiments at CIRAA and Horta in this booklet on pages 52 and 67). The legume ideotype suitable for relay intercropping should have high early vigour so that it germinates below the wheat stand, have a prostrate habit to cover the soil and control weed growth, should not accumulate too much biomass to avoid over-competition with the crop during the wheat growing season, and be able to contrast weed germination and growth as dead or living mulch after wheat harvest, until the sowing of the following cash crop. The catalogue field experiments identified a number of potentially suitable perennial and annual self-reseeding legumes. Annual legumes did not possess all the necessary characteristics. In this on-farm field trial, we tested two of these legumes sown in a farmer's field with machinery the farmer had at his disposal.

Objectives

The objectives of this trial were to monitor legume development, weed control, N availability, grain yield and grain quality in winter wheat up to the harvest of the following cash-crop (sorghum). We wanted to compare legume and wheat behaviour in a farmer's field when the crops were sown with the machinery and tools available at this representative farm on the Tuscan plain.

Materials and methods

This on-farm trial was set up with one of the representative farmers on the Pisa Plain, Graziano Del Sarto. The aim was to test two of the most successful legumes from the previously mentioned catalogue field trials: *Medica sativa* cv Gamma and *Trifolium subterraneum* subsp. Brachycalcinum cv Mintaro.
The trial was positioned in a 1.8 ha area consisting of two fields of 25 x 300 m separated by a small drainage channel down the centre (Figure 2).
The fields are divided into two areas of 150x25 m for a total of four testing areas. Since previous observations revealed a potential weed gradient along the length of the field, it was decided to test the two legumes against the wheat sole crop in the upper and lower parts of both fields in a paired comparison. The field was previously cropped with maize and left uncropped until January 2020.
Due to very wet autumn conditions, the crop was sown on 12 January 2020, two months later than usual. We sowed Minosse durum wheat, provided by our project partner ISEA, at 250 kg/ha (about 490 seeds/ha) with a row-width of 13 cm. This is unusually dense due to the fact that the farmer's seeder was not able to enlarge the row-width up to 17 or 18 cm, which is usually done in the case of relay intercropping to provide more space for the legume to establish. Minosse was used because this variety was successfully tested in the catalogue field and is not prone to lodging. Before sowing, the field was fertilised with 130 kg/ha of mineral fertiliser N-P 12-52. Mid-February, the crop had established well

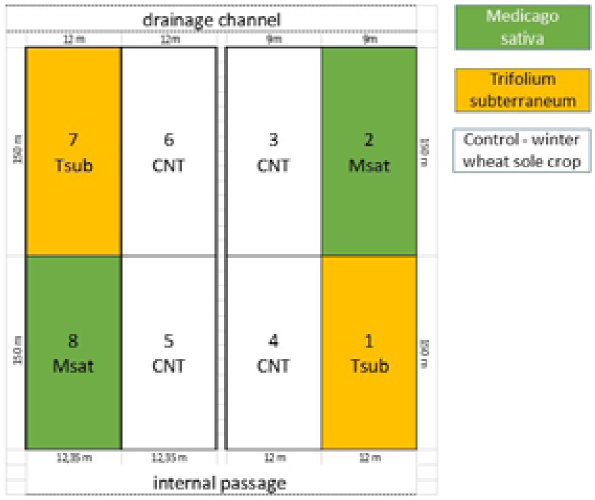

Figure 2 - Experimental layout.

Figure 3 - Durum wheat cv Minosse at emergence.

with a mean density of 277 plants/m^2 (Figure 3); it was fertilised with 150 kg/ha of mineral fertiliser containing 32% urea nitrogen and 6% ammoniacal nitrogen. On 25 March, at the start of stem elongation, the legumes were broadcast seeded at a density of 40 kg/ha for both legumes (Figure 4), and the seeds were incorporated by the pass of a harrow (Figure 5). A video was produced about this experiment: https://www.youtube.com/watch?v=gs-wltuzhss&t=30s . English subtitles are available.

Results

The farm trial was harvested in July 2020. The field was heavily infested with *Lolium multiflorum* L. Despite this, the wheat yield was acceptable, but the two legume cover crops were suffocated. The wet soil conditions at broadcast sowing in February resulted in suboptimal coverage of the legume seeds and emergence was patchy. In fact, at wheat harvest biomass of *Medicago sativa* (Msat) was low and the biomass of *Trifolium subterraneum* (Tsub) almost non-existent (Table 1). Preliminary analysis revealed that weeds were controlled rather well by the legumes, and yield was slightly higher in the presence of legumes. After wheat harvest, the two legumes did not establish very well and during summer 2020 both died completely. They were suffocated by the abundant *Lolium multiflorum* L. infestation in the wheat crop. Besides this, extreme drought impeded the legumes from re-establishing. The idea was to sow the legumes in autumn, but continuous heavy rainfall (about 1000 mm from October to February) made it impossible to access the field and sow the legumes.

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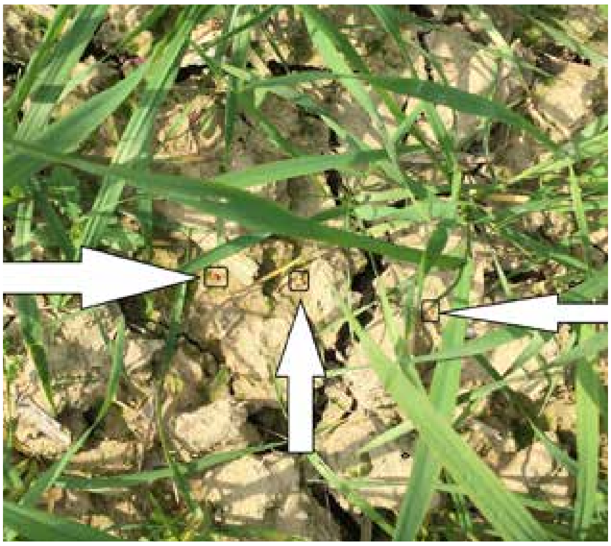


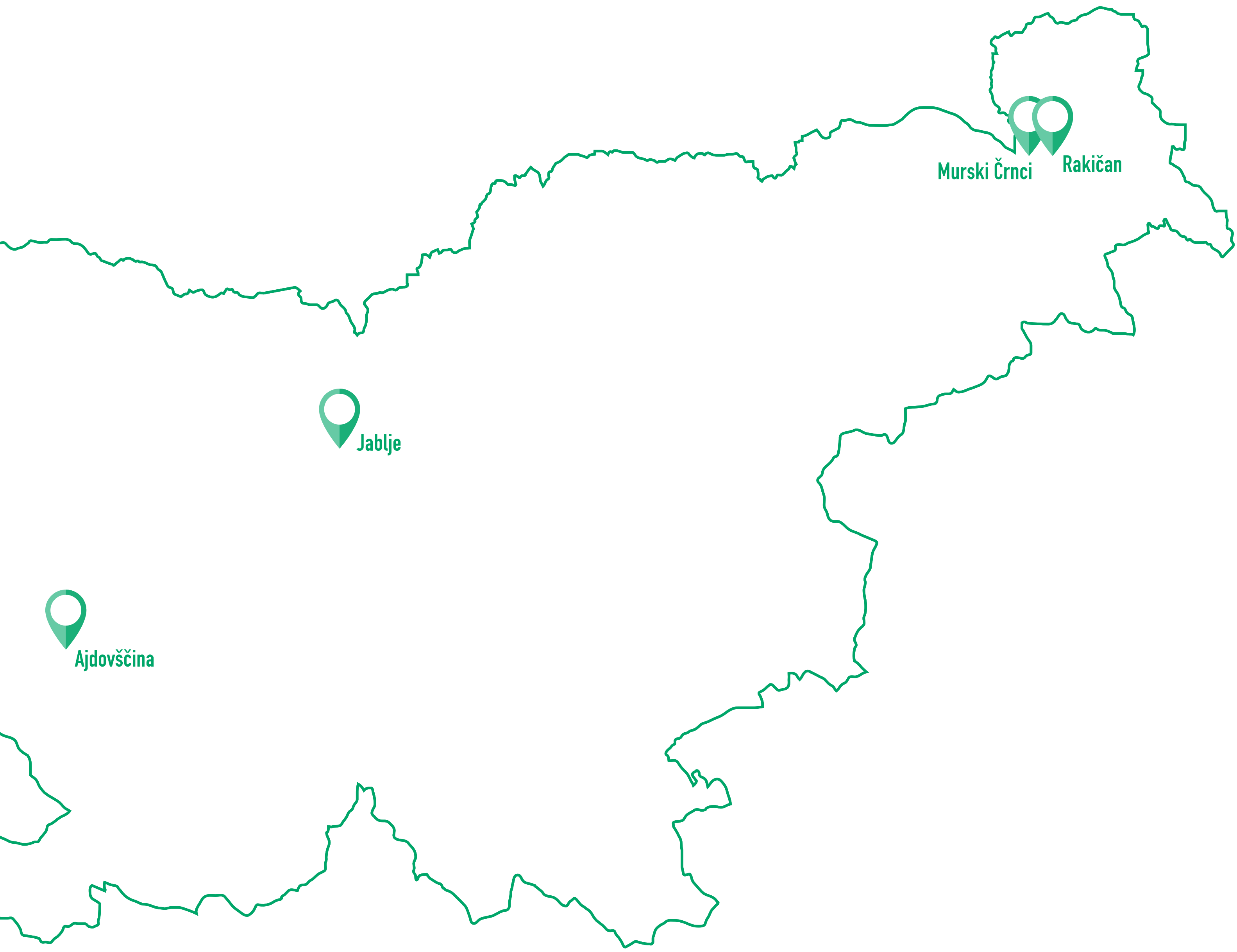
Figure 4 - *Trifolium subterraneum* seeds under wheat after broadcast sowing.

Figure 5 - Harrowing to incorporate the legume seeds on a very dry soil with a crust that was only partly broken by the passage of the harrow.

Treatment	Legume biomass (g/m^2)		Weed biomass (g/m^2)		Wheat production (g/m^2)	
	Mean	**sd**	**Mean**	**sd**	**Mean**	**sd**
Wheat+Msat	63.97	12.69	53.14	23.44	3.96	0.25
Wheat+Tsub	11.65	7.79	142.49	14.65	4.75	0.61
Wheat (cnt)	-	-	348.99	62.29	3.34	0.48

Table 1 - Legume and weed biomass (g/m^2) and wheat yield (t/ha) in July 2020 in the Del Sarto on-farm field experiment.

SLOVENIA



EXPERIMENTAL TRIALS MANAGED BY THE AGRICULTURAL INSTITUTE OF SLOVENIA – INFRASTRUCTURE CENTER JABLJE (IC JABLJE)

Kmetijski inštitut Slovenije
Agricultural Institute of Slovenia

Figures 1 and 2 - Location of the WP3 winter barley and WP4 maize trials in Jablje in 2019

IC Jablje is a part of the Agriculture Institute of Slovenia and is successfully implementing and transferring new scientific findings into agricultural practice. The IC Jablje site is located in central Slovenia, which has a mild, humid continental climate. The farm operates on aproximatelly 410 ha of arable land with a range of soil types, from light sandy-loam to heavier silty-clay. Crop production is based on conventional management practices, with substantial restrictions on water protected areas and minor organic production in the transition phase. The farm has a crew with experience in field research and collaborates closely with an advisory service. Field experiments, joint workshops, education courses and other dissemination events make IC Jablje a leading agricultural research and knowledge transfer centre for end-users, i.e. national experts, farmers and students.

Address:
Kmetijski inštitut Slovenije
IC Jablje, Grajska cesta 1
1234 Mengeš - Slovenia
GPS coordinates: 46°08'31.02"N 14°33'17.6"E
http://www.kis.si/en/Presentation_ICJ/

IWMPraise experimental trials in Jablje:
WP3 - Winter cereals trial
WP4 - Maize trial

For information and guided visits of WP3 and WP4 trials, please contact:
Robert Leskovšek, e-mail: robert.leskovsek@kis.si
tel. +386 1 280 52 61
or Anže Rovanšek, e-mail: anze.rovansek@kis.si
tel. +386 1 280 51 15

IWMPRAISE trials at other locations in Slovenia:
WP5 - Rumex trial on two sites
Location 1: Ajdovščina (45°52'37.294"N 13°54'2.4"E)
Location 2: Murski Črnci (46°37'15.2"N 16°6'15.3"E)

For information and guided visits of WP5 trial, please contact:
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WP3 – EXPERIMENTAL TRIALS ON WINTER CEREALS AT IC JABLJE

Winter cereals are the second most important crops grown in Slovenia after maize. Mixed farming systems are predominant in the central part of the country where winter cereals are not only produced for grain, but also for straw as it is considered an important resource for livestock bedding. Winter cereals are often included in the crop rotation to break maize pest cycles, as well as to increase crop diversification, especially when cover crops are sown on the cereal stubble. Environmental conditions in central Slovenia are not optimal for very high yields, and weed infestation is usually not considered as a limiting factor in winter cereal production. Farmers nevertheless control weeds very intensely. Slovenia greatly relies on the use of herbicides. Standard practice usually includes post-emergence herbicide application in the spring, or pre-emergence application in autumn when the weather conditions are favourable.

Objectives

The objective of the experiments conducted on winter cereals in seasons 2017/2018, 2018/2019 and 2029/2020 was to reduce herbicide consumption by developing alternative solutions based on reduced herbicide doses and mechanical weed control. Strategies aimed to limit early weed establishment and germination in the autumn, as well as reduce weed competition in spring. Field trials were performed at the Infrastructure Center (IC) Jablje, an experimental farm of the Agricultural Institute of Slovenia. Jablje is located in central Slovenia and is characterised by medium-heavy soil type and a humid climate. Since weather conditions strongly affect the performance of mechanical tools, field trials aimed to assess both the feasibility and control efficacy of mechanical tools on a site representing central Slovenian pedoclimatic conditions.

Season 2017-2018

A field trial with five weed management strategies was established in autumn 2017 at the AIS research station IC Jablje with winter wheat variety Vulkan. Details of the crop and weed management are presented in Table 1.
The previous crop in the experimental field was buckwheat. After harvest in August, the site was ploughed and the seedbed was prepared with the spring tine cultivator at the end of September 2017. The experiment was arranged in 300 m long by 24 m wide strips. Winter wheat was planted on 16 October 2017 and 30 October 2017, i.e. the optimum sowing date and delayed sowing date respectively.
Weather conditions in autumn and spring were

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Label	HER_spring	HER_autumn	HAR_autumn + HER_early spring	DEL_sow + HER_late spring	FALSE_seedbed + HER_late spring
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
False seed bed	NO	NO	NO	YES	YES
Sowing time	optimum	optimum	delayed 14 days	delayed 14 days	optimum
Herbicide rate	recommended *	recommended **	recommended ***	recommended ***	recommended ***
Application time	early spring	autumn	early spring	late spring	late spring
Growth stage	BBCH 32	BBCH 12	BBCH 32	BBCH 39	BBCH 39
Mechanical weeding	NO	NO	autumn harrowing	spring harrowing	spring harrowing

* iodosulfuron-methyl 10g/ha + metsulphuron-methyl 1,5 g/ha
** pendimethalin 600g/ha + chloroluron 500 g/ha + diflufenican 80 g/ha
*** due to ineffective harrowing, a recommended dose was applied instead of a reduced dose

Table 1 - Description of the weed management strategies in the winter wheat experiment at IC Jablje in season 2017-2018.

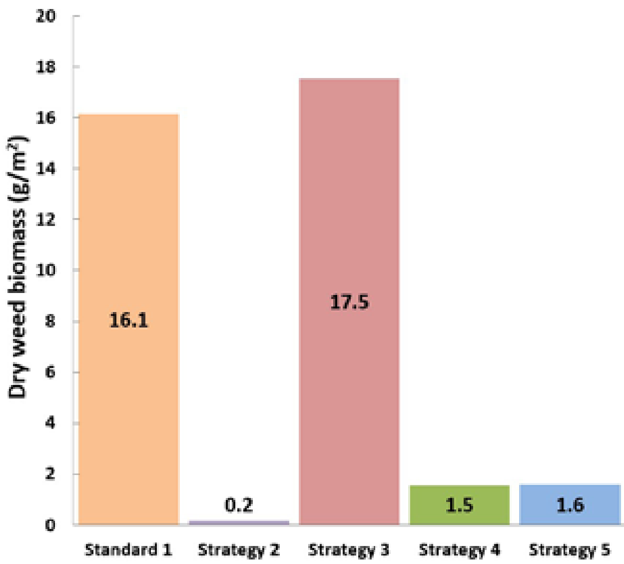

Figure 1 - Weed dry biomass determined in winter wheat in June 2018.

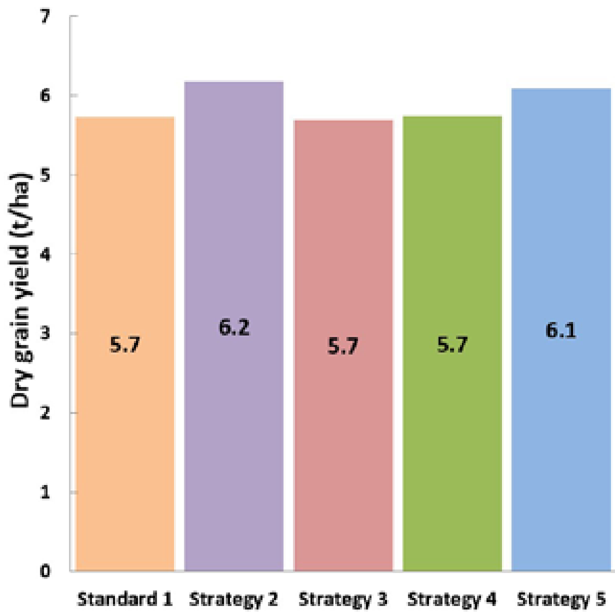

Figure 2 - Winter wheat dry grain yields obtained with the five weed management strategies in 2018.

extremely unfavourable for mechanical weed control and tine harrowing was completely ineffective.
Thus, it was decided to omit planned reduced herbicide application and perform spring herbicide applications at two timings using recommended doses. Autumn pre-emergence chemical weed control was performed in Strategy 2 (23 November 2017; BBCH 12).
Weed assessment was performed at the beginning of June (07/06/2018) when winter wheat was at the end of the flowering stage. Due to extended weed germination, late spring applications performed better (Strategies 4 and 5) when compared with early spring application (Strategies 1 and 3). Weed control was by far the best in Strategy 2 (0.2 g/m^2), with good residual efficacy remaining visible until the harvest.
The highest dry grain yield (14% moisture) was also measured when herbicide was applied in the autumn (Strategy 2: 6.2 t/ha), followed by Strategy 5 (6.1 t/ha), while other treatments (Strategies 1, 3 and 4) were similar in terms of dry grain yields (5.7 t/ha).

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	HER_spring	HER_autumn	HAR_spring + HER_reduced	FALSE + DEL_sow + HAR_spring + HER_ reduced
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
False seed bed	NO	NO	NO	YES
Sowing time	optimum	optimum	optimum	delayed 14 days
Herbicide rate	recommended *	recommended **	reduced * 60 %	reduced * 60 %
Application time	spring application	autumn application	spring application	spring application
Growth stage	BBCH 24	BBCH 24	BBCH 24	BBCH 24
Mechanical weeding	NO	NO	spring harrowing	spring harrowing
* iodosulfuron-methyl sodium 10 g/ha ** prosulfocarb 4000 g/ha				

Table 2 - Description of the weed management strategies in the winter barley experiment at IC Jablje in the season 2018-2019.

Season 2018/2019

A winter barley demonstration trial with the Sandra variety was set up at the IC Jablje AIS research station in October 2018, in which two IWM strategies were compared to two purely chemical standard approaches. Broadcast herbicide application in autumn or spring represented the standard weed management practice, while the IWM strategies involved reduced herbicide application in combination with mechanical tools.

The previous crop on the experimental field was grain maize. After harvesting, the field was ploughed and the seedbed prepared with the spring tine cultivator at the end of September 2018. Winter barley at the optimum sowing date was drilled on 03/10/2018 (Strategies 1 to 3). In Strategy 4, a false seedbed was prepared in the delayed sowing period. Conditions were very suitable for promoting weed germination due to warm weather and moist soil. Soil structure was not suitable for spring tine harrowing in the false seedbed preparation. Therefore, in Strategy 4, one pass with a fine spring tine cultivator was carried out. The effect of shallow cultivation was excellent, and a considerable portion of autumn emerged weeds was controlled with this measure.

Winter barley in Strategy 4 was drilled 14 days later (18/10/2018), followed by tine harrowing in the spring. In standard Strategy 1, herbicide was applied early in the spring, while in standard Strategy 2, herbicide was sprayed in the autumn (24/10/2018; BBCH 12) and recommended doses of herbicides were used in both strategies.

Dry weed biomass was assessed on 05/06/2019 at the winter barley milking stage (Figure 3). Autumn herbicide application (Strategy 2) performed excellently with good residual efficacy visible until harvest. In this treatment, only 4 g/m^2 of dry weed biomass was observed. Standard Strategy 1 with spring herbicide application (11 g/m^2) and Strategy 4 with delayed drilling, false seedbed, spring harrowing and reduced herbicide application (14 g/m^2) were also very effective. Weed density was greatest in Strategy 3, which was drilled at the optimal time, followed by spring harrowing and reduced herbicide application. Significantly greater dry weed biomass was determined (64 g/m^2) compared to the other strategies.

Winter barley grain yields were closely related to the results of weed infestation within the tested strategies (Figures 3-4). Dry grain yields were greatest in the standard autumn herbicide application (standard Strategy 2 and Strategy 4 with delayed drilling, false seedbed, spring harrowing and

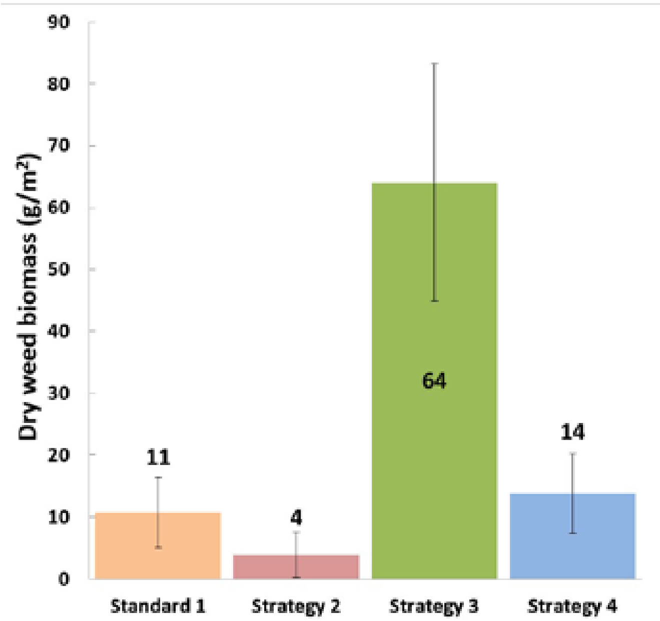

Figure 3 - Weed dry biomass determined in winter barley in June 2019 (vertical bars represent standard errors).

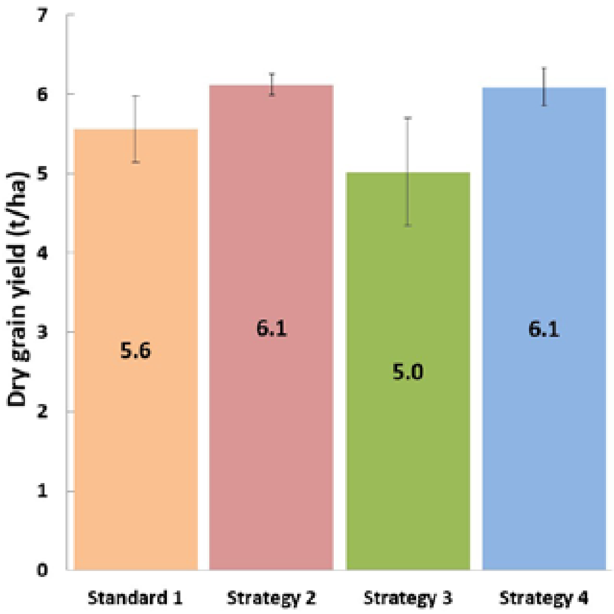

Figure 4 - Winter barley dry grain yields obtained with the four weed-management strategies in 2019 (vertical bars represent standard errors).

reduced herbicide application (6.1 t/ha). Standard spring application treatment yielded 5.6 t/ha, while the lowest yield was determined in Strategy 3 with spring harrowing followed by reduced herbicide application (5.0 t/ha).

Season 2019/2020

A winter barley demonstration trial with the Sandra variety was set up in October 2019 at IC Jablje in which three alternative IWM strategies were compared with a standard strategy, i.e. a solely herbicide-based approach. A broadcast recommended herbicide dose applied in the spring represented the standard weed-management practice, while the IWM strategies involved reduced herbicide application in combination with mechanical tools.

The following strategies were included in the trial: standard spring herbicide application (Standard 1), spring tine harrowing + application of reduced

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	HER_spring	HAR_spring + HER_reduced	FALSE + DEL_sow + HER_reduced	FALSE + DEL_sow
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
False seed bed	NO	NO	YES	YES
Sowing time	optimum	optimum	delayed 14 days	delayed 14 days
Herbicide rate	recommended *	reduced * 60 %	reduced * 60 %	NO
Application time	spring application	spring application	spring application	spring application
Growth stage	BBCH 24	BBCH 24	BBCH 24	/
Mechanical weeding	NO	spring harrowing (2x)	spring harrowing (2x)	spring harrowing (2x)

* 45 g/ha pinoxaden + 4.8 g/ha florasulam + 39 g/ha diflufenican + 3.9 g/ha metsulfuron-methyl

Table 3 - Description of the weed-management strategies in the winter barley experiment at IC Jablje in the season 2019/2020.

herbicide rates (Strategy 2), delayed sowing with false seedbed + spring harrowing + application of reduced herbicide rates (Strategy 3), and strategy with only mechanical weed control (Strategy 4).
The previous crop on the experimental field was maize. After harvest, the site was ploughed and the seedbed was prepared with a fine tine cultivator. The trial was arranged in a block design with 300 m long strips. A false seedbed was performed in the period of delayed sowing. The conditions for promoting weed germination in the false seedbed technique were very suitable, due to extremely warm weather for the autumn period and moist soils. Soil structure was fine enough for implementation of spring tine harrowing, therefore one pass working at 3-5 cm depth was performed. The effect of shallow cultivation was excellent and a considerable number of weeds emerged in autumn were controlled with this measure (Figures 5-6). Winter barley at the optimum sowing date was drilled on 8 October 2019, while delayed drilling was performed on 21 October 2019. The rainy period after sowing, which accounted for an unusually wet autumn, did not allow autumn herbicide application, therefore only spring herbicide application was carried out.
The first weed assessment was conducted on 26 November 2019, with prevailing weed species in the trial being *Stellaria media, Lamium purpureum, Viola arvensis* and *Veronica persica*. Weed density was much higher (470 plants/m^2) in strategies where winter barley was drilled at the optimum sowing time. In the plots with delayed sowing where a false seedbed was performed in the autumn the number of emerged weeds was reduced to 245 plants/m^2.
Spring harrowing was performed very early on 24 February 2020 in favourable crop conditions, but had a poor effect due to rain events in the following days. We decided to perform another harrowing operation two weeks later in moist, windy and sunny weather on 12 March 2020. The following days were warm and dry, and the overall effect of tine harrowing was better. Spring herbicide application was carried out on 6 April 2020. Soil conditions were good and despite low temperatures in the following days, weed suppression was adequate.
There were significant differences in winter barley development between the optimum (standard Strategy 1 and Strategy 2) and delayed drilling strategies (Strategies 3 and 4), since the weather was warm after the early drilling date. The later-drilled strategy was 7 to 10 days behind the plots with optimum drilling date, both in the autumn and early spring, but this difference decreased to 5 days when the winter barley reached the maturity stage (Figure 7).

Figures 5 and 6 - Difference between the optimum drilling strategy (left) and delayed sowing strategy (right) in the autumn.

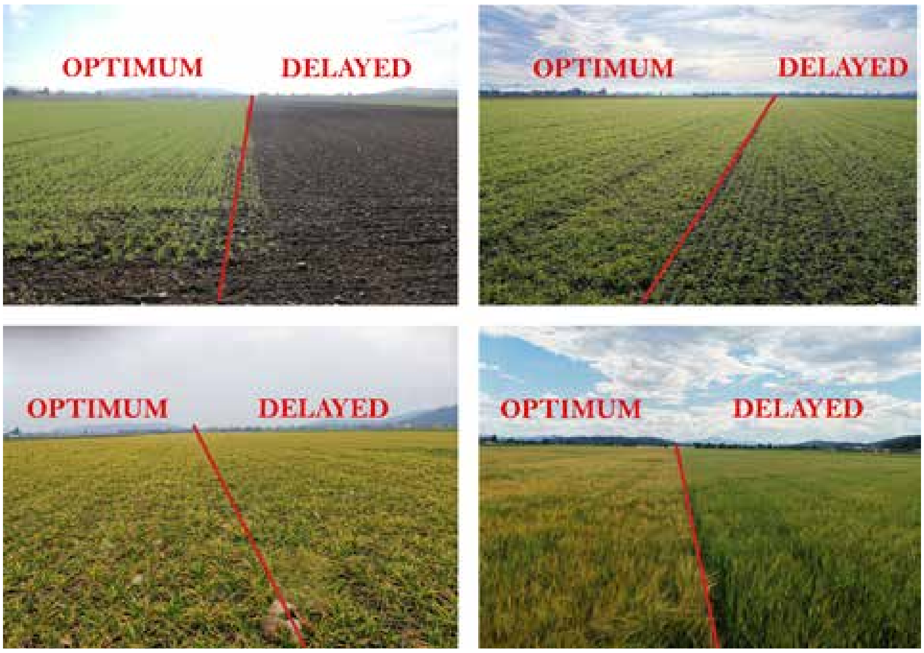

Figure 7 - Difference in the winter barley development in the optimum and delayed drilling strategies in autumn (top) and spring (bottom).

The weather in April was unusually dry, followed by rain and a severe cold front in May. As a consequence, a secondary tillage was performed, with the effect being more pronounced in Strategies 1 and 2, which were drilled earlier. Yields on these patchy areas were considerably reduced and they were excluded from the yield sampling subplots. Dry weed biomass was assessed on 02/06/2020 at the winter barley milking stage (Figure 8). Weed dry biomass was greatest in the treatment where only mechanical measures of weed control were used (44 g/m^2). The standard strategy with solely chemical approach did not produce the best weed reduction results when compared to the previous seasons (23.4 g/m^2), since the dry weed biomass was similar to Strategy 2 with spring harrowing followed by a reduced herbicide rate (19.4 g/m^2). The same efficacy was also seen in Strategy 3 with false seedbed, delayed sowing, spring harrowing and reduced herbicide rate.

Winter barley grain yields (Figure 9) were not related to the intensity of weed infestation. Dry grain yield was greatest in Strategy 4 (7.7 t/ha), followed by Strategy 3 (7.1 t/ha). Strategy 2 yielded 6.5 t/ha,

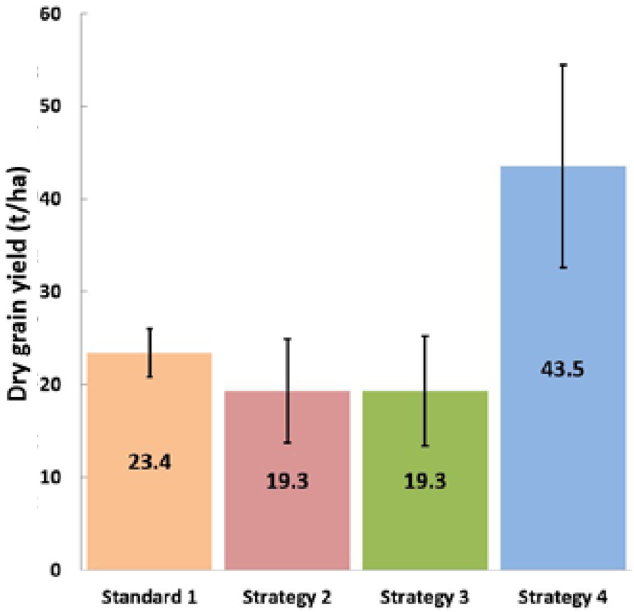

Figure 8 - Weed dry biomass determined in winter barley in June 2020 (vertical bars represent standard errors).

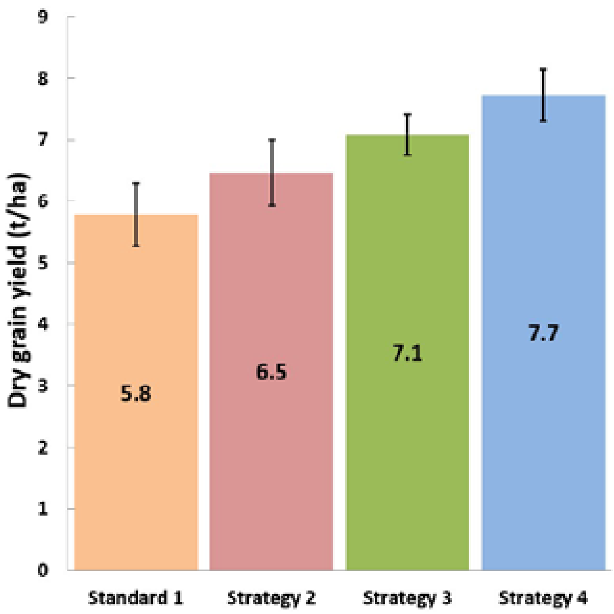

Figure 9 - Winter barley dry grain yields obtained with the four weed management strategies in 2020 (vertical bars represent standard errors).

while the lowest yield was determined in standard Strategy 1 (5.8 t/ha).
Outcomes of the trial were displayed to around 50 participants (mostly farmers, advisory specialists and experts) with the presentation at the 2020 Cereal Field Day in Jablje. Due to COVID-19 restrictions, the event was held outside in a hay barn. The use of the barn led to very positive reactions from the attendees and it will probably become a regular venue for similar events.
As IWMPRAISE outcomes were regularly presented on Cereal Field Days and at other expert events, several farmers expressed interest in taking part in field trials and testing specific IWM strategies in their fields with their own equipment. As a result, a joint trial in winter barley was conducted in 2021 at farmers' field in Žalna, near Grosuplje. In collaboration with the national cluster

Figure 10 - 2020 Cereal Field Day in Jablje was well-attended.

Figure 11 - In 2021, Cereal Field Day was held in a farmer's field.

partner KGZS-KGZ Ljubljana, a field day was also organised in early summer, where the local farmer presented his experience of performing weed-management practices with lower herbicide inputs to neighbouring farmers. This partnership was well-received by both the farming community and advisory service, and a further step in establishing a network of farmers practicing more advanced IWM practices is being considered.

General conclusions

Weed-management strategies suitable for central Slovenian conditions were designed and selected considering local environmental conditions, as well as the current socio-economic situation for the typical livestock and cereal-producing farms in the region. According to the winter cereal yield and weed biomass results obtained in the three-year study, the most promising approach in our field trials was the strategy with false seedbed and delayed drilling in autumn, and tine harrowing with reduced herbicide dose in the spring. When isolating individual tools within this strategy, the false seedbed and delayed drilling were the most effective in reducing weed competition in autumn and early spring. It has to be stressed that this strategy is more complex to implement and costly to perform, however it has proven to be very effective in terms of weed control and delivered a 40% reduction in herbicide use. We expected better performance by both the recommended and reduced herbicide applications in the spring, but weather conditions in April were often very unpredictable, with unexpected low temperatures in the morning affecting herbicide performance. Furthermore, weed control with reduced herbicide doses was lower and more variable, especially when more difficult-to-control species established in greater density (*Lolium* spp., *Apera spica-venti*). Results of our field study showed considerable variation in both efficacy and winter cereal yields. This was particularly noticeable in the last season, where the best yield was obtained with the least effective treatment. In the long-term, such a level of weed control will certainly result in a gradual increase in weed infestation, but it also suggests that the observed medium level of weed competition does not necessarily result in yield loss. Our results indicate that autumn herbicide application was more effective than post-emergence herbicide use in the spring. Thus, for early drilled winter cereals, i.e. a winter barley combination of reduced herbicide application in autumn combined with mechanical weed control in spring could also be a viable option in central Slovenian conditions. Recent advances in machinery development and studies showing only a minor effect of wider inter-row spacing on cereal yield suggest that hoeing could also be an effective tool for more professional cereal producers in Slovenia and should be tested in real field conditions in the future.

WP 4 – EXPERIMENTAL TRIALS ON MAIZE AT IC JABLJE

Maize is the most important crop grown in Slovenia. Suitable environmental conditions favour crop development and with proper crop management high maize yields can be obtained. In the past, a very broad selection of herbicides was available for weed control in maize and this crop has gained a reputation as a "cleaning crop", where even perennial weeds can be controlled to a sufficient level. Slovenian maize growers thus have very high expectations for the performance of weed control in maize, and intensive maize production relies heavily on the use of synthetic herbicides.
Standard weed-management practice includes the use of pre-emergence or early post-emergence herbicides, and sometimes additional herbicide treatments, to control perennial weeds, such as field bindweed, creeping thistle, broadleaved dock, couch grass and other troublesome species. The heavier soil type and humid climate of central Slovenia often hinder the efficacy of mechanical weed control and there is a general perception by farmers that mechanical weeding is simply not effective enough to be considered a relevant tool for weed control. Hence, mechanical weed control is rarely implemented in Slovenian maize production, with farmers not wanting to invest effort in repeated field operations, nor often owning suitable machinery.

Objectives

The objective of the field trials conducted on maize was to reduce herbicide consumption by developing alternative solutions based on reduced herbicide doses combined with mechanical weed control. Reduced herbicide doses and band herbicide application aimed to limit early weed establishment and competition in maize, whereas mechanical weed control was performed subsequently to minimise weed interference in the later development stages of maize.
Field testing and validation of IWM strategies were performed at the Infrastructure Center (IC) Jablje in seasons 2018, 2019 and 2020 to compare the following strategies:

- Strategy 1 (standard): broadcast early post-emergence herbicide application in recommended doses
- Strategy 2: reduced broadcast herbicide application (60%) + 1x hoeing
- Strategy 3: band herbicide application (40% dose on the whole area) + 1x hoeing
- Strategy 4: mechanical weed control (2x hoeing)

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	CON	HER_red	HER_row	MECH
Soil tillage	spring ploughing	spring ploughing	spring ploughing	spring ploughing
Herbicides	YES	YES	YES	NO
Application time	early post	early post	early post	/
Growth stage	BBCH 13	BBCH 13	BBCH 13	/
Rate	recommended *	reduced * 60 %	recommended **	/
Mechanical weeding	/	finger weeder BBCH 18	finger weeder BBCH 18	finger weeder BBCH 18

* isoxaflutole 99 g/ha + thiencarbazone-methyl 40 g/ha + cyprosulfamide safener 66 g/ha

** recommended dose was applied in the 30 cm band along the row combined with hoeing (40 % of dose in the whole area).

Table 4 - Description of the weed-management strategies in the maize field trial at IC Jablje in 2018.

Season 2018

A field experiment on maize was established at the end of April 2018 at the AIS research station IC Jablje. The trial was arranged in 200 m long by 12 m wide strips and consisted of three alternative weed-management strategies which were compared with a standard early post-emergence broadcast herbicide application (Table 4). In the two alternative Strategies 2 and 3, reduced herbicide doses and band application were combined with a precise camera-guided finger weeder. The fourth strategy was based on sole mechanical weed control, with the same machine being used to control weeds.
The same protocol was used in all three field trial seasons, with the exception of herbicide use. In the season 2018, a different herbicide mixture was used. Also note that the mechanical Strategy 4 in the first season was less intensive, with only one pass being used in the sole mechanical treatment.
The trial was planted with the Phyton variety in warm conditions on 30 April 2018. Maize germinated fast (in 7 days) and the first early post herbicide applications were performed on 18 May 2018 (BBCH 13).
The growing season was extremely humid and warm, which facilitated excellent efficacy of applied herbicides. In Strategy 4, the mechanical weeding was planned at two maize growth stages. Extreme rain events and soil conditions in May and June did not allow hoeing at the 6-leaf stage, therefore only one pass at the maize 8-leaf stage was performed in Strategy 4 (Table 4).
Substantial dry weed biomass was measured at the end of August (227 g/m^2) in the treatment with mechanical weed control only (Strategy 4). The finger weeder was effective in the interrow space, however most of the weed infestation was recorded along the maize rows and had a significant impact on competition with maize. In the strategy with band spraying (Strategy 3), maize rows were adequately controlled, however late application of hoeing was less efficient in the inter-row space. A reduced dose of herbicide (60%) in Strategy 2 did not show any reduction in weed control when compared with the recommended dose (Figure 12).
Overall environmental conditions in 2018 were favourable, with high temperatures and sufficient rainfall. Maize did not suffer any water shortage, therefore relatively high yields were achieved this season. In Strategies 2 and 3, weed infestation did not cause any significant effect on yield loss. Lower yields were, in our opinion, a consequence of maize stand loss due to very agressive hoeing with a finger weeder. The highest yield was measured in standard Strategy 1 (14.6 t/ha), followed by 13.0 t/ha and 12.4 t/ha in Strategies 2 and 3 respectively. The lowest yield was obtained in Strategy 4 (10.6 t/ha), where considerably higher weed infestation was observed (Figure 13).

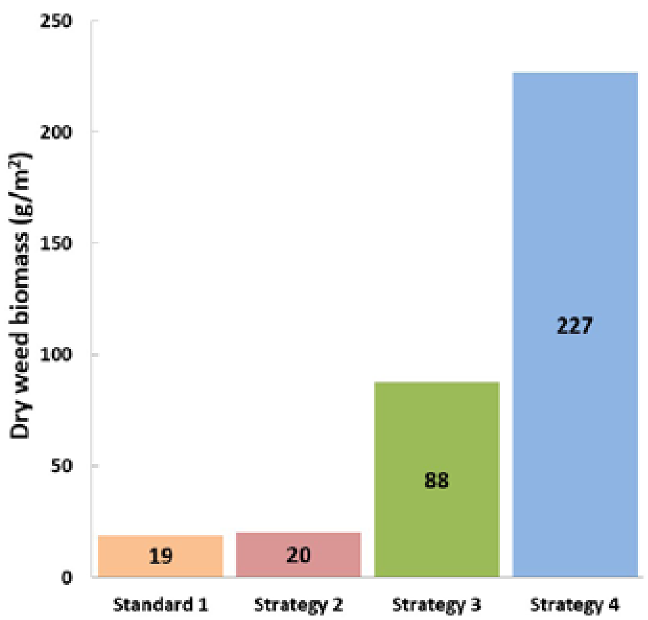

Figure 12 - Weed dry biomass determined in maize at the end of August 2018.

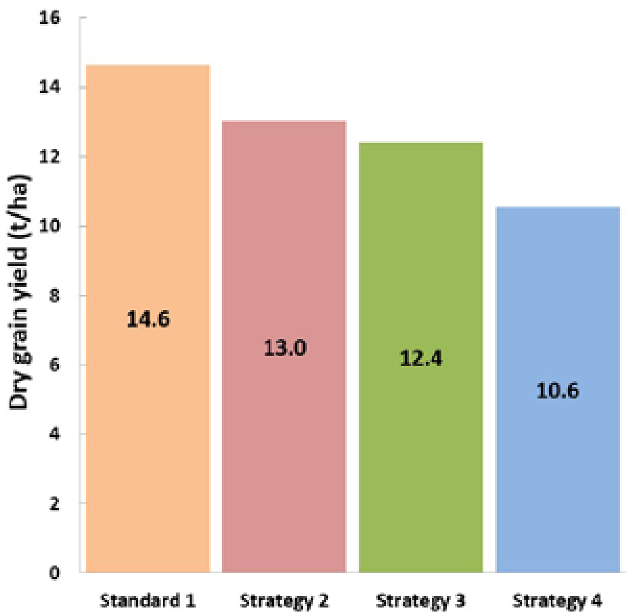

Figure 13 - Maize dry grain yields obtained with the four weed-management strategies in 2018.

Season 2019

A field trial for demonstration purposes was established at the end of April 2019 to test various combinations of herbicide treatment and mechanical weed control in maize. Due to unfavorable weather conditions, weed management strategies were not fully implemented in the previous 2018 season. Therefore, it was decided to follow the same protocol and the description of the weed strategies is presented in Table 5.

The trial was planted on 26 April 2019 with the Fisixx variety in warm, dry conditions. A couple of days after planting, a cold, wet period started, lasting practically the whole month of May. On top of that, we had two severe weather events with strong showers and hail. Herbicide applications were performed according to the protocol (Table 5). In Strategy 1, the recommended dose of standard herbicide was applied in the optimum conditions at the 2-3 leaf stage of maize, while most of the weeds were at the 2-3 leaf stage. In Strategy 2 (reduced dose) and Strategy 3 (band application), the same herbicide was applied at the same time as Strategy 1, i.e. at the 2-3 leaf stage of maize. Mechanical weeding with a finger weeder was planned at two growth stages of maize in both Strategy 3 (band application) and Strategy 4 (mechanical weed control only).

In general, conditions for herbicide performance were suitable, the soil was adequately supplied with moisture, and most of the weeds germinated in the spring and early summer flush. Extremely rainy conditions in May and June caused severe crusting of the top-soil layer, therefore inter-row hoeing instead of finger weeding had to be executed at the maize 4-leaf stage in Strategy 4 (mechanical treatment), while a second mechanical pass was performed with the finger weeder (Strategies 2, 3 and 4). By the time the conditions and maize growth stage were suitable for implementing the finger weeder (6-leaf stage), most of the weeds exceeded the optimum growth stage for effective control along the row.

Results of weed infestation at the end of August 2019 (Figure 14) showed that the most effective strategy was reduced herbicide treatment (60% dose) followed by hoeing (Strategy 2; 13 g/m^2). The standard herbicide treatment (Strategy 1; 31 g/m^2) and herbicide application in the row followed by hoeing (Strategy 3; 52 g/m^2) were somewhat less effective. This result can be largely attributed to an uneven infestation of field horsetail (*Equisetum arvense*). The greatest dry weed biomass was recorded in the sole mechanical treatment (Strategy 4; 171 g/m^2).

Overall, season 2019 was very difficult due to wet conditions. Additionally, a hail event at the end of June caused some damage and probably had a minor effect on the maize yield at the end of the season.

The greatest average yield (11.0 t/ha) was achieved in standard Strategy 1 (Figure 15). Similar yields were obtained in Strategy 2 (10.4 t/ha) and Strategy 3 (10.5 t/ha), which were followed by finger weeding.

The wet season had a strong influence on the performance of mechanical weed tools and, due to considerably greater weed infestation, the lowest yield was observed in Strategy 4 (8.4 t/ha).

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	CON	HER_red	HER_row	MECH
Tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
Herbicides	YES	YES	YES	NO
Rate	recommended broadcast *	reduced (60 %) broadcast *	recommended in the row (30 cm) **	/
Application time	early post	early post	early post	/
Growth stage	BBCH 12	BBCH 12	BBCH 12	/
Mechanical weeding	NO	finger weeder BBCH 16	finger weeder BBCH 16	interrow cultivator BBCH 14 finger weeder BBCH 16

* S-metolachlor 1406 g/ha + therbuthylazine 469 g/ha + mesotrione 141 g/ha

** recommended dose was applied in the 30 cm band along the row (40 % of dose in the whole area).

Table 5 - Description of the weed management strategies in the maize field trial at IC Jablje in 2019.

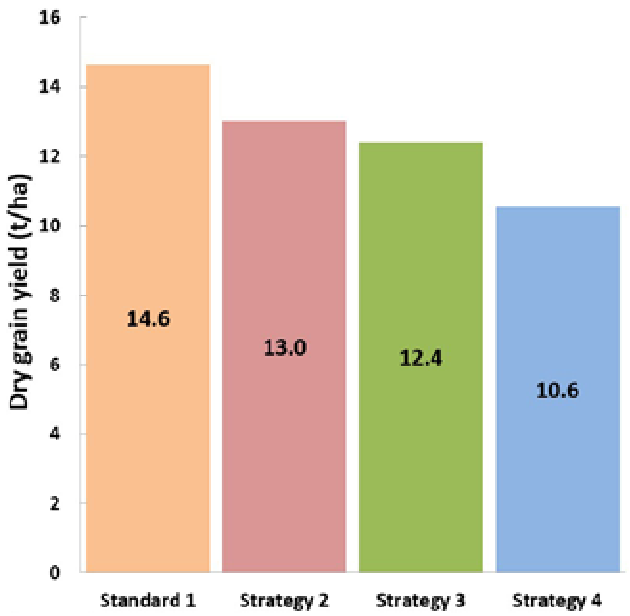

Figure 14 - Weed dry biomass determined in maize at the end of August 2019.

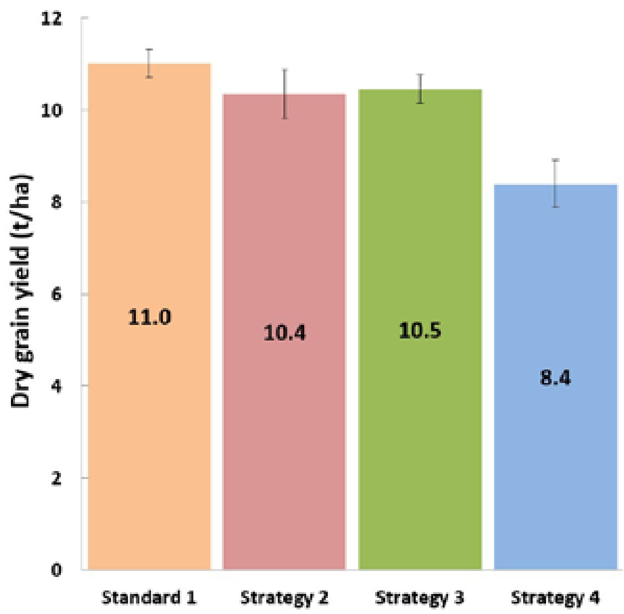

Figure 15 - Maize dry grain yields obtained with the four weed-management strategies in 2019 (vertical bars represent standard errors).

Season 2020

A field trial for demonstration purposes was established at the end of April 2020 to test various combinations of reduced herbicide inputs and mechanical weed control in maize. Trial results from the previous seasons were encouraging, despite weather conditions that prevented full execution of the proposed strategies. Thus, it was decided to follow the protocol designed at the start of the trial campaign (Table 6).

The trial was planted on 22 April 2020 with the DKC 4569 variety. The soil was very dry, with the lack of irrigation meaning that the maize germinated longer than usual. Early post-emergence herbicide was used according to the protocol in Table 6. In standard Strategy 1 the recommended dose of the herbicide was applied in optimum conditions at the 2-leaf stage of maize, while most of the weeds were in the 2-3 leaf stage. In Strategy 2 (reduced dose) and Strategy 3 (band application), the same herbicide was applied concurrently with Strategy 1. The first mechanical weed control in Strategy 4 was implemented on 27 May 2020 (Figure 16). The second mechanical weed control in Strategy 4 and first hoeing in Strategies 2 and 3 were carried out with a finger weeder on 16 June 2020 (Figures 17 and 18).

Results of dry weed biomass collected at the end of August 2020 showed that the lowest dry weed biomass (56 g/m^2) was determined in Strategy 2 with a reduced herbicide dose (60%) combined with mechanical weed control (Figure 19). The standard strategy with the recommended herbicide dose was also effective, with relatively low weed biomass observed at the end of the growing season (Strategy 1; 72 g/m^2). Herbicide band application followed by finger weeding was less effective (Strategy 3; 234 g/m^2). The most dry weed biomass was observed in the treatment with mechanical weed control only (Strategy 4; 383 g/m^2).

Maize dry grain yields obtained in 2020 were strongly above the average for this region, due to favourable weather conditions, with enough precipitation through the entire season. Maize yields were also closely related to the dry weed biomass, with a moderately negative effect on grain yield. The greatest maize dry grain yield (16.0 t/ha) was achieved by Strategy 2, with a similar yield being achieved in Strategy 1 (15.8 t/ha); the yield of Strategy 3 (15.1 t/ha) was similar to Strategy 4 (14.9 t/ha) (Figure 20).

Due to restriction measures related to the COVID-19 pandemic, the results of the experiment were presented with an online lecture and an additional IWM workshop at the 2020 Maize Field Day in Jablje. A lively discussion was held in the field, where about 40 visitors (mostly farmers and consultants) were able to observe the results of the tested strategies (Figure 21).

General conclusions

Strategies relevant for the central Slovenian region were selected considering their efficiency in local conditions, farm structure, and the availability of

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	CON	HER_red	HER_row	MECH
Tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
Herbicides	YES	YES	YES	NO
Rate	recommended broadcast *	reduced (60 %) broadcast *	recommended in the row (30 cm) **	/
Application time	early post	early post	early post	/
Growth stage	BBCH 12	BBCH 12	BBCH 12	/
Mechanical weeding	NO	finger weeder BBCH 16	finger weeder BBCH 16	interrow cultivator BBCH 14 finger weeder BBCH 16

* S-metolachlor 1406 g/ha + therbuthylazine 469 g/ha + mesotrione 141 g/ha
** recommended dose was applied in the 30 cm band along the row (40 % of dose in the whole area).

Table 6 - Description of the weed-management strategies in the maize field trial at IC Jablje in 2020.

machinery for mechanical weed control.
Results obtained in the three-year field study showed that the strategy with reduced post-emergence herbicide application combined with hoeing proved to be efficient in terms of maize yield and level of weed control. This strategy is simple-to-use and allows 40% herbicide savings, but it also shows less flexibility in less favourable weather conditions, when the application period for mechanical weeding is shortened. However, the risk of yield failure is small and mainly arises from crop plant loss caused by mechanical weeding. This could be largely prevented with a more precise machinery set-up and a small increase in the maize-seeding rate.
Additional herbicide savings were achieved in the strategy with band herbicide application supplemented with hoeing, but further investments in machinery are needed to implement this approach in large-scale farming. When compared to the two strategies with broadcast herbicide application, the level of weed control in the band herbicide application significantly decreased. This was probably because the mechanical weeding in the untreated inter-row space was performed too late, i.e. when weeds were already beyond the optimum stage for hoeing.

Figure 16 - First mechanical weeding in maize at the end of May 2020.

The level of weed control obtained in the sole mechanical weed control approach was inadequate and this strategy in the present form cannot provide a long-term management solution. However, it contains an important message for farmers who are unwilling to move from absolute chemical weed management. Additional IWM tools are indeed needed to improve the performance of this mechanical strategy, but most of the maize yield can be preserved with the two hoeing approaches used in our study.

Figures 17 and 18 - Second finger weeding operation in maize in the middle of June 2020.

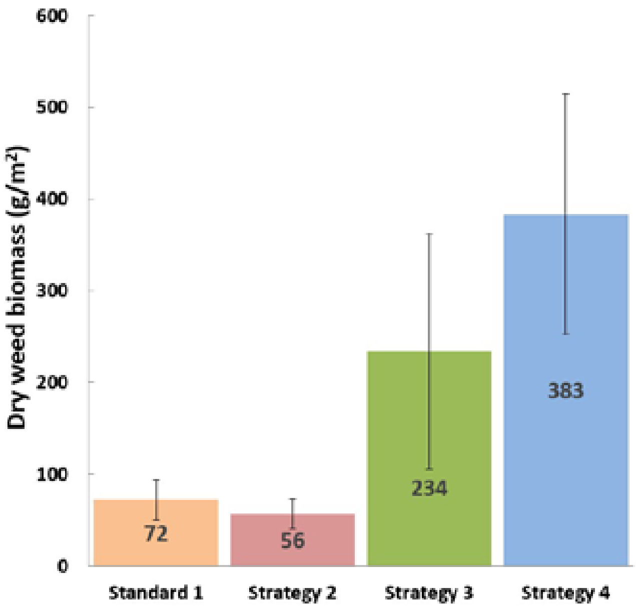

Figure 19 - Weed dry biomass determined in maize at the end of August 2020 (vertical bars represent standard errors).

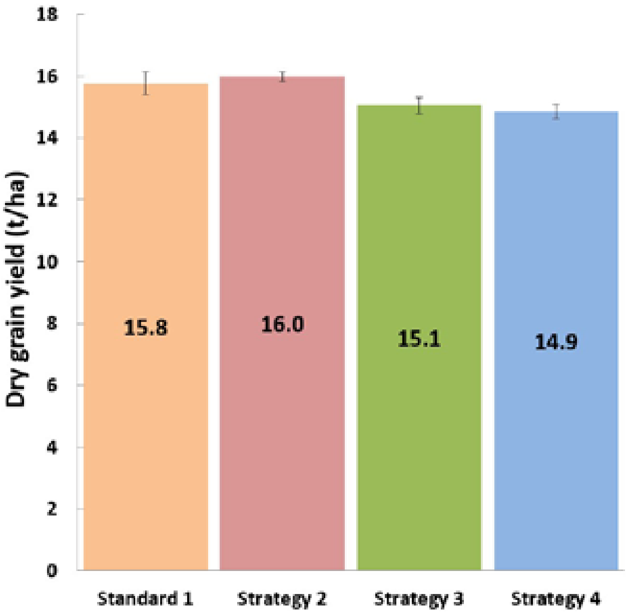

Figure 20 - Maize dry grain yields obtained with the four weed-management strategies in 2020 (vertical bars represent standard errors).

Figure 21 - Images from the IWM workshop and 2020 Maize field day.

WP5 – BIOLOGICAL CONTROL OF RUMEX IN SLOVENIA

Rumex obtusifolius L. (broad-leaved dock) is a perennial weed species widespread on meadows and pastures but also frequently found in other cropping systems. Due to its extensive root system, it is capable of regrowing after frequent defoliation and soil disturbance. Large production of highly dispersive and persistent seeds adds to its successful establishment in agricultural settings. A common management practice for *R. obtusifolius* control is the use of herbicides, tillage and mechanical weeding (including hand-removal), where repeated measures are needed to obtain long-term control. To develop more sustainable management of this troublesome weed species, suitable insect species for biological control of *R. obtusifolius* are being investigated. The latest results from studies conducted in Switzerland (CABI) showed the potential of inundative applications of a Sesiidae species, *Pyropteron chrysidiforme*, to control *R. obtusifolius*. Larvae of the insect feed on *R. obtusifolius* roots, thus weakening its growth capability. With sufficient larvae infestation, high plant mortality is expected.

Figure 22 - Laboratory rearing, mating and egg collection of *P. chrysidiformae.*

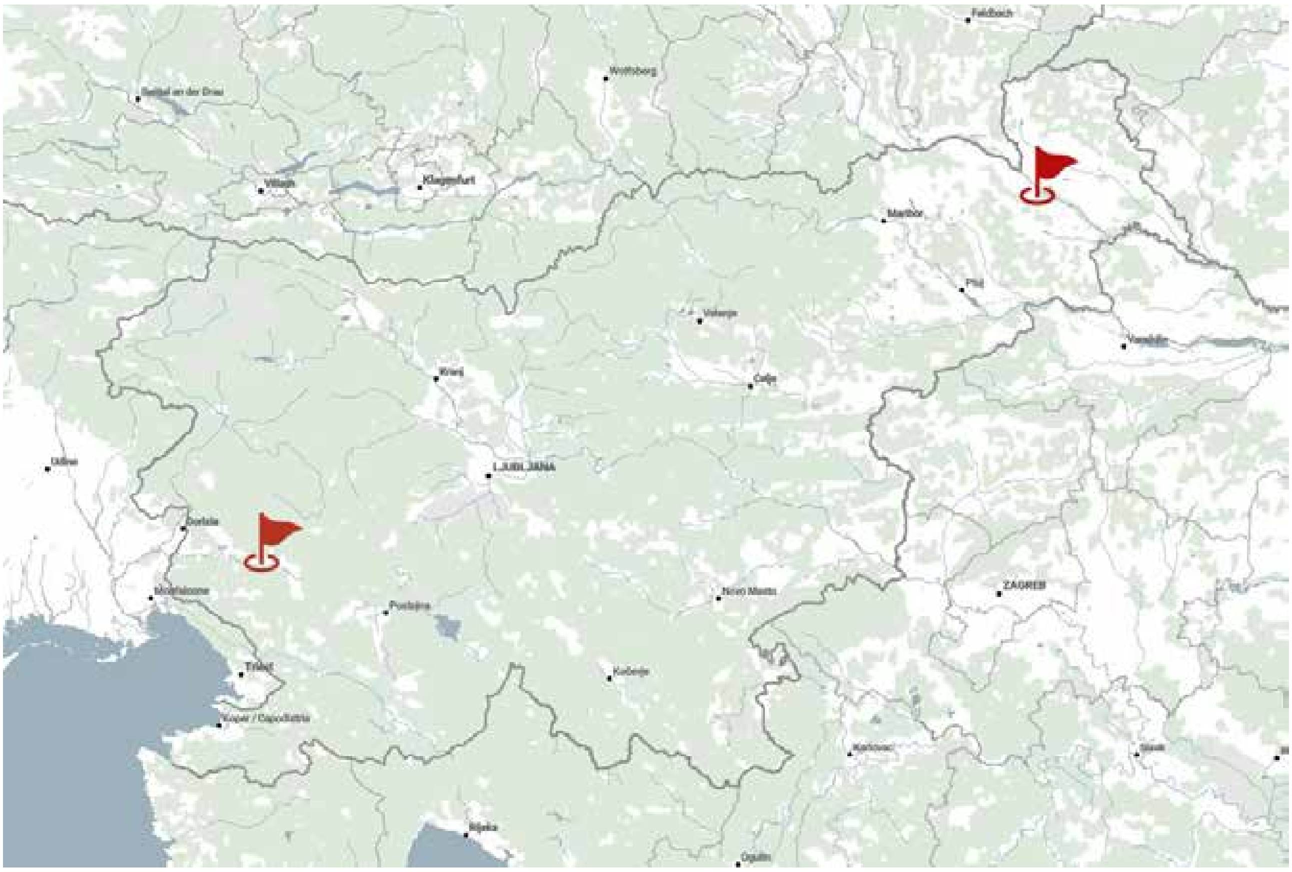

Figure 23 - Locations of the two study sites in Slovenia.

Objectives

A 3-year study using mass-release of *P. chrysidiforme* for biological control of *R. obtusifolius* was conducted. The aim of the study was to determine whether more favorable environmental conditions will affect insect population build-up. Establishment of *P. chrysidiforme* after targeted release as well as the impact of the insect on *R. obtusifolius* mortality, were assessed in the years of the study.

Material and methods

Laboratory procedures

Rootstocks with *P. chrysidiformae* pupae were sent from partner institution CABI Switzerland to the AIS entomology laboratory. Emergence of adults was monitored and once insects had emerged, mating was carried out following the protocol. Eggs from the female insects were collected and glued to toothpicks (30 eggs per toothpick). Material was stored for field inoculation.

Field application

Two locations with distinctive climatic differences were selected for the study: one in SW Slovenia – the Vipavska dolina region (Location 1), with a mild Mediterranean climate; the other site in NE Slovenia – the Prekmurje region (Location 2), with a continental climate (hot and dry summers but cold winters).
In each location, a meadow with relatively high *R. obtusifolius* population was selected.
Inoculation of selected plants was performed for three consecutive years from 2018 to 2020. In the first year of the field trial 200 *R. obtusifolius* plants per location were selected. The plants were marked and the coordinates recorded using a high precision GNSS device (Stonex S9 GNSS). The plants were inoculated according to the protocol once, twice or three times during the experiment in spring/early summer.

Four different treatments were applied:
1 - inoculation with *P. chrysidiforme* in year 1
2 - inoculation with *P. chrysidiforme* in years 1 and 2
3 - inoculation with *P. chrysidiforme* in years 1, 2 and 3
4 - untreated (natural level of attack).
Each year, 25 additional plants were inoculated to determine annual variation in establishment rate. In autumn of each year, these plants were dug out and inspected for larvae presence and damage of the rootstock was assessed.
Spring 2021 marked the end of field experiment on both field sites. Plants were inoculated with *P. chrysidiformae* once, twice, three times, and the untreated plants were located in-field using a high precision GNSS device (Stonex S9i). Plant diameter and height were measured, and the number of rosettes counted. Live plants were dug out, put into plastic bags and transferred to the AIS laboratory. Plant roots were dissected and inspected for *P. chrysidiformae* larvae. Root damage and decay was also assessed.

Final results

Annual establishment rate

Every year of inoculation, an additional 25 *R. obtusifolius* plants were inoculated with *P. chrysidiformae* eggs. In autumn of the same year, plants were dug out and inspected for larvae presence and root damage.
In the first year (2018) we found 24 out of the 25 plants in Location 1 with signs of root damage (avg. 55% damage) and 16 rootstocks had 1 or 2 larvae inside. Eight inoculated plants were found to be dead. The plants had between 1 and 3 rosettes.
Similarly, in Location 2 there were 20 dugout plants with signs of root damage (avg. 30% damage). Thirteen of those plants had 1-3 larvae inside. All of the plants were still alive. The plants had between 1

Figures 24 and 25 - Field maps from the two sites with GNSS marked *R. obtusifolius* plants.

Figures 26 and 27 - Locating the plants using a high-precision GNSS device (left) and inoculation of *R. obtusifolius* plant in the field (right).

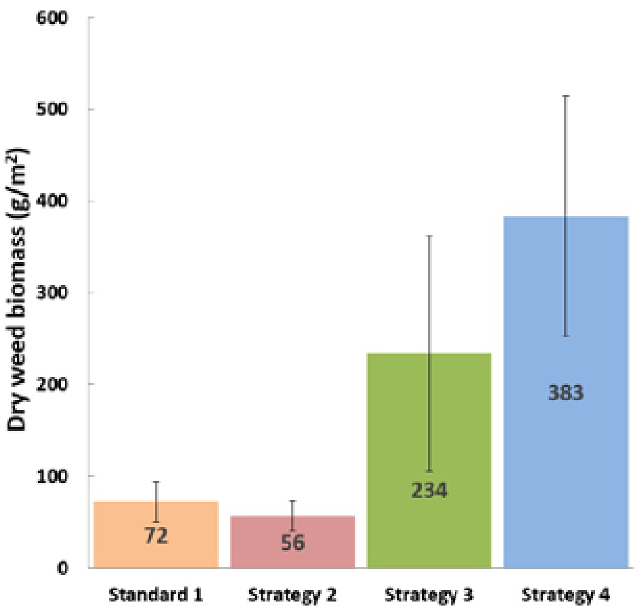

Figure 28 - Plant root damage results from annual establishment rate evaluation in 2020 (locations combined).

and 7 rosettes.
In the second year (2019) 5 out of the 25 plants inoculated in spring were found to be dead in Location 1, with root damage being almost 100%. Other plants were alive, but all showing signs of insect action (average 56% root damage). Larvae of *P. chrysidiformae* were found in all but two dug-out rootstocks. When examining the plants in Location 2, two inoculated plants were found dead, while the other 23 plants were still growing. Root damage varied between live plants being in the region between 1% and 75%. Larvae of *P. chrysidiformae* were found in 10 of the growing plants, and no larvae were found in 13 plants, although signs of insect damage on roots were present on all of them (average 30% root damage).
In the third year of the study (2020), 6 out of the 25 inoculated *Rumex* plants were found dead and 19 were still growing in Location 1. Rootstock damage to the live plants varied from non-existent (0) to almost 98%, with only a small amount of rootstock surviving. The rootstocks of dead plants were almost always totally decayed. Only a few larvae were found in the rootstocks (8 in total).
In Location 2, there were 5 plants, inoculated earlier in 2020, dead at the time of assessment and 20 were

still alive. Rootstock damage to the living plants varied from 0% to 95%, while damage to the roots of the dead plants was 100%. A total of 7 larvae were found inside the plant rootstocks when dissecting them.

Plant mortality

Larvae induced damage to rootstocks and plant mortality was in general higher in Location 1 - Ajdovščina. The Mediterranean climate with its milder winter and hot dry summer could have increased *P. chrysidiformae* survival.
In Location 1, plants were in general younger with smaller rootstock which suffered more damage, due to *P. chrysidiformae* larvae boring proportionally more than larger ones, and almost 90% of plants with 1 or 2 rosettes dead at the end of the experiment (Figure 31). This is why there was a large number of inoculated plants found dead even after only one inoculation in first year (78%). When inoculated 3 times, the percentage of dead plants was 96%. Furthermore, a large number of control plants found dead (12 plants) or infested with *P. chrysidiformis* larvae (7 plants) suggests that a warmer, drier climate facilitates the establishment of *P. chrysidiformis*.
As it turned out, a major factor influencing plant survival was the inoculated plant size. *R. obtusifolius* plants in Location 2 - Murski Črnci were more established, with larger rootstock which survived, despite *P. chrysidiformae* damaging them. Around 68% of plants with one or two rosettes were found dead (Figure 32), while only 29% of inoculated plants with more than 4 rosettes were dead. 40% of plants inoculated only in year 1 were dead.
During the field trial, we were faced with a situation which was unexpected but showed how successful the method of control was, especially in Location 1. For example, when searching for the marked *R. obtusifolius* plants selected for second inoculation in 2019, we found a large number of previously inoculated plants dead (73/100 dead plants on Location 1 and 18/100 dead plants on Location 2). The biological control method tested here


Figures 29 and 30 - *P. chrysidiformae* larvae inside the rootstock (left) and regrowth of damaged *R. obtusifolius* plant (right).

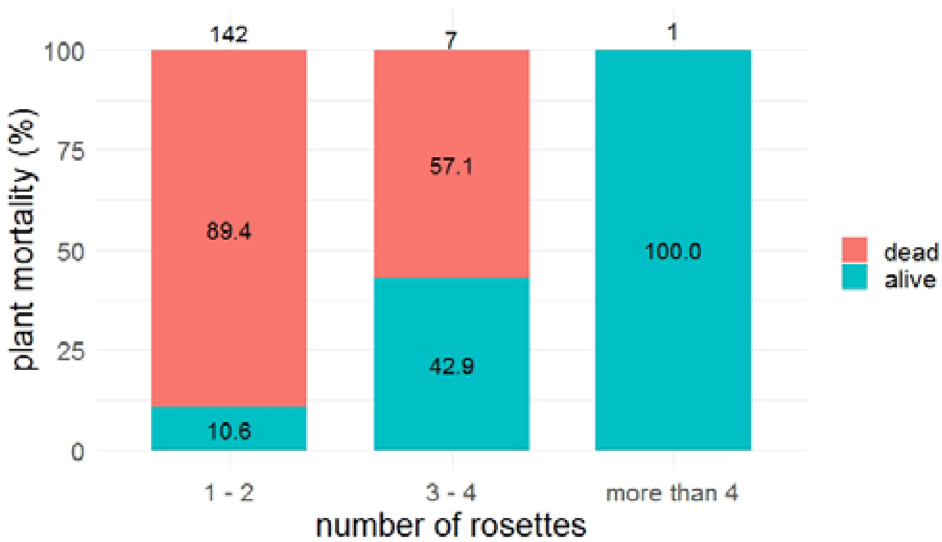

Figure 31 - Mortality of inoculated *R. obtusifolius* plants influenced by the plant growth stage (Location 1- Ajdovščina).

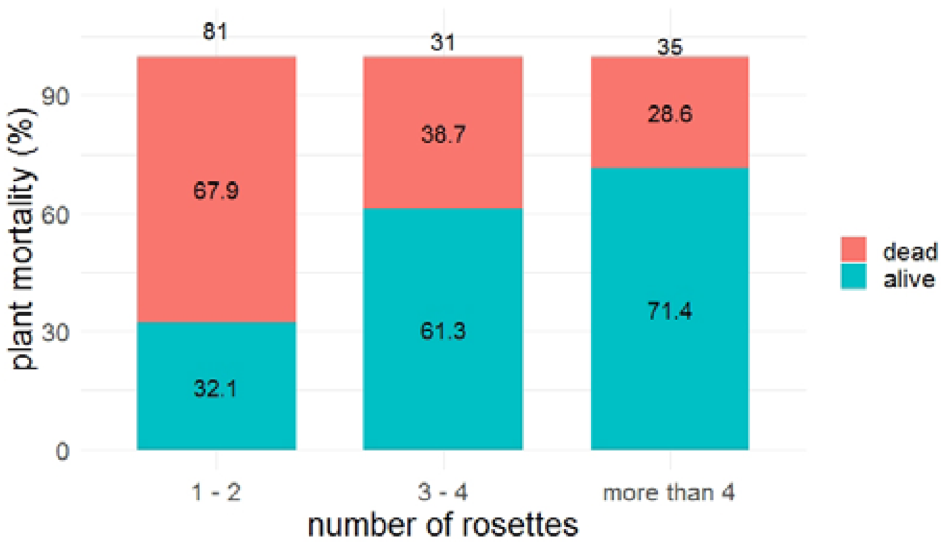

Figure 32 - Mortality of inoculated *R. obtusifolius* plants influenced by the plant growth stage (Location 2- Murski Črnci).

showed considerable potential for non-chemical management of *R. obtusifolius*, especially in warmer climates, where a single season of *P. chrysidiformis* release resulted in a significant reduction in the number of *R. obtusifolius* plants. Results suggest that increased annual temperatures facilitate *P. chrysidiformis* development as a higher number of larvae was found to cause considerably greater plant damage. Since the plant growth stage was the most important factor in plant survival, future studies will be focused on possibilities to control *R. obtusifolius* with a more extensive root system.

EXPERIMENTAL TRIALS AT THE BIOTECHNICAL SCHOOL RAKIČAN (BSR)

BIOTEHNIŠKA ŠOLA RAKIČAN

BSR Rakičan is a public agricultural high school in the Panonian lowland. Besides basic, mainly agricultural education programmes, it conducts various research activities that focus on arable production with variety testing and implementation of new technology and management in practical settings. BSR Rakičan owns around 18 ha of arable land with high-quality silty-loam soil. A warm continental climate offers excellent conditions for outdoor experiments. BSR Rakičan's skilled staff regularly carry out demonstration trials and education courses in collaboration with the local advisory service. Well-attended events, such as traditional wheat and maize field days, confirm that BSR Rakičan is a strong regional education and knowledge-transfer centre.

Address:
Biotehniška šola Rakičan
Lendavska ulica 3
9000 Murska Sobota - Slovenia
GPS coordinates: 46°39'3.57"N 16°11'32.83"E
http://www.solarakican.si/index.php/en/
tel. +386 2 530 37 50

For information and guided visits of WP3 and WP4 trials at BSR Rakičan, please contact:
Primož Titan
e-mail: titan.primoz@gmail.com
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WP3 WINTER WHEAT TRIALS AT BSR RAKIČAN

The Rakičan experimental site is located in the Northeastern part of Slovenia. Farm size in this region is considerably bigger than in the rest of Slovenia and it represents the main cereal production area in the country. Environmental conditions are favourable, and specialised winter cereal producers implement intensive cultivation and weed-management measures, leading to expectations of high yields. Standard practice usually includes post-emergence herbicide application in the spring. However, due to favourable autumn weather conditions in the recent decade, chemical weed control is increasingly shifting to pre-emergence herbicide application in the autumn. The region is characterised by a medium-light soil type and dry climate, which enables better efficiency and a wider application window for the use of mechanical weed control. However, mechanical weed management is not commonly used and the majority of winter cereal relies heavily on the use of herbicides.

Objectives

The objective of the experiments conducted on winter cereals in seasons 2017/2018, 2018/2019 and 2029/2020 was to reduce herbicide use in winter wheat production by developing alternative solutions based on reduced herbicide doses and mechanical weed control. Alternative weed management approaches, including mechanical weed control, aimed to reduce weed establishment in autumn and spring, as well as competition in the later development stages of winter wheat.
Field trials and assessments were carried out at the experimental farm of the Biotechnical School Rakičan (BSR) to determine performance of selected strategies and individual mechanical tools in representative northeastern environmental conditions of Slovenia. In the three seasons of field experimentation, the following strategies were tested in real field conditions:

- Strategy 1 (standard): spring herbicide application in recommended doses
- Strategy 2: autumn herbicide application in recommended doses
- Strategy 3: spring tine harrowing (1x) + application of reduced herbicide dose (50%)

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	HER_spring	HER_autumn	HAR_aut + HAR_spring + HER_ spring_reduced	DEL_sow + HAR_ spring
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
Sowing time	optimum	optimum	optimum	delayed 14 days
False seed bed	NO	NO	NO	YES
Herbicide rate	recommended *	recommended **	reduced * 50 %	NO
Application time	spring application	autumn application	spring application	/
Growth stage	BBCH 31	BBCH 12	BBCH 31	/
Mechanical weeding	NO	NO	autumn (1x) and spring harrowing (1x)	spring harrowing (1x)

* iodosulfuron-methyl 10g/ha + metsulphuron-methyl 1,5 g/ha
** iodosulfuron-methyl-sodium 7,5 g/ha + mesosulfuron-methyl 9 g/ha + diflufenican120 g/ha + mefenpyr-diethyl 27 g/ha

Table 1 - Description of the weed-management strategies in the winter wheat trial at BSR Rakičan in the season 2017/2018.

- Strategy 4: delayed sowing with false seedbed + spring tine harrowing (2x). Reduced herbicide dose application in autumn (70%) + spring tine harrowing (2x) in the 2019/2020 season only.

Season 2017/2018

A field trial at the Biotechnical School Rakičan was established in autumn 2017. Two alternative strategies and one standard weed-management practice were compared in winter wheat production. The experiment was arranged in 15 m wide strips. In the two standard weed-control strategies, herbicides were applied broadcast in autumn and spring.
In one of the alternative strategies, autumn and spring tine harrowing were combined with reduced herbicide use in spring. In the second alternative approach, delayed sowing and spring tine harrowing were utilised and herbicides were used in spring as needed.
The soil conditions in the period of the optimal sowing date were favourable, with warm weather and adequate water supply. Winter wheat at its optimum sowing date was drilled on 16 October 2017 for Strategies 1,2 and 3. The plot in Strategy 4 was sown 14 days later on 30 October 2017. The winter wheat in the delayed sowing plot needed 12 days to emerge when compared with just 6 days at the optimum sowing date. Unusually, warm weather continued into the late autumn, which enabled the implementation of weed-management measures in optimum conditions.
Autumn spraying in Strategy 2 was performed on 22 November 2017, while autumn harrowing in Strategy 3 was carried out two days later, on 24 November 2017. The overwintering of the crop was adequate, despite harsh winter temperatures and long snow cover, which caused a significant delay in vegetation development and execution of crop-management measures.
The crop on the delayed sowing plots was thinner in the spring, however at harvest time approximately 600 heads were counted on average in all treatments. Only a minor delay in development was recorded: the late drill of plots started only two days later than the optimal sowing date.
After fertilisation at the end of March, a tine harrow was used in Strategies 2 and 3. Both autumn and spring harrowing performed well, mainly because of adequate soil conditions and optimal crop development. Weed infestation was generally low across all plots, with only *Cirsium arvense* appearing on some spots.
The highest weed biomass was recorded in Strategy 4, where delayed sowing with a false seedbed was performed in autumn, while in spring, only one post-emergence spring harrowing was conducted (Figure 1). Although weed biomass was considerably greater in Strategy 4, the level of weed infestation

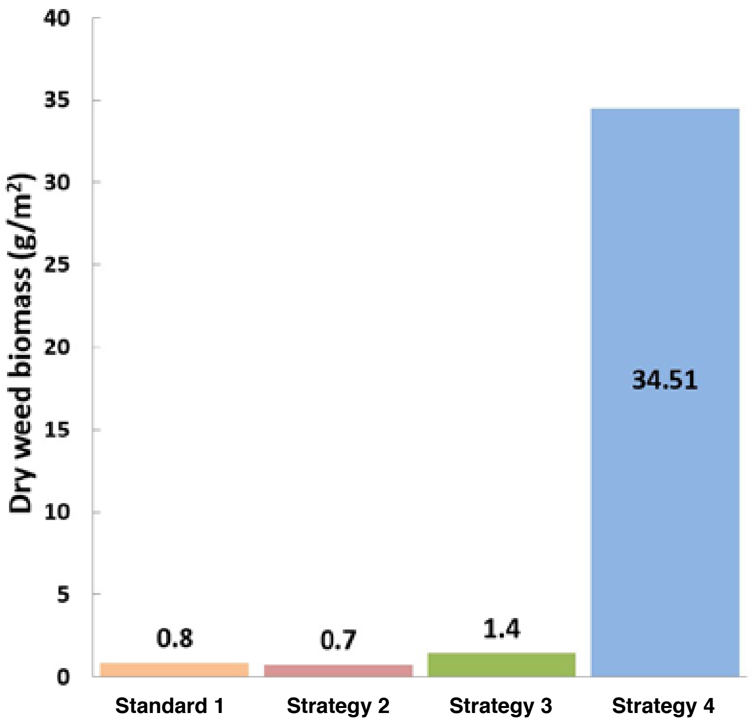

Figure 1 - Weed dry biomass determined in winter wheat at the beginning of June 2018.

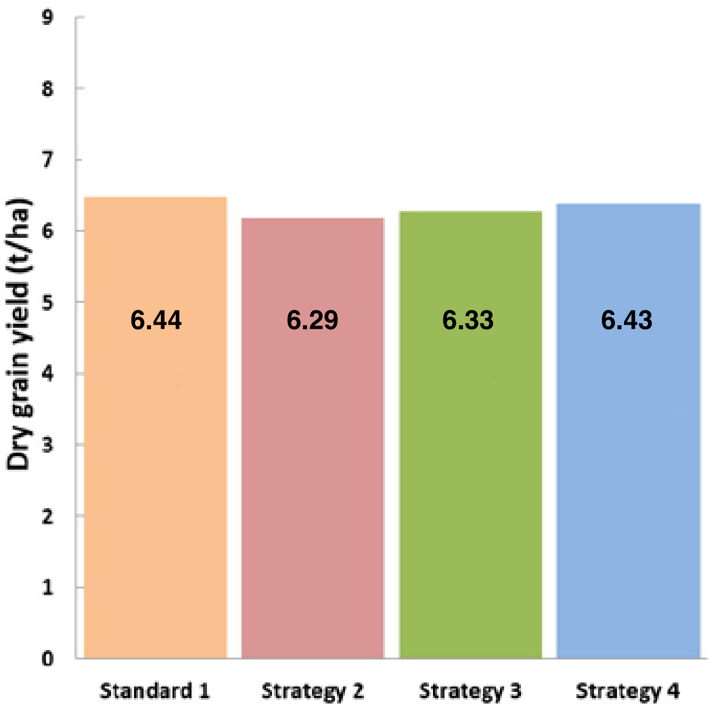

Figure 2 - Winter wheat dry grain yields obtained with the four weed-management strategies in 2018.

did not have any effect on yield performance when compared to the other strategies (Figure 2).
The environmental conditions in 2018 were in general not favourable, with high temparatures and a water shortage in the spring greatly reducing winter wheat yields. In all of the strategies, remarkably similar yields were recorded, ranging from 6.3 t/ha to 6.4 t/ha. All of the tested strategies were then repeated in the following 2018/19 season.

Season 2018/2019

A winter wheat (Falado variety) demonstration trial was set up in October 2018 to compare two IWM strategies with two standard solely chemical approaches. Autumn and spring broadcast herbicide application represented the standard weed-management practice, while IWM strategies included reduced herbicide inputs combined with mechanical tools. Strategies were followed according to the protocol in Table 2.
The previous crop on the experimental field was maize and the site was ploughed one week before sowing. The seedbed was prepared afterwards with the spring tine cultivator on 12/10/2018.
Soil conditions on both the optimal and delayed sowing dates were favourable, with the weather being warm and water supply adequate. Winter wheat for the optimum sowing date strategies was drilled on 18/10/2018. The plot with Strategy 4 was drilled 11 days later on 29/10/2018, with excellent conditions for germination and crop establishment. Unusually warm weather continued into the late autumn, which enabled the implementation of weed-management measures in optimal conditions.
A first tine harrowing pass was performed in Strategy 3 just one month after drilling on 14/11/2018, while autumn spraying in Strategy 2 was performed on 5/11/2018.
A considerable difference in the winter wheat growth stage was observed before winter in the delayed sowing treatment (Strategy 4). Winter wheat in this plot reached only stage BBCH 12-13 when compared to the BBCH 15 stage in other strategies. Despite this difference, overwintering of the crop was optimal and no stand loss was determined due to winter conditions. The first tine harrowing in the spring for Strategies 3 and 4 was performed on 04/03/2019, while a second pass in Strategy 4 was executed three weeks later. Both autumn and spring harrowings performed well, mainly because of adequate soil conditions and crop development.
The crop in the delayed drilling plot had a minor delay in development and produced 50 heads/m^2 less than the other strategies. Weed infestation was generally low across all the plots, with only Silky bent-grass (*Apera spica-venti*) appearing in some spots.
Dry weed biomass was assessed on 21/06/2019

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	HER_spring	HER_autumn	HAR_aut + HAR_spring + HER_spring_reduced	DEL_sow + HAR_spring
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
False seed bed	NO	NO	NO	YES
Sowing time	optimum	optimum	optimum	delayed 11 days
Herbicide rate	recommended *	recommended **	reduced * 50 %	NO
Application time	spring application	autumn application	spring application	/
Growth stage	BBCH 32	BBCH 12	BBCH 32	/
Mechanical weeding	NO	NO	autumn (1x) and spring harrowing (1x)	spring harrowing (2x)

* pyroxsulam 18.75 g/ha
** pendimethalin 600 g/ha + chlortoluron 500 g/ha + diflufenican 80 g/ha

Table 2 - Description of the weed-management strategies in the winter wheat trial at BSR Rakičan in the season 2018-2019.

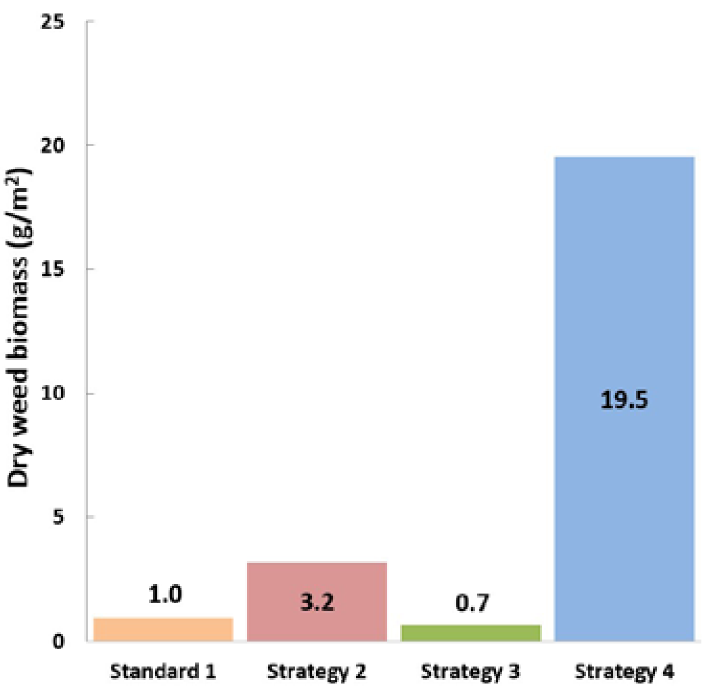

Figure 3 - Weed dry biomass determined in winter wheat at the end of June 2019.

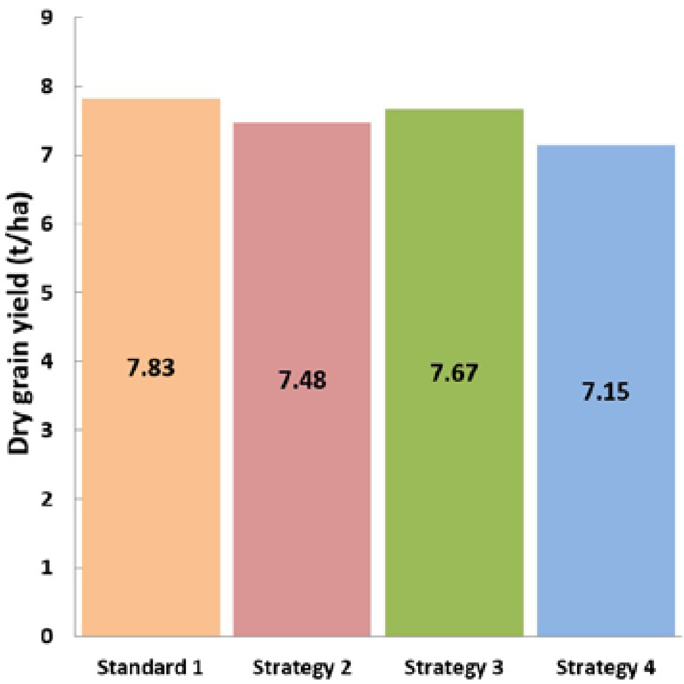

Figure 4 - Winter barley dry grain yields obtained with the four weed-management strategies in 2019.

at the winter wheat milking stage (Figure 3). The highest weed biomass (19.5 g/m^2) was recorded in Strategy 4 with delayed drilling, followed by two spring harrowings. Most of the weed infestation in this strategy occurred at the beginning of summer, but the greatest effect on yield loss may be due to less effective tillage. Strategy 3 with two harrowings followed by reduced herbicide application performed excellently, with only 0.7 g/m^2 of dry weed biomass, and was comparable to standard spring herbicide application (1.0 g/m^2). The autumn herbicide Strategy 2 was also relatively effective, with 3.2 g/m^2 of dry weed biomass.
Environmental conditions in the 2018/2019 growing season were not favourable; therefore only average winter wheat yields were achieved in the northeast region of Slovenia. Results of winter wheat dry grain yield were correlated with the results of weed density (Figures 3 and 4). With the exception of Strategy 4, which implemented mechanical weed control only, all strategies were very effective in terms of weed control.
Compared to the best yielding standard strategy (Strategy 1; 7.83 t/ha), only minor yield decrease was observed in IWM Strategy 3 (7.67 t/ha). Surprinsingly, minor yield loss was also determined in Strategy 2, which was very effective (7.48 t/ha). The lowest yield was determined in Strategy 4, the most weedy, with no herbicide application (7.15 t/ha).

Season 2019/2020

In season 2019/2020, the experiment was run at the same location, and IWM strategies similar to the previous two years were tested in winter wheat.
A winter wheat (variety Falado) demonstration trial was set up in October 2019, during which various strategies of chemical and mechanical weed control measures were tested. Two IWM strategies were compared with two standard solely chemical approaches. Based on the experience and results achieved in the previous two field trial seasons, it was decided to adapt Strategies 3 and 4. In Strategy 3, autumn harrowing in November did not significantly reduce weed density and was excluded from the plan. Likewise, delayed sowing in Strategy 4 was seen to have a large effect on winter wheat yield; therefore a reduced herbicide dose was introduced. Strategies were performed according to the protocol in Table 3.

The previous crop in the experimental field was maize. After harvest, the site was ploughed and the seedbed prepared with a rotary harrow. The trial was arranged in a block design with 200 m long strips. Winter wheat at the optimum sowing date was drilled on 18 October 2019, and autumn herbicide application was performed on 26 November 2019. Crop development after drilling was favourable, with the weather warm and water supply adequate.
The first weed assessment was conducted on 12

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	HER_spring	HER_autumn	HAR_spring + HER_spring_reduced	HER_autumn_reduced + HAR_spring
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
False seed bed	NO	NO	NO	NO
Sowing time	optimum	optimum	optimum	optimum
Herbicide rate	recommended *	recommended **	reduced * 50 %	reduced ** 70 %
Application time	spring application	autumn aplication	spring application	autumn application
Growth stage	BBCH 32	BBCH 12	BBCH 32	BBCH 12
Mechanical weeding	NO	NO	spring harrowing (2x)	spring harrowing (2x)

* pyroxulam 18,75 g/ha
** pendimethalin 600 g/ha + chlortoluron 500 g/ha + diflufenican 80 g/ha

Table 3 - Description of the weed-management strategies in the winter wheat trial at BSR Rakičan in the season 2019-2020.

December 2019 at the BBCH 13 winter-wheat growth stage. The first mechanical weed control in Strategies 3 and 4 was spring tine harrowing, which was performed in optimal conditions on 21 February 2020.

The 2019/20 season was characterised by a pronounced lack of precipitation in winter and in spring at the beginning of wheat vegetation. There was a significant difference in weed density in February and March between strategies with autumn application (Strategy 2 and Strategy 4; 25 plants/m^2) and strategies where spring herbicide application had not been performed yet (Standard 1 and Strategy 3; 8 plants/m^2).

Dry weed biomass (Figure 6) was assessed before harvest on 21/06/2020, and the highest value was observed in Strategy 3 (4.1 g/m^2), where a reduced rate of herbicide was combined with tine harrowing in spring. Strategy 4 produced 3.3 g/m^2 of dry weed biomass, while Strategies 1 and 2, with a solely chemical approach, produced the best results of weed control efficacy (2.7 and 1.9 g/m^2 respectively).

Harvest was carried out on 15 July 2020 (Figure 8). The highest winter wheat grain yield was achieved in the treatment where the recommended herbicide dose was applied in autumn. The mild winter of 2019/20 in combination with the lack of precipitation

Figure 5 - Weed assessment before the herbicide application in spring 2020.

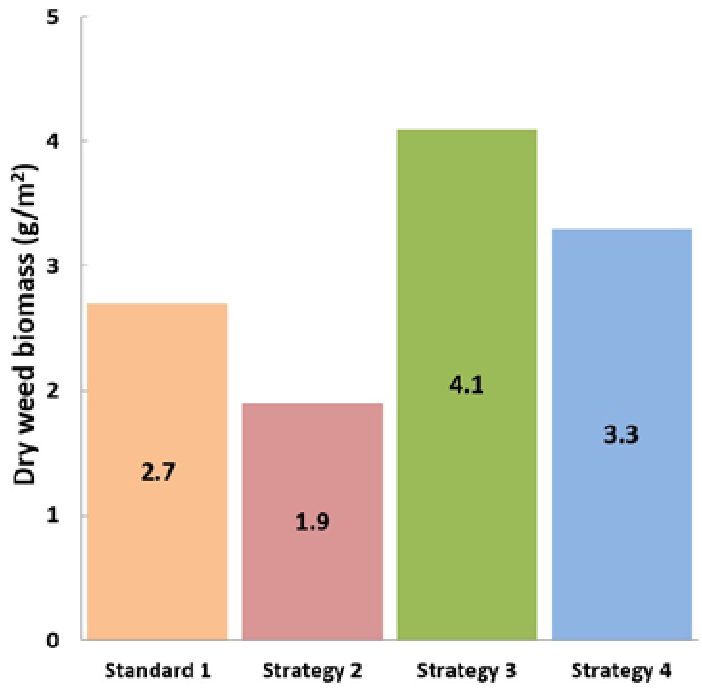

Figure 6 - Weed dry biomass determined in winter wheat at the end of June 2020.

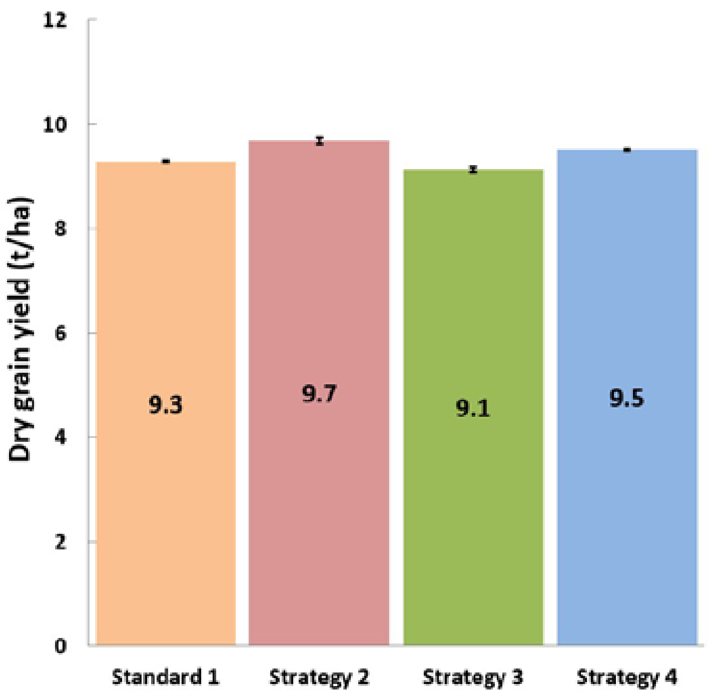

Figure 7 - Winter barley dry grain yields obtained with the four weed-management strategies in 2020.

at the beginning of vegetation had a negative impact on the initial growth and development of the wheat. This influenced weed development, with the majority of weed species emerging in the early autumn and summer.
In general, in the 2019/2020 trial season, above average yields were recorded for this region. Similar to the previous two field trial seasons, the results of this season also showed that a reduced herbicide rate had a negative effect on wheat yields when comparing strategies with the same herbicide application timing (Standard 1 vs Strategy 3 and

Strategy 2 vs Strategy 4; Figure 7).
Considerably higher yield was obtained in the autumn herbicide application (Strategy 2; 9.7 t/ha) when compared to the standard spring herbicide application (Standard 1; 9.3 t/ha), which is in contrast with the previous two trial seasons. In this season, adapted Strategy 4 proved to be efficient both in terms of weed control and winter wheat yield (9.5 t/ha). The lowest yield (9.1 t/ha) was determined in Strategy 3, where reduced herbicide rate combined with spring tine harrowing was applied in the spring.
The results of the IWMPRAISE trial were presented at an open-air lecture and an additional guided experiment tour at the traditional Wheat Field Day in Rakičan (Figure 9).

Figure 8 - Winter wheat harvest at the BSR trial site in the middle of July 2020.

General conclusions

The winter cereal production in northeastern Slovenia is highly specialised and the weather conditions increase both the feasibility and efficacy of mechanical weed control measures.
Results from the three-year field study in Rakičan showed that the weed control obtained with the strategy using reduced herbicide dose combined with mechanical weed control was comparable to the spring and autumn herbicide application. Considering both weed control efficacy and the winter wheat yield, this IWM strategy delivers a 50% reduction in herbicide use without any risk of yield loss or of a long-term increase in weed population. Likewise, the strategy with an autumn herbicide reduced dose (70 %) and spring harrowing also proved to be effective, although it was performed in the last season only. There was a considerable variation in winter wheat yields among years, especially when comparing spring and autumn herbicide application of recommended dosages; therefore the weed biomass data were considered more relevant in years with very low yield differences between treatments.
In the strategy where no herbicides were applied and only mechanical weed control was used, the level of weed control was significantly lower and unacceptable yield loss for most of the professional cereal producers in the region was observed. However, with further improvement, this approach could be used in organic wheat production, where other strategies (i.e. crop diversification) are employed to prevent a long-term increase in weed infestation.
Although the outcomes of field experimentation are encouraging, a further validation of results is needed. In contrast to the Jablje experimental site, extremely low weed pressure was observed at the Rakičan site. In all three seasons of field experimentation, a particularly small number of winter and early spring annual weed species were observed, and the weed-competition effect was much lower than in the central Slovenia site. Results were regularly presented to researchers, experts and farming communities, with important feedback being collected during the field experimentation, which represents a valid resource for future improvement of IWM in Slovenian winter cereal production.

Figure 9 - Images from the 2020 Wheat fiel day in Rakičan.

WP4 – MAIZE TRIALS AT BSR RAKIČAN

Maize is a very important part of cropping systems in northeastern Slovenia. In years with sufficient rainfall, intensive crop management usually delivers high maize grain yields. In the past few decades, a wide range of active ingredients has been banned. Additionally, an increasing number of restrictions on specific areas, such as water protection zones, have also been imposed. However, there is still a sufficient number of efficient herbicide solutions to control weeds in maize, including perennial species. Thus, maize growers in this region have very high expectations on the performance of weed control in maize, with intensive maize production relying heavily on the use of synthetic herbicides. Strategies suitable for this region were selected considering efficiency in local conditions, farm structure and availability of machinery for mechanical weed control. The experimental location in Rakičan has different pedoclimatic conditions to the Jablje site in central Slovenia, and tine harrowing was considered a relevant tool for lighter, loamy soil. In contrast to the central region and Jablje site, farmers in this area are better equipped with hoeing machinery, as they often incorporate urea fertilisers because of the dry conditions in early summer. Although farmers do not consider this particular mechanical intervention for direct weed control, it certainly contributes to the control of perennial and late-emerged weed species.

Objectives

The objective of the field trials conducted on maize was to reduce herbicide consumption by developing alternative solutions based on reduced herbicide doses, combined with mechanical weed control. Validation of IWM strategies was performed at the Biotechnical School Rakičan (BSR) in years 2018, 2019 and 2020. In the three seasons of field

experimentation, the following strategies were tested and compared to local standard practice:
- Strategy 1 (standard): broadcast early post-emergence herbicide application in recommended doses
- Strategy 2: reduced broadcast herbicide application (50% dose), + 1x hoeing
- Strategy 3: band herbicide application (40% dose on the whole area) + 2x hoeing
- Strategy 4: mechanical weed control (2-3x harrowing + 1x hoeing)

Season 2018

The objective of this demonstration trial was to include mechanical measures in weed-management strategies in maize production, using only herbicides for weed control in the standard practice. Strategies were demonstrated in real field conditions and designed to reduce reliance on herbicides. To achieve this goal, herbicide use was partially replaced by mechanical tools and band spraying.
A field experiment in maize was established at the beginning of April 2018 at the Biotechnical School Rakičan. The demonstration trial was arranged in 12 m wide strips and consisted of three alternative weed-management strategies which were compared with standard early post-emergence broadcast herbicide application. In alternative Strategy 2, an inter-row weeder was adapted for the band application of herbicides in the row and combined with hoeing. In the second alternative, Strategy 3, a reduced herbicide dose was applied, while in Strategy 4 only mechanical weed management was implemented.
Conditions after planting were favourable. Maize germinated in seven days and, with optimum water supply, it developed rapidly. Afterwards, heavy rain caused compaction of the soil and a delay in performing weed-management operations.
The harrowing operation in Strategy 4 was postponed due to standing water on part of the field. Furthermore, weeds overgrew their optimum development stage, therefore harrowing was less effective than expected, with the majority of the grass

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	CON	HER_red	HER_row	MECH
Soil tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
Herbicides	YES	YES	YES	NO
Application time	early post	early post	early post combined with hoeing	/
Growth stage	BBCH 12	BBCH 12	BBCH 13	/
Rate	recommended *	reduced * 50 %	recommended **	/
Mechanical weeding	/	interrow cultivator BBCH 16	interrow cultivator BBCH 13 *** BBCH 16	harrowing BBCH 12 BBCH 14; interrow cultivator BBCH 17

* isoxaflutole 99 g/ha + thiencarbazone-methyl 40 g/ha + cyprosulfamide safener 66 g/ha
** recommended dose was applied in the 30 cm band along the row combined with hoeing (40 % of dose in the whole area).
*** mechanical weeding combined with herbicide spraying

Table 4 - Description of the strategies in the maize field trial at BSR Rakičan in 2018.

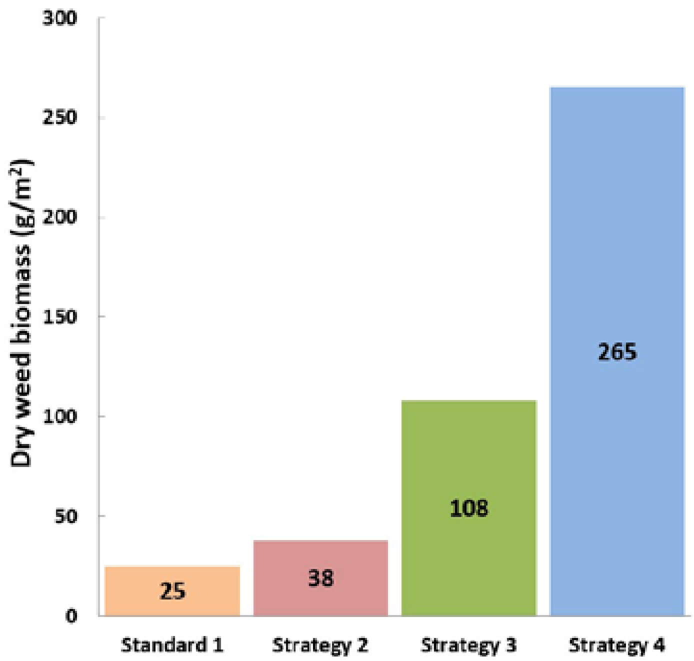

Figure 10 - Weed dry biomass determined in maize at the beginning of August 2018.

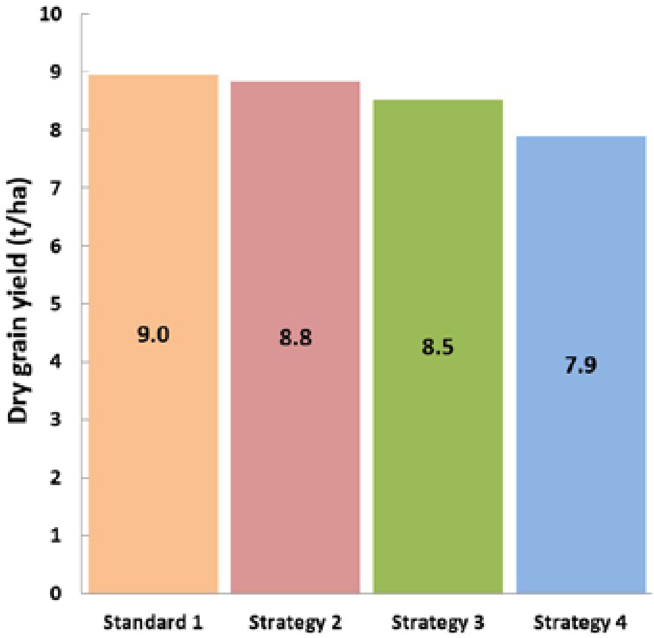

Figure 11 - Maize dry grain yields obtained with the four weed-management strategies in 2018.

weeds surviving in the compacted soil area. Even after two passes with a harrow and one hoeing pass, the weeds were not sufficiently controlled. In Strategy 3, soil conditions for herbicides were favourable and enabled effective weed control in the early season. Late-emerging weeds were controlled with hoeing at the maize 6-leaf growth stage and did not create any significant competition with maize in the early growth period. Our prototype, which was developed for band-spraying and inter-row hoeing, showed some deficiencies. The nozzles were placed in front of the hoes and created problems, with dust deposition on the weed plants reducing the efficacy of just-applied herbicides. A range of weeds, especially perennial ones, such as bindweed, were not sufficiently controlled. In Strategy 4, sole mechanical measures

were implemented. Overall, this strategy was less effective, and substantial dry weed biomass (265 g/ m²) was measured at the beginning of August 2018. Band spraying and inter-row hoeing in Strategy 3 was less effective when compared to standard Strategy 1, mostly because the band sprayer prototype was still under development at the time. A reduced dose of herbicide (50%) in Strategy 2 did not lead to a considerable reduction in weed control when compared with the recommended dose (Figure 10).
Overall, environmental conditions in 2018 were not favourable in this region. Excessive water supply after planting and high temparatures in late summer greatly reduced maize yield potential. Minor yield losses in Strategies 3 and 4 were related to difficult soil conditions and to the timing of mechanical weeding. Consequently, the efficacy of harrowing and hoeing was not at the expected level.
Dry grain yields of maize (Figure 11) were correlated to weed infestation. The highest yield was measured in standard Strategy 1 (9.0 t/ha), followed by 8.8 t/ha and 8.5 t/ha in Strategies 2 and 3, respectively. The lowest yield was in Strategy 4 (7.9 t/ha); in this case, substantially higher weed infestation was observed.

Season 2019

A similar protocol to the previous year was executed at the Rakičan site in 2019. The weather conditions in the previous season prevented full implementation of the originally scheduled mechanical weed-control measures, therefore only minor modifications to the weed-control strategies were made (Table 5).
The trial was planted very early, on 19 April 2019, with variety P 9234. After planting, maize germination was fast and uniform, however cold, rainy conditions afterwards hindered further development of maize substantially. Excessive rain caused difficulties in executing weed-management operations. Due to the wet conditions, the false seedbed planned in Strategies 2, 3 and 4 was not performed, while stale seedbed treatment (with tine harrow) was executed in unfavourable conditions four days after planting within Strategy 2.

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	CON	HER_red	HER_row	MECH
Tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
Herbicides	YES	YES	YES	NO
Rate	recommended broadcast *	reduced (50 %) broadcast *	recommended in the row (30 cm) **	/
Application time	early post	early post	early post	/
Growth stage	BBCH 13	BBCH 13	BBCH 13	/
Mechanical weeding	NO	interrow cultivator BBCH 15	interrow cultivator BBCH 12 BBCH 13 *** BBCH 15	harrowing BBCH 03 BBCH 12 BBCH 13 interrow cultivator BBCH 15

* isoxaflutole 99 g/ha + thiencarbazone-methyl 40 g/ha + cyprosulfamide safener 66 g/ha
** recommended dose was applied in the 30 cm band along the row combined with hoeing (40 % of dose in the whole area).
*** mechanical weeding combined with herbicide spraying

Table 5 - Description of the strategies in the maize field trial at BSR Rakičan in 2019.

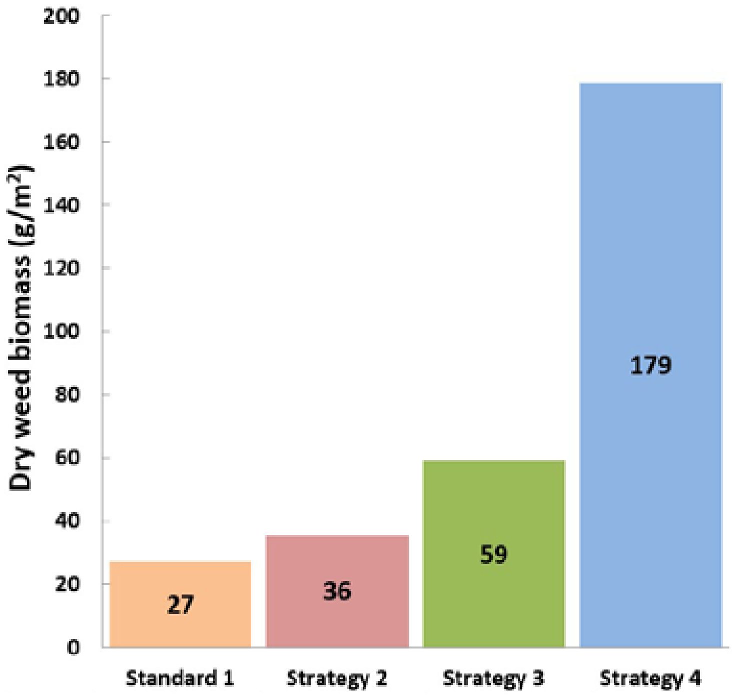

Figure 12 - Weed dry biomass determined in maize at the end of September 2019.

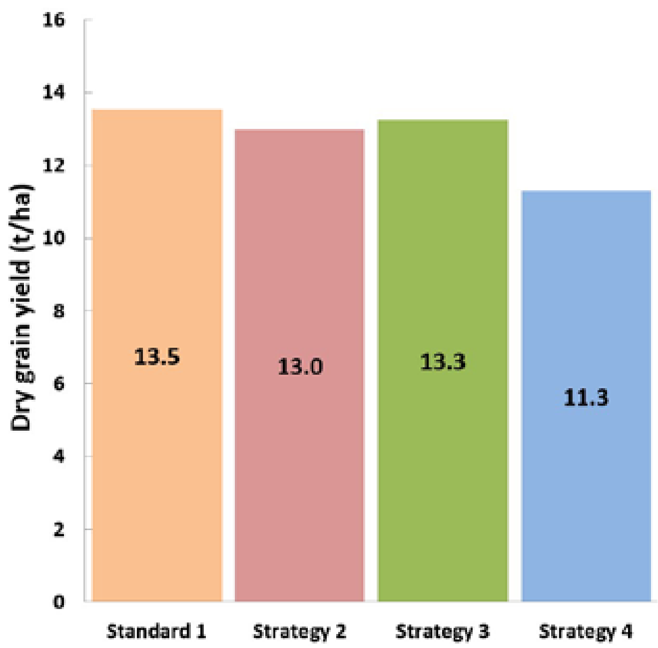

Figure 13 - Maize dry grain yields obtained with the four weed-management strategies in 2019.

Herbicide applications were performed in optimal soil conditions in the 2-leaf growth stage of maize. In Strategy 1, the recommended dose was used, while in Strategy 2 a reduced dose of herbicide was applied. For Strategy 3, a prototype for band spraying and inter-row cultivation was developed in which the recommended herbicide dose was applied along the maize rows. Herbicide application in Strategies 2 and 3 was followed by hoeing at the 5-leaf maize growth stage. Mechanical weed control only was implemented in Strategy 4, during which three passes with a tine harrow and one hoeing pass at the 5-leaf maize growth stage were performed. Results of weed biomass assessment before maize

Strategy	Standard 1	Strategy 2	Strategy 3	Strategy 4
Label	CON	HER_red	HER_row	MECH
Tillage	autumn ploughing	autumn ploughing	autumn ploughing	autumn ploughing
Herbicides	YES	YES	YES	NO
Rate	recommended broadcast *	reduced (50 %) broadcast *	recommended in the row (30 cm) **	/
Application time	early post	early post	early post	/
Growth stage	BBCH 12	BBCH 12	BBCH 12	/
Mechanical weeding	interrow cultivator BBCH 16	interrow cultivator BBCH 16	interrow cultivator BBCH 12 *** BBCH 16	harrowing BBCH 03 BBCH 12 BBCH 14; interrow cultivator BBCH 16

* isoxaflutole 99 g/ha + thiencarbazone-methyl 40 g/ha + cyprosulfamide safener 66 g/ha
** recommended dose was applied in the 30 cm band along the row combined with hoeing (40 % of dose in the whole area).
*** mechanical weeding combined with herbicide spraying

Table 6 - Description of the strategies in the maize field trial at BSR Rakičan in 2020.

harvest in Strategies 1 and 2 showed that both performed very efficiently, with 27 and 36 g/m^2 of dry weed biomass respectively. In Strategy 3 with band application of herbicide followed by hoeing, 59 g/m^2 of biomass was measured, while in Strategy 4 with mechanical weed control only, 179 g/m^2 of dry weed biomass was determined (Figure 12).
The highest yield (Figure 13) was measured in standard Strategy 1 (13.5 t/ha), followed by 13.0 t/ha and 13.3 t/ha in Strategies 2 and 3 respectively. The lowest yield was in Strategy 4 (11.3 t/ha), in which substantially higher weed infestation was observed when compared to the other strategies.

Season 2020

In 2020, a similar protocol as the previous year was executed at the Rakičan site. Only minor modifications to the planned weed-control strategies were made in this experimental season, mostly by adapting the weed-management measures to the weather and field conditions (Table 6).

The trial was sown very early, on 15 April 2020, with variety P 9234. Herbicide applications were performed in optimal soil conditions in the 2-leaf growth stage of maize. In Strategy 1, the recommended dose was used, while in Strategy 2 a reduced dose of herbicide was applied. In Strategy 3, a prototype for band-spraying and inter-row cultivation was used, and the recommended herbicide dose was sprayed along the maize rows. Hoeing was performed in Strategies 1, 2 and 3 at the 6-leaf growth stage of maize. In the sole mechanical Strategy 4, intensive mechanical weeding consisted of three passes with a tine harrow and one operation with inter-row cultivator.
Weed biomass assessment data before maize harvest in Strategies 1 and 2 showed that both strategies performed very efficiently, resulting in 7 g/m^2 and 9 g/m^2 of dry weed biomass respectively. In Strategy 3, 89 g/m^2 of weed biomass was observed, while in Strategy 4, 144 g/m^2 of dry weed biomass was determined at the end of September (Figure 16).

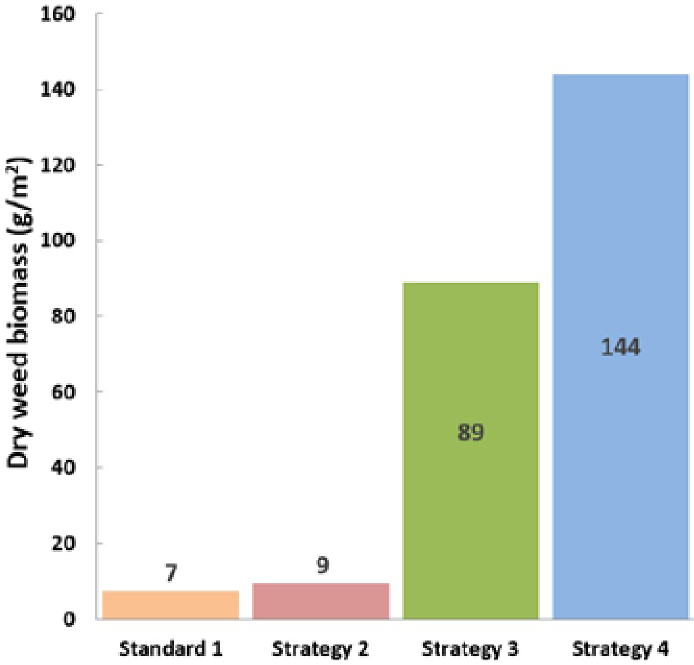

Figure 14 - Weed dry biomass determined in maize at the end of September 2020.

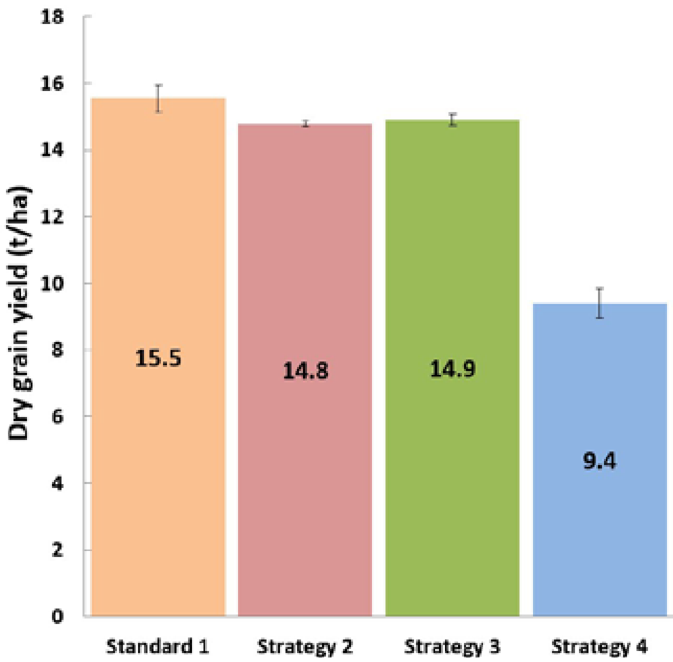

Figure 15 - Maize dry grain yields obtained with the four weed-management strategies in 2020 (vertical bars represent standard errors).

The results in 2020 are in line with the previous season outcomes, when it was shown that reduced doses of herbicides supplemented with hoeing had only a minor negative impact on maize yield. The highest maize dry grain yield was measured in standard Strategy 1 (15.5 t/ha), followed by 14.8 t/ha and 14.9 t/ha in Strategies 2 and 3 respectively.

Since season 2020 was extremely humid, with a strong weed competitive effect and unfavorable conditions for mechanical weeding, Strategy 4 with sole mechanical weed control had a significant yield loss (-6.1 t/ha) when compared to the best-yielding standard treatment (Figure 17).

Due to restrictions during the COVID-19 pandemic,

Figures 16 and 17 - Tine harrow (left) and inter-row cultivator (right) were used for mechanical weed control.

the results of the IWMPRAISE trial experiment were presented by open-air lecture and an additional guided experiment tour at the Maize Field Day in Rakičan. The number of visitors was similar to previous years, with about 50 attendees (mostly farmers and consultants) observing the results of the tested weed-control strategies (Figures 18, 19, 20 and 21).

Figures 18, 19, 20 and 21 - Images from the 2020 Maize field day in Rakičan.

General conclusions

Climatic conditions and soil type in northeastern Slovenia allow more intensive mechanical weed control. The three-year results of field testing suggest that the strategy with reduced herbicide application supplemented by hoeing was comparable with the standard strategy in terms of efficacy and maize grain production. Although minor yield loss was observed in certain years, this was probably the result of plant stand loss and can be prevented in the future. When compared to the standard practice, this strategy delivers a 50% reduction in herbicide consumption, with only one mechanical hoeing operation used.
The weed biomass and yield results of the strategy with band herbicide application and mechanical weed control suggest that maize can withstand weed competition to a considerable extent. Despite a significant amount of weed biomass being observed in this strategy, maize yield was not compromised. This strategy could be further improved as BSR had built its own prototype for band-spraying, which was still being tested during the field experimentation.
In the strategy with solely mechanical weeding, the level of weed control achieved was not satisfactory and, in particular seasons, yield losses greater than 6 t/ha of dry grain maize were observed. This result suggests that a more targeted approach is needed to prevent weed proliferation, but with further development it can be used in organic maize production, as well.
Farmers were very much interested in the outcomes of the trials, as we were regularly presenting the results to researchers, experts and farming communities. The next step will include encouraging farmers to perform strategies in their fields, as farmer-to-farmer experience exchange is the most efficient way to transfer the results into practice.

SWITZERLAND

EXPERIMENTAL TRIALS MANAGED BY AGROSOPE AND GFF

Agroscope is the Swiss centre of excellence for agricultural research and is affiliated with the country's Federal Office for Agriculture (FOAG). Agroscope makes an important contribution to sustainable agriculture and the food sector, as well as to maintaining the environment, thereby contributing to an improved quality of life. Agroscope engages in research along the entire value chain of the agriculture and food sector. Its goals are to uphold a competitive and multifunctional agricultural sector, high-quality food for a healthy diet, and good environmental standards.
As grasslands account for about 75% of Switzerland's agriculturally utilized area, they are of outstanding importance for the Swiss agricultural sector and the environment. Agroscope's Grassland Systems and Forage Production research group focuses on agricultural ecology and grassland management, covering both the conventional and organic sectors. The group's mission is to contribute to the development of site-adapted, sustainable and multifunctional grassland production systems for a wide range of management intensities and site conditions, from highly productive sites in the lowlands to marginal sites in the Alps.

The Swiss Grassland Society (Arbeitsgemeinschaft zur Förderung des Futterbaues AGFF) is governed by a joint body of farmers, advisors, and representatives of industry partners, associations and agricultural research institutes. Its main activity consists of establishing close ties between all interested partners to achieve high quality forage and sustainable, site adapted management of grassland. This setting facilitates the rapid and effective exchange of ideas and research results between practitioners and researchers.
AGFF is a nationally recognized organization for all technical aspects of grasslands and grassland production systems. AGFF grassland management tools and fact sheets are widely disseminated, being used by advisory services and all Swiss agricultural schools for the training of future farmers.

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MANAGEMENT OF *RUMEX OBTUSIFOLIUS* IN PERENNIAL GRASSLANDS

Rumex obtusifolius L. (broad-leaved dock) is one of the most problematic weeds in intensively managed permanent grasslands in Europe (Grossrieder and Keary 2004) and is considered to be a major obstacle for conversion to organic farming in Switzerland. There is thus a need to develop effective non-chemical control measures against *R. obtusifolius*. Augmentative biological control offers a potentially effective, but largely unexplored opportunity to control native weeds with native phytophagous insects. Two native European clearwing moths (Lepidoptera; Sesiidae), the central and southern European species *Pyropteron chrysidiforme* (Esper), and the Mediterranean species *Pyropteron doryliforme* (Ochsenheimer) have been proposed as candidates for augmentative biological control of *R. obtusifolius* (Grossrieder and Keary 2004) because their root-boring larvae can promote degradation of the plant's storage organ (Scott and Sagliocco 1991a, Scott and Sagliocco 1991b).
Rumex obtusifolius is characterised by a high seed production of up to 60,000 seeds per plant and year, with seeds remaining viable in the soil for up to 40 years (Cavers and Harper 1964); an additional characteristic is that its deep taproots allow the species to compete efficiently for resources with the valuable grasses and forbs in permanent grasslands. Measures to prevent the further spread of *R. obtusifolius* and the building-up of high-density populations in permanent grasslands are therefore essential. To this aim, we performed an on-farm study across three countries with different pedo-climatic conditions to identify management practices and environmental factors that prevent the infestation of permanent grasslands with *R. obtusifolius*. The design of the study followed a case-control study, as previously used for *Senecio jacobaea* (Suter et al. 2007) and *Senecio aquaticus* (Suter and Lüscher, 2008).

ASSESSING THE POTENTIAL OF APPLYING MULTIPLE BIOLOGICAL CONTROL AGENTS FOR THE MANAGEMENT OF *RUMEX OBTUSIFOLIUS*

Objectives
In a previous field study, only moderate impact by *P. chrysidiforme* on the performance of *R. obtusifolius* was observed. However, only low numbers of larvae were recovered per plant in this study, despite a high number of eggs being applied (Hahn et al. 2016), raising the possibility of intraspecific competition between *P. chrysidiforme* larvae. Provided that interspecific competition between the two *Pyropteron* species is less pronounced than intraspecific competition, a joint application of the two species might lead to increased herbivore load and impact on *Rumex* plants.

Material and methods
In order to test this hypothesis, a 'behavioural experiment' was set up in 2018 in which larvae of the two congeneric *Pyropteron* species (*P. chrysidiforme* and *P. doryliforme*) were subjected to intraspecific, interspecific and no competition in Petri dishes containing root pieces of either *R. obtusifolius* or *Rumex pulcher*. Larval survival was assessed at different points in time. Additionally, to compare the infestation and impact potential of *P. chrysidiforme* and *P. doryliforme* on *R. obtusifolius* and *R. pulcher*, eggs of the *Pyropteron* species were applied on potted plants in a common garden experiment ('infestation & impact experiment'), with the treatments 'single species application' (one herbivore species applied) and 'mixed application' (both herbivore species applied). The number of eggs applied was standardised, with 30 eggs transferred in the single species application and 15 eggs of each *Pyropteron* species in the mixed application. The experiment was set up in 2018 and completed by the end of 2019. Two harvest seasons were evaluated. For further details regarding the material and methods of the two experiments, please refer to IWMPRAISE booklets year 2018 and year 2019.

Results
The behavioural experiment revealed that larval survival probability was significantly reduced when larvae were subjected to competition, and that the reduction was comparable under intra- and interspecific competition. Across assessment times and *Rumex* species, average larval survival was 0.76, 0.44 and 0.46 for the no-competition treatment, intraspecific and interspecific competition treatments, respectively. Survival probability decreased with time for all treatments. Similarly, the results of the infestation & impact experiment revealed that single species and mixed species applications only marginally differed for the number of larvae retrieved (Table 1), with this outcome being independent of harvest season. These results indicate that the joint application of the two *Pyropteron* species does not result in increased herbivore load on *Rumex* plants.
Yet, the proportion of root decay in both *Rumex* species increased under *Pyropteron* application (*R. obtusifolius*: on average 22% in the *Pyropteron*

Rumex plants	*Pyropteron* treatment	Total number of larvae per plant		Proportion of root decay	
		Mean	SE	Mean	SE
Rumex obtusifolius	Control	0	0	0,07	0,01
	Pch	3,87	0,44	0,2	0,02
	Pdo	2,95	0,4	0,19	0,02
	Pch-Pdo mixed	4,45	0,46	0,27	0,04
Rumex pulcher	Control	0	0	0,06	0,01
	Pch	1,82	0,38	0,37	0,06
	Pdo	1,67	0,33	0,24	0,05
	Pch-Pdo mixed	1,87	0,3	0,27	0.05

Table 1 - Total number of larvae retrieved from infested plants and proportion of root decay on two *Rumex* plants (*R. obtusifolius* and *R. pulcher*) as affected by different *Pyropteron* treatments (control treatment [Control], *P. chrysidiforme* application [Pch], *P. doryliforme* application [Pdo], mixed application [Pch-Pdo mixed]) in the infestation & impact experiment. SE = Standard Error.

treatments versus 7% in the control; *R. pulcher*: 29% in the *Pyropteron* treatments versus 6% in the control; Table 1), suggesting that increased herbivore load does indeed lead to increased impact on the host plant.

Summary

Rather than applying many eggs of two *Pyropteron* species at the same time, other ways should be considered to increase larval establishment rate and impact. A possible alternative may be repeated application of low numbers of *Pyropteron* eggs on *Rumex* plants, which may reduce larval interference, particularly during the first days after larval hatching. Another alternative may be the use of multiple agents using different feeding niches to increase the top-down effects of herbivores on the target plant, thus possibly reducing competition among the agents.

FIELD EXPERIMENT ON THE IMPACT OF TWO SESIID BIOLOGICAL CONTROL CANDIDATES ON *RUMEX OBTUSIFOLIUS* UNDER COMPETITIVE STRESS

Objectives

As noted, in a previous study the impact of the clearwing moth *P. chrysidiforme* was insufficient to significantly reduce the performance of established *R. obtusifolius* plants in permanent grasslands (Hahn et al. 2016). The effect of herbivory can possibly be enhanced by interspecific plant competition, and a potential competitor of *R. obtusifolius* is *Lolium perenne* L., a perennial ryegrass (Keary and Hatcher 2004, Niggli et al. 1993). In this experiment, we assessed the interactive effects of herbivory by *P. chrysidiforme* and competition with *L. perenne* on *R. obtusifolius* plants differing in initial size.

Material and methods

In June 2019, field-collected roots of *R. obtusifolius* (432 roots in total) were planted on grassland near Zürich, Switzerland, in plots with either pure swards of *L. perenne* or with bare soil (16 plots in total: dimension 1.8 m × 5 m). The *Rumex* roots were weighed after cutting them at 15 cm length and assigned to size categories. Results are presented here for two groups of initially small and large plants (106 plants in total). The average fresh mass of transplanted small and large roots was 2.9 g (SE ±0.20 g) and 57.5 g (SE ±5.19 g), respectively. On each plot, one third of the roots from each size class was inoculated with eggs of the biological control candidate *P. chrysidiforme*; one third of the roots from each size class with eggs of the biological control candidate *P. doryliforme*; and the remaining third served as the control with no application (split-plot design). Aboveground biomass of *Rumex* plants was harvested three times in autumn 2019 and twice in spring 2020, dried to a constant weight, and summed over harvests to obtain the cumulative aboveground biomass. Roots were excavated in May 2020, washed free of soil, and weighed. Data were analysed with generalised linear mixed-effects models (GLMMs) using a log link function. Explanatory factors were competition from *L. perenne* (2 levels), application of *P. chrysidiforme* (2 levels), and initial root mass of *R. obtusifolius* (2 levels), including all interactions. The split-plot structure was accounted for by a random intercept

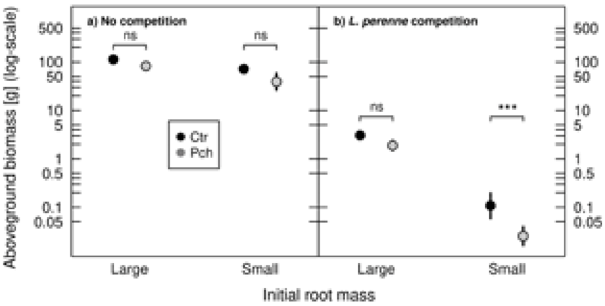

Figure 1 - Aboveground biomass of *R. obtusifolius* plants grown under no competition (a) and competition from a *L. perenne* sward (b), depending on the initial root mass and *Pyropteron* treatments (no application [Ctr], *P. chrysidiforme* [Pch]). Displayed are means ± standard error. Non-visible standard errors are due to small values. The statistical inference is based on a GLMM. *** P < 0.001, ns: not significant.

per plot (analyses performed with software R, version 4.1.1 (R Core Team 2021)). For further details about material and methods of the field experiment, please refer to IWMPRAISE booklet year 2020.

Results

The results presented here only include application of *P. chrysidiforme*. Results obtained for *P. doryliforme* were comparable, with a trend showing that *P. chrysidiforme* had a higher impact on *R. obtusifolius* than *P. doryliforme* (results not shown). The aboveground biomass of all *R. obtusifolius* plants was significantly reduced by competition from *L. perenne*. Yet, plants from initially small roots were more suppressed by competition than plants grown from large roots. While there was no effect of *P. chrysidiforme* application when *R. obtusifolius* plants grew without competition, *P. chrysidiforme* significantly reduced the aboveground biomass of initially small roots under competition from the *L. perenne* sward (compare contrasts in Figure 1). Similar to aboveground biomass, final root mass of all *R. obtusifolius* plants was negatively affected by competition from *L. perenne*, and the competition effect was stronger for initially small roots. Furthermore, final root mass of initially small roots was significantly impacted by the application of *P. chrysidiforme* (Figure 2), but only under competition from the *L. perenne* sward (compare contrasts in Figure 3).

Figure 2 - Degraded root of *R. obtusifolius* plant of initially small size, with *P. chrysidiforme* larva in it.

Summary

Our findings provide evidence that interspecific plant competition and herbivory cause an interactive impact on the growth of *R. obtusifolius*. Overall, competition from the grass sward strongly reduced aboveground biomass and root mass of *R. obtusifolius*. The herbivory effect, although generally weaker than the competition effect, further suppressed initially small roots, but not the larger roots when subjected to competition from *L. perenne*. Our results indicate that joint effects between augmentative biological control and plant competition can reduce the growth of a major grassland weed. Combining augmentative biological control and plant competition can thus increase the impact on *R. obtusifolius* above that imposed by the individual treatments. Such combined effects should therefore more often be explored in integrated weed management.

PREVENTION: *RUMEX OBTUSIFOLIUS* CASE-CONTROL SURVEY

Objectives

This on-farm study aimed to identify management practices that reduce the risk of *R. obtusifolius* infestations on permanent grasslands across three countries: Great Britain, Slovenia and Switzerland. The study adopted a case-control design used in Suter et al. (2007) and Suter and Lüscher (2008) by comparing parcels with high densities of *R. obtusifolius* with nearby parcels free of, or with

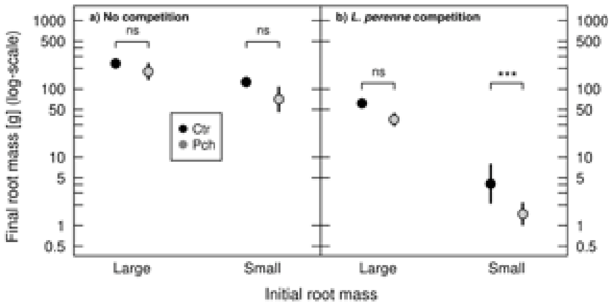

Figure 3 - Final root mass of R. obtusifolius plants grown under no competition (a) and competition from a *L. perenne* sward (b), depending on the initial root mass and *Pyropteron* treatments (no application [Ctr], *P. chrysidiforme* [Pch]). Displayed are means ± standard error. Non-visible standard errors are due to small values. The statistical inference is based on a GLMM. *** P < 0.001, ns: not significant.

very low densities of *Rumex* plants. Thus, the pedo-climatic conditions of these pairs of parcels are very similar, but their management can differ substantially.

Material and methods

The sampling occurred on 40 farms in Switzerland, 20 farms in Slovenia, and 18 farms in Great Britain; data from a pair of parcels (case/control) was recorded at each farm. Contacts with farmers managing parcels with occurence of high *Rumex* densities were established with support from agricultural advisory services.

On each parcel, the sampling was performed on two sub-plots of 3 m × 3 m and included a vegetation census (species list, percentage of functional groups and of the three most abundant species), records of vegetation cover (0.1–5 cm) and of plant basis covering the soil surface (point-intercept method), as well as the collection of soil samples for assessing physical and chemical soil properties and the soil seedbank of *R. obtusifolius*. For further details about the material and methods of the case-control survey, please refer to IWMPRAISE booklet year 2020.

To assess the soil seedbank of *R. obtusifolius*, a germination experiment was performed with the Swiss and the Slovenian samples at Agroscope, Zürich, according to methods described in the previous IWMPRAISE booklet 2020. A similar germination experiment with the British samples was conducted at Rothamsted in winter 2020, using a common protocol.

Face-to-face interviews took place in 2020/2021 with farmers managing the parcels in Slovenia, Switzerland and Great Britain. Farmers were asked about management practices and the history of the parcels. Variables taken into account in the final analyses were, amongst others, number and type of defoliation events (mowing, grazing), grazing intensity, amount and type of fertilizer, type of disturbances, oversowing, renovation, type of regulation, and type of herbicides applied.

Multiple logistic regression was used to estimate the relative risk for the occurrence of high densities of *R. obtusifolius* in grasslands of the three countries, the response variable being the presence (case) or absence (control) of *R. obtusifolius*. Predictor variables were the physical and chemical soil properties and the management variables received from the farmer interviews. A further analysis was performed for the determination of indicator species occurring in plots with or without *R. obtusifolius* per country by calculating the Ind-Val (Indicator value of species) following Dufrêne and Legendre (1997).

Results

The number of germinated seeds of *R. obtusifolius* in case parcels was on average 866 ±152 (SE), 628 ±183 and 752 ±183 per m^2 in Switzerland, Slovenia and Great Britain, respectively. Yet, the numbers of germinated seeds of *R. obtusifolius* varied greatly among case parcels. The number of germinated *R. obtusifolius* seeds in control parcels was 51 ±18 (SE), 75 ±52 and 98 ±52, per m^2 in Switzerland, Slovenia and Great Britain, respectively. Overall, comparable number of viable seeds of *R. obtusifolius* in highly infested parcels (cases) and similar differences in seedbanks between case and control parcels were observed in Switzerland, Slovenia and Great Britain, despite substantially different pedo-climatic conditions.

Across all three countries, increased vegetation cover reduced the risk of high *R. obtusifolius* abundances (Figure 4), while high land use intensity (in terms of number of defoliations and applied nitrogen fertilizers) and high phosphorus content in the soil raised the risk. Furthermore, in Switzerland grazed parcels had an increased risk for the occurrence of *Rumex* plants as compared to mown parcels. The latter can be explained by sward damage by grazing livestock that allows recruitment of *Rumex* plants from the (large) soil seedbank in the case parcels.

Across countries, indicator species for the group of plots with *R. obtusifolius* were typical species of disturbed areas, such as *Plantago major*. For the group of plots without *R. obtusifolius*, species characteristic of medium productive meadows were identified, including *Anthoxantum odoratum*, *Festuca rubra* and *Festuca arundinacea*.

Summary

Overall, the results of the case-control study indicate that (very) high management intensities, manifested by a high availability of nitrogen and phosphorus and a large number of defoliations, increase the risk of high infestation with *R. obtusifolius*.

Overall summary

Successful management of the weed *R. obtusifolius* in permanent grasslands can be increased by considering the two aspects of integrated weed management studied here: control and prevention. Augmentative biological control with native root-boring *Pyropteron* larvae offers great potential for controlling *Rumex* plants in permanent grasslands, as the use of this approach is compatible with grasslands management practices and is less labour-intensive than manual up-rooting. Our study showed reduction in aboveground and belowground biomass, as well as an increase of root decay with *Pyropteron* application. Reduction in biomass and increase in root decay were emphasised by interspecific plant competition and on small initial *Rumex* plants. Even when both plant performance variables did not lead to mortality of the *Rumex* plants, they significantly decreased the vigour of the weed.

The case-control study highlighted factors that are important for practitioners because they increase the risk of occurrence of high densities of *R. obtusifolius*: high management intensity parameters increase the risk of high infestation of *Rumex*, with vegetation cover decreasing it. The seed germination experiment highlighted the high seedbanks in parcels with high *Rumex* infestations. Prevention of new inputs of *Rumex* seeds and the maintenance of dense vegetation cover are therefore important prevention measures for managing *R. obtusifolius* in grasslands.

Figure 4 - Example of sampling plot in a case parcel with high *R. obtusifolius* density and low vegetation cover.

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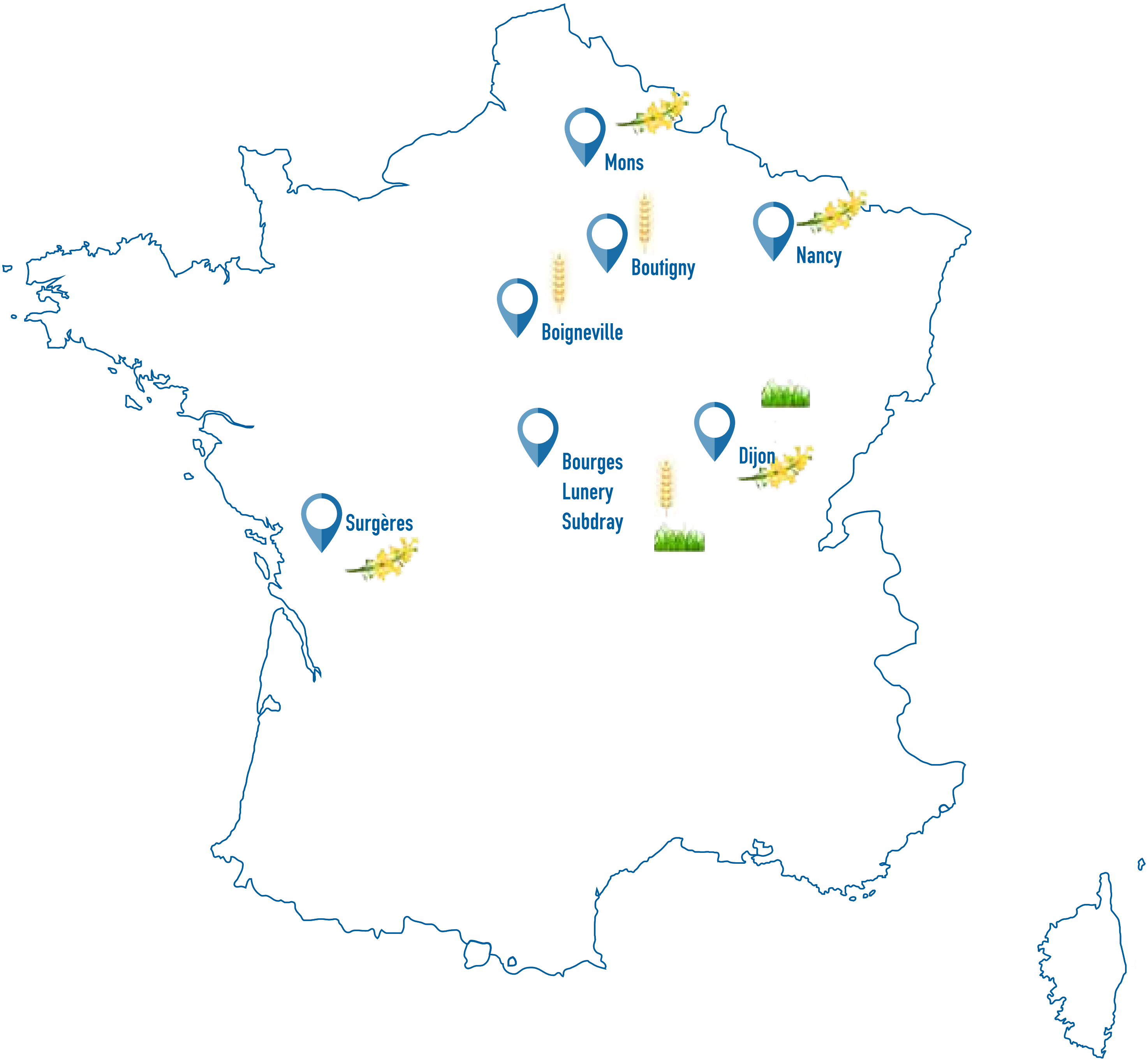
FRANCE WP3


Mons
Boutigny
Nancy
Boigneville
Bourges
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Subdray
Dijon
Surgères

WP3 – EXPERIMENTAL TRIALS IN ANNUALLY DRILLED CROPS IN NARROW ROWS

The 2019-2020 campaign was disturbed due to the Covid crisis and only six trials were completed: three on oilseed rape and three on cereals. The 2020-2021 campaign was no longer dedicated to the acquisition of references, but to the valorisation of the acquired data. There were a few demonstrations, mainly for visitors, but no data acquisition trials for the project.

EXPERIMENTATION ON OILSEED RAPE

All trials were conducted by the partner Terres Inovia over two seasons.

2019/2020 SEASON

Three trials were set up on oilseed rape (OSR) to acquire references on broadleaved weed control with a new herbicide applied post-emergence (MOZZAR – picloram 48 g/l + halauxifen 10g/l at 0.25 l/ha) and on mechanical weed control (tine harrowing).
Strategies in oilseed rape are traditionally based on pre-emergence herbicides. To decrease the use of herbicides, strategies based solely on post-emergence herbicides are preferable, as they can be applied after observations to choose the best programme. It is also possible to combine herbicides with mechanical weed control (e.g. tine harrowing) to improve efficacy. Trials were designed to include tine harrowing on half the area. The following table describes the trial sites and application dates.

Trial	Soil type	Oilseed rape seeding	Row spacing	Tine harrowing pre-emergence	Tine harrowing 4 to 6 leaves	Tine harrowing late (around 1 November)	Weeds
Nancy (Lorraine)	silty clay	22/08	45 cm	27/08	25/09	too wet	*Veronica hederifolia*
Mons (Picardy)	silty clay	27/08	45 cm	30/08	03/10	too wet	*Galium aparine, Matricaria inodora*
Surgères (Charente)	sandy clay	22/08	17.5 cm	26/08	28/10	06/12	*Geranium sp. & Galium aparine*

Table 1 - Trial sites and application conditions.

	Strategy code	Modalities			Cost (€/ha)	TFI*
		pre-emergence	4 to 6 leaves of OSR (around 1 october)	around 1 november		
1	Standard herbicide 1	-	Mozzar @ 0.25 L/ha	-	45	0.5
2	Standard herbicide 2	-	-	Mozzar @ 0.25 L/ha	45	0.5
3	Mixed strategy 1	-	harrow	Mozzar @ 0.25 L/ha	45	0.5
4	Mixed strategy 2	harrow	harrow	Mozzar @ 0.25 L/ha	45	0.5
5	Mechanical weed control 1	-	harrow	-	≈15	0
6	Mechanical weed control 2	harrow	harrow	-	≈30	0
7	Mechanical weed control 3	harrow	harrow	harrow	≈45	0

Mozzar : picloram 48 g/l + halauxifen-méthyl 10 g/l
* TFI = ratio used dose/legal dose

Table 2 - Common protocol of the three trials on oilseed rape. The design of the field trial was adapted to common mechanical strategies, due to the width of the tine harrowing.

	Veronica hederifolia Average of 3 blocks		
	12/12/2019 (B10 stage of OSR)	20/02/20 (C2 stage of OSR)	
Strategy code	**Density of weeds (pl/m²)**	**Efficacy (%)**	**Efficacy (%)**
Standard herbicide 1	43.3	90	90
Standard herbicide 2	44.0	90	90
Mixed strategy 1	53.7	90	90
Mixed strategy 2	36.7	91.67	91.67
Mechanical weed control 1	38.3	43.33	43.33
Mechanical weed control 2	60.7	43.33	43.33
Mechanical weed control 3*	47.3	43.33	43.33

*The third pass of the tine harrow was not performed due to wet weather conditions (therefore Strategies "Mechanical 2" and "Mechanical 3" are similar).

Table 3 - Results of Nancy trial.

Figure 1 - Mixed strategy 1 (20/02/2020) in the Nancy trial (Lorraine).

TRIAL 1 – NANCY (LORRAINE)

The trial had a homogeneous infestation of *Veronica hederifolia*. Dry conditions during summer delayed the emergence of this weed, which arrived in mid-September. As a result, the first harrowing operation did not have any impact on weeds, but damaged the OSR crop during emergence (i.e. 26% loss of plants when compared to the control plot). In addition, a small difference in vigour was observed in the mechanical strategies. Crop growth was "disturbed" and therefore appeared a little less vigorous than in the control plot, probably due to the effect of tine harrowing on the remaining plants.
All-mechanical strategies, with 1 or 2 passes (the third could not be performed due to wet conditions in autumn), were at the same level of efficacy, i.e. 43%. As there were no weeds at the time of the first pass

	Galium aparine Average of 3 blocks			
	21/11/19 (B10 stage of OSR)		13/03/20 (D1 stage of OSR)	
Strategy code	**Density of weeds (pl/m²)**	**Efficacy (%)**	**Density of weeds (pl/m²)**	**Efficacy (%)**
Standard herbicide 1	1.33	100	2.33	98.33
Standard herbicide 2	1	50	1.66	98.33
Mixed strategy 1	2.33	66.66	5.66	100
Mixed strategy 2	1.33	83.33	3.66	100
Mechanical weed control 1	1.33	10	4.66	30
Mechanical weed control 2	1.33	0	3.33	40
Mechanical weed control 3*	1	50	4.66	50

*The third pass of the tine harrow was not performed due to wet weather conditions (therefore Strategies "Mechanical 2" and "Mechanical 3" are similar).

Table 4 - Results on *Galium aparine* in Mons trial.

Matricaria inodora Average of 3 blocks				
	21/11/19 (B10 stage of OSR)		13/03/20 (D1 stage of OSR)	
Strategy code	**Density of weeds (pl/m²)**	**Efficacy (%)**	**Density of weeds (pl/m²)**	**Efficacy (%)**
Standard herbicide	2	100	2.5	95
Standard herbicide 2	1.5	75	3.66	95
Mixed strategy 1	2	100	1.66	100
Mixed strategy 2	2	50	4	100
Mechanical weed control 1	2	100	2	40
Mechanical weed control 2	1.5	100	1.5	60
Mechanical weed control 3*	2	100	2	70

*The third passage of the tine harrow was not performed due to wet weather conditions (therefore Strategies "Mechanical 2" and "Mechanical 3" are similar).

Table 5 - Results on *Matricaria inodora* in Mons trial.

(pre-emergence), it can be deduced that it was the second pass (post-emergence at 4-6 leaves of OSR) that was effective.
For chemical and mixed strategies, the levels of efficacy were very good (above 90%). Thus, mixed strategies are equivalent to chemical references. Nevertheless, from this trial on *Veronica hederifolia*, (Table 3) we can conclude that tine harrowing, post-emergence only, or pre-emergence followed by post-emergence provide no or little benefit to the herbicide strategy.

TRIAL 2 – MONS (PICARDY)

The lack of rain led to a heterogeneous emergence of OSR and to weed emergence, as well. Although weed infestation was low, differences in efficacy were observed between strategies. *Galium aparine* (Table 4) and *Matricaria inodora* (Table 5) were present in the trial with less than 5 pl/m². Results must be carefully interpreted.
Mixed and standard strategies showed very good efficacy, especially in late winter. There was a small benefit in the use of tine harrowing when compared to the standard herbicide alone. It is possible to delay the use of herbicide until 1 November because it is as effective as application at 4-6 leaves of OSR in October. Tine harrow use does not seem to facilitate delay because it only led to a few more efficacy points. In the mixed strategies, herbicide application is very important, because mechanical weed control only provides low efficacy. Therefore, all-mechanical strategies are not very useful in these conditions.

TRIAL 3 – SURGÈRES (CHARENTE)

This trial was heavily infested with *Geranium* spp. (Table 6) and *Galium aparine* (Table 7). Both weeds are particularly difficult to control in OSR. Tine harrowing was performed at all periods, as mentioned in the protocol, and was selective to the crop. Nevertheless, the efficacy of tine harrowing was low. This is probably due to the high density of weeds (around 150 pl/m²), especially in the late pass (weeds at 4-6 leaves). The settings of the tine harrow were not too aggressive in order to limit the loss of OSR plants.
Mixed strategies were equivalent to the Standard herbicide strategy 2 (herbicide on 1 November), and better than the herbicide alone at 4-6 leaves (Standard herbicide 1). Nevertheless, tine harrowing did not add any benefit to the herbicide strategy.
The results of delaying chemical application until 1 November were even more interesting than those of the October treatment with 4-6 leaves of OSR.
Mixed strategies proved to be useful and satisfactory,

Figure 2 - Mixed strategy 1 (21/11/2019) in the Mons trial (Picardy).

	Geranium sp. Average of 3 blocks			
	06/12/19	08/11/19	04/03/20 (D1 stage of OSR)	
Strategy code	**Density of weeds (pl/m²)**	**Efficacy (%)**	**Density of weeds (pl/m²)**	**Efficacy (%)**
Standard herbicide	123	50	177	90
Standard herbicide 2	123		177	95
Mixed strategy 1	123	5	177	95
Mixed strategy 2	123	5	177	95
Mechanical weed control 1	123	5	177	5
Mechanical weed control 2	123	5	177	5
Mechanical weed control 3*	123	5	177	5

Table 6 - Results on *Geranium* spp. in Surgères trial.

	Galium aparine Average of 3 blocks			
	06/12/19	08/11/19	04/03/20 (D1 stage of OSR)	
Strategy code	**Density of weeds (pl/m²)**	**Efficacy (%)**	**Density of weeds (pl/m²)**	**Efficacy (%)**
Standard herbicide	18	50	18	80
Standard herbicide 2	18		18	90
Mixed strategy 1	18	5	18	90
Mixed strategy 2	18	5	18	90
Mechanical weed control 1	18	5	18	5
Mechanical weed control 2	18	5	18	5
Mechanical weed control 3*	18	5	18	5

Table 7 - Results on *Galium aparine* in Surgères trial.

with results showing that mechanical weeding alone is not advisable in these situations with high weed densities.

Conclusion

The efficacy of early herbicide application was slightly lower at the Surgères location when compared to the late application, while there was no difference at the Mons and Nancy locations. Adding tine harrowing to herbicide application only increased the efficacy level marginally at the Mons location, and adding a second tine harrowing did not affect efficacy level (Figure 3). Omitting the herbicide application only provided efficacy levels between 30% and 50% at the Mons and Nancy locations, with some increase in the efficacy of the second pass at the Mons location. The efficacy of tine harrowing at the Surgères location was very low, even with three passes (5%).

2020/2021 SEASON

Four demonstration trials were set up in France in 2020/2021, as described in Table 8 below.
As in the previous season, trials in oilseed rape were set up to assess strategies that partially or totally replaced herbicides with mechanical alternatives, or strategies combined with mechanical tools. The three trials had a similar protocol. The details of these trials are presented in the Table 9 below.
Unfortunately, there were no weeds in the Dijon trial and only two trials could be validated. The protocol is described in Table 10 below.

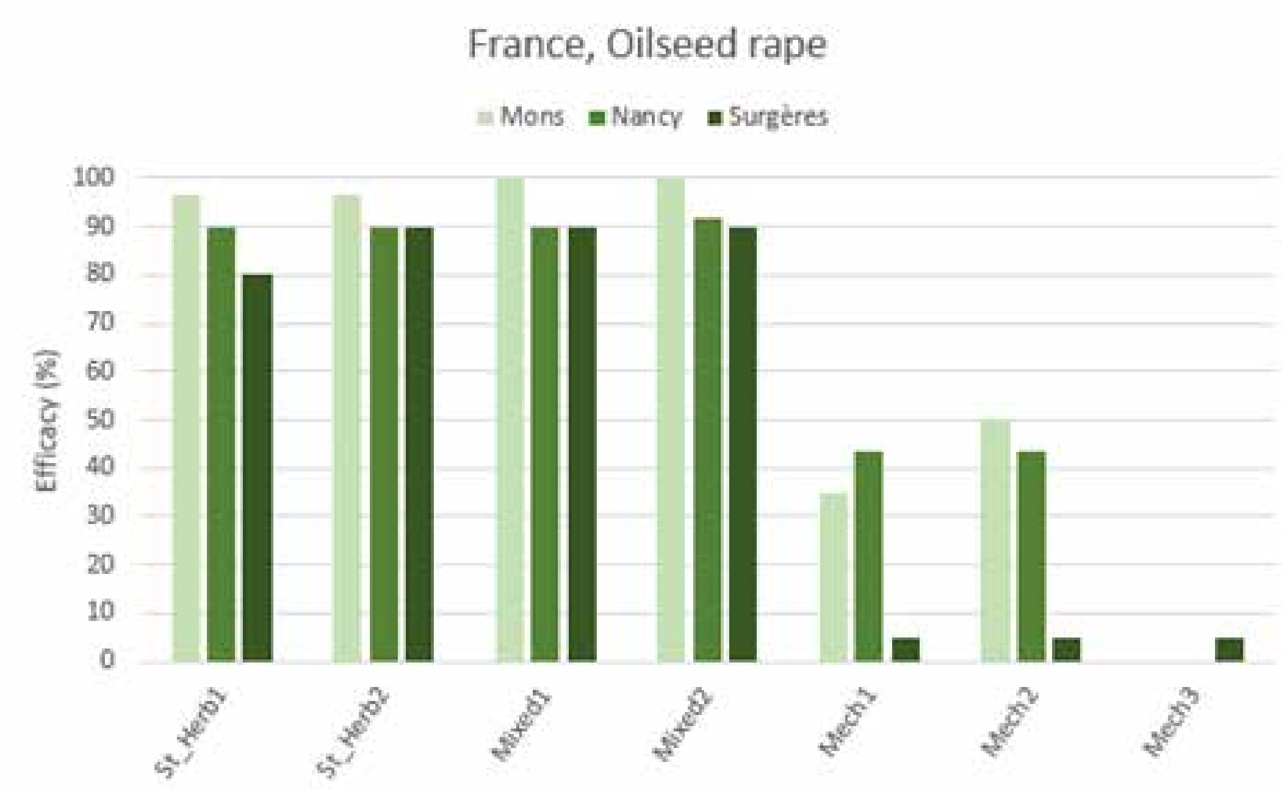

Figure 3 - Efficacy of weed control in oilseed rape at three locations in France with either solely herbicide application, a combination of herbicides and mechanical control, or solely mechanical control.

Trial site	Main objective	Method studied
Nancy (Lorraine)	Optimise mechanical weed control/ strategies in oilseed rape	Mechanical weed control
Surgères (Charente)	Optimise mechanical weed control/ strategies in oilseed rape	Mechanical weed control
Dijon (Burgundy)	Optimise mechanical weed control/ strategies in oilseed rape	Mechanical weed control
Mons (Picardy)	Optimise mechanical weed control/ strategies in oilseed rape	Mechanical weed control, and comparison of tools (precision tine harrow vs "classic" tine harrow)

Table 8 - Trials set in France in 2020/2021.

	Soil type	Sowing date (OSR)	Pre-emergence (tine harrowing)	Tine harrowing in October	Hoeing in October	Weeds
Nancy	superficial clay-limestone	19/08/20	21/08/20	14/10/20 + 22/10/20	14/10/20	*Geranium dissectum*, *Sonchus* sp., *Matricaria* sp.
Surgères	medium clay-limestone	14/08/20	too wet	21/10/20	16/10/20	*Volunteer barley*, *Mercurialis annua*, *Senecio vulgare*, *Veronica persica*
Dijon	deep clay-limestone	28/08/20	too wet	21/10/20	too wet	No weeds

Table 9 - Details of the three trials on oilseed rape.

STRATEGY	Modalities				COST (€/ha)	TFI*
	PRE-EMERGENCE	4 to 6 leaves of OSR	around 1 OCTOBER	around 1 NOVEMBER		
REFERENCE 1	-	-	Mozzar @ 0.25 L/ha	-	45	1
REFERENCE 2	-			Mozzar @ 0.25 L/ha	45	0.5
STRAT 1	-	Tine Harrow		Mozzar @ 0.25 L/ha	45	0.5
STRAT 2	-	Hoeing		Mozzar @ 0.25 L/ha	45	0.5
STRAT 3	Metazachlor 1.2 L/ha	Tine harrow or hoeing		-	26	0.6
MECH 4	Tine harrow	Hoeing		-	0	0

Table 10 - Details of weed-management strategies in Nancy and Surgères.

TRIAL 1 – NANCY (LORRAINE)

The dry conditions at the end of the summer delayed weed emergence, which arrived in mid-September.
As a result, the first pass of the weeder harrow in pre-emergence had no impact on weeds; moreover, it did not damage the rapeseed. Thanks to the favourable conditions in October, two passes of the weeder harrow were carried out. The final weeding efficacies at the end of winter showed that the all-mechanical strategy had a very average efficiency of 43% on the three weeds present.
For the chemical alone and mixed modalities, the levels of efficacy were very good (over 90%) on *Sonchus* and *Matricaria*.
On *Geranium dissectum*, Chemical reference 2 with Late Mozzar was not so stisfactory (65%) due to the development of this weed at the time of treatment, which shows the importance of weeding harrows in October when Mozzar is applied late.
Mixed strategy 3, which combined pre-emergence herbicide then two post-emergence applications, was average (80%) because the conditions were very dry at the time of pre-emergence application; however, we can see that the two-passes strategies worked quite well.
Mixed strategy 1 with two passes of the weeder harrow before the late Mozzar treatment was equivalent to Mixed strategy 2 with one pass of the weeder harrow before the late Mozzar treatment; it was the same for all 3 weeds.
Thus, it is possible to postpone the application of Mozzar to November, provide a half dose only,

	Weeds				*Geranium dissectum*		*Sonchus* sp.		*Matricaria* sp.	
	Observation date				24/02/2021		24/02/2021		24/02/2021	
	Crop stage				C2 -		C2 -		C2 -	
Strategy	**Pre-em**	**4 L of OSR**	**Around 1 Oct.**	**Around 1 Nov.**	**Pl/m²**	**Efficacy (%)**	**Pl/m²**	**Efficacy (%)**	**Pl/m²**	**Efficacy (%)**
REFERENCE 1	-	-	Mozzar 0.25 L/ha 13/10	-	21.5	95.0	7.5	92.5	8.5	95.0
REFERENCE 2	-	-	-	Mozzar 0.25 L/ha 04/11	22.0	65.0	8.5	92.5	6.5	90.0
STRAT 1	-	Tine Harrow 14/10 @ 5-6 l of OSR + Tine harrow 22/10 @ 6 l of OSR		Mozzar 0.25 L/ha 04/11	19.0	93.3	10.7	95.0	6.0	93.3
STRAT 2		Hoeing 14/10 @ 5-6 l of OSR		Mozzar 0.25 L/ha 04/11	21.7	93.3	9.0	93.3	5.7	95.0
STRAT 3	Butisan S 1.2 L/ha	Tine Harrow 14/10 @ 5-6 l of OSR + Tine harrow 22/10 @ 6 l of OSR		-	20.5	80.0	7.5	95.0	5.5	92.5
MECH 4	Tine Harrow	Hoeing 14/10 @ 5-6 l of OSR		-	19.7	43.3	7.7	43.3	6.7	43.3

Table 11 - Results of alternative strategies in Nancy.

especially on *Geranium*, and complete with passes of the weeder harrow or hoe beforehand in October. The mixed strategy with pre-emergence herbicide combined with spring tine harrowing seems less satisfactory (despite being more than 80% effective). Finally, the all-mechanical strategy with weeder harrow in pre-emergence and hoeing is not satisfactory (only 43% efficacy).

TRIAL 2 – SURGÈRES (CHARENTE)

The very quick emergence of the crop did not allow the first pre-emergence harrowing. Subsequently, wet conditions during mechanical weeding did not allow full effectiveness. On *barley volunteers*, Mozzar alone is not at all effective. The weed harrow was only 10% effective (STRAT 1) on this weed; on the other hand, hoeing (STRAT 2) was 77% effective. However, this efficacy seems to be purely random since the MECHANICAL strategy, with hoeing at the same time (MECHA 4), was only 53% efficient. On this flora, the metazachlor strategy in pre-emergence and then tine harrowing (STRAT 3) managed 75% efficacy.
On *Mercurialis annua*, the late Mozzar treatment in November (REF 2) worked well, making mechanical treatments (tine harrowing or hoeing) beforehand in October almost useless. Hoeing alone (MECHA 4) was 73% effective. The pre-emergence herbicide strategy followed by hoeing (STRAT 3) was not satisfactory (30% efficacy).
On *Senecio vulgare*, Mozzar (REF 1 & 2) was insufficient (70% efficacy). The addition of tine harrowing beforehand (STRAT 1) raised the percentage of efficacy, but adding hoeing (STRAT 2) did not, which is a surprising result that needs to be re-evaluated in other trials. Hoeing alone (MECHA 4) gave 77% efficacy. Finally, the pre-emergence herbicide strategy followed by tine harrowing (STRAT 3) gave 77% efficacy on this weed.

TRIAL 3 – MONS (PICARDY)

This trial was different because it was a comparison of alternative strategies with different tools: precision tine harrow vs traditional tine harrow (Table 13). The oilseed rape was sown on 3 September 2020 and mechanical weed control was performed on 4 November 2020. The main weeds were *Galium aparine* and *Matricaria* sp. (Table 14). On both *Galium* and *Matricaria*, we clearly observed the effect

	Weeds				*Geranium dissectum*		*Sonchus* sp.		*Matricaria* sp.	
	Observation date				04/03/2021		04/03/2021		04/03/2021	
	Crop stage				C2 -		C2 -		C2 -	
Strategy	**Pre-em**	**4 l of OSR**	**Around 1 Oct.**	**Around 1 Nov.**	**Pl/m²**	**Efficacy (%)**	**Pl/m²**	**Efficacy (%)**	**Pl/m²**	**Efficacy (%)**
REFERENCE 1	-	-	Mozzar 0.25 L/ha 16/10/20	-	31	0	11	95	4	67
REFERENCE 2	-	-	-	Mozzar 0.25 L/ha 16/11/20	27	0	12	95	3	70
STRAT 1	-	Tine harrowing 21/10 @ 12 l of OSR		Mozzar 0.25 L/ha 16/11/20	28.66	10	9	95	4	90
STRAT 2	-	Hoeing 16/10 @ 12 l of OSR		Mozzar 0.25 L/ha 16/11/20	27	77	8	92	7	70
STRAT 3	Herbicide (Metazachlor 1.2 L/ha)	Tine harrowing 21/10 @ 12 l of OSR		-	21.66	75	8	30	5	77
MECH 4	0	Hoeing 16/10 @ 12 l of OSR		-	23	53	10	73	6	77

Table 12 - Results of Surgères trial.

Figure 4 - Details of the precision tine harrow (Agronomic).

of the herbicide (comparison of pre-emergence vs post-emergence with Mozzar) (REF 1 & 2). The post-emergence application was very effective (this flora is in the herbicide spectrum). Due to the very good performances of the post-emergence application, the effect of mechanical weed control showed no clear benefits (STRAT 1 vs STRAT 1 bis).

In addition to pre-emergence application, it was also hard to distinguish the effect of the tools. Precision tine harrowing seems similar to traditional harrowing.

STRATEGY	PRE-EMERGENCE	Modalities 4 to 6 leaves of OSR	around 1 OCTOBER	around 1 NOVEMBER	COST (€/ha)	TFI*
REF 1	-	-	Mozzar @ 0.25 L/ha	-	45	1
REF 2	-	-		Mozzar @ 0.25 L/ha	45	0.5
STRAT 1	-	Tine harrowing		Mozzar @ 0.25 L/ha	45	0.5
STRAT 1 bis	-	Precision tine harrowing (Agronomic)		Mozzar @ 0.25 L/ha	45	0.5
STRAT 4	Metazachlor 1.2 L/ha	Tine harrowing		-	26	0.6
STRAT 4 bis	Metazachlor 1.2 L/ha	Precision tine harrowing (Agronomic)		-	26	0.6

Table 13 - Details of weed-management strategies and crop stages in the Mons trial for oilseed rape.

	Weeds				*Galium aparine*		*Matricaria* sp.	
	Observation date				19/02/2021		19/02/2021	
	Crop stage				C2		C2	
Strategy	Pre-em	4 l of OSR	Around 1 Oct.	Around 1 Nov.	Pl/m²	Efficacy (%)	Pl/m²	Efficacy (%)
REF 1	-	-	Mozzar 0.25 L/ha 16/10/20	-	11.3	100	14.7	98.3
REF 2	-	-	-	Mozzar 0.25 L/ha on 09/11	12	100	11.7	97.7
STRAT 1	-	Tine harrowing on 04/11, 5-6 l stage, medium to low aggressiveness		Mozzar 0.25 L/ha on 04/11	11.7	96.7	16.3	95
STRAT 1 bis	-	Precision tine harrowing on 04/11, 5-6 l stage, medium aggressiveness		Mozzar 0.25 L/ha on 04/11	11.7	100	14.3	91.7
STRAT 4	Alabama 2.5 L/ha	Tine harrow on 04/11, 5-6 l stage, medium to low aggressiveness		-	15.3	76.7	11.7	86.7
STRAT 4 bis	Alabama 2.5 L/ha	Precision tine harrowing on 04/11, 5-6 l stage, medium aggressiveness		-	13.7	80	16.3	75

Table 14 - Results on *Galium* and *Matricaria* sp. in Mons trial.

EXPERIMENTS ON CEREALS

Trials were mainly conducted by the partner Arvalis, and one trial was set up by the partner Chambre d'Agriculture d'Île-de-France.

2019/2020 SEASON

On cereals, the trials focused on the integration of mechanical weeding (single or multiple passes) into various herbicide programmes. In this season, the trials managed by Arvalis focused on integration of agronomic methods and their effects on weeds, and the reduced use of herbicides in crops.

TRIAL 1 – BOURGES: TINE HARROWING IN WHEAT (PARTNER ARVALIS)

Results from the previous season showed that mechanical weeding could be integrated into the weed control strategy in wheat. This year's trial has been integrated with a tine harrow (a fast, economical tool that meets the needs of large farms). The objective is to combine different herbicide programmes (from "light" use [Herbicide strategies 2 and 4] to "strong" use [Herbicide strategies 1 and 3]) with combinations of weed harrowing (0 to multiple passes), with a first pass in autumn. The situation in the control shows a strong presence of ryegrass

Application/Mechanical weed control	Date	Herbicide strategy	Weeds
Sowing	26/10/2019	CONTROL	Ryegrass (600 to 700/m²)
Pre-emergence application	30/10/2019		
Post-emergence application	19/11/2019		
End of winter/spring application	14/02/2020	1/ PRE-EMERGENCE fb POST-EMERGENCE (DEFI 3L + CODIX 1.5L Pre-em / FOSBURI 0.6L Post-em)	
Mechanical weed control 1 pass	24/02/2020 - Tine harrowing. Settings on "aggressive"	2/ PRE-EMERGENCE alone (DEFI 3L + CODIX 1.5L Pre-em)	
Mechanical weed control 2 passes	24/02/2020 - Tine harrowing (this extra pass was carried out on the "multiple pass" part of the trial, but at a higher speed)	3/ POST-EMERGENCE alone (DEFI 2.5L + FOSBURI 0.5L Post-em)	
Mechanical weed control 3 passes	19/03/2020 - Tine harrowing. Settings on "aggressive", carried out on the "multiple pass" part of the trial	3/ PRE-EMERGENCE fb SPRING (DEFI 2.5L + FOSBURI 0.5L Post-em / AXIAL PRATIC1.2L + Actirob B 1L Spring)	
Mechanical weed control 4 passes	21/03/2020 - Tine harrowing. Settings on "aggressive", carried out on the "multiple pass" part of the trial. This extra pass was decided due to an ineffective previous pass	4/ SPRING alone (AXIAL PRATIC 1.2L + Actirob B 1L Spring)	

Defi: prosulfocarb 800 g/l
Fosburi: flufenacet 200 g/l + diflufenican 400 g/l
Axial Pratic: pinoxaden 50 g/l + cloquintocet 12.5 g/l
Actirob B: esterified rapeseed oil 842 g/l

Table 15 - Strategies studied and characteristics of the trial in Bourges. The design of the field trial was adapted to suit common mechanical strategies, due to the width of the tine harrowing.

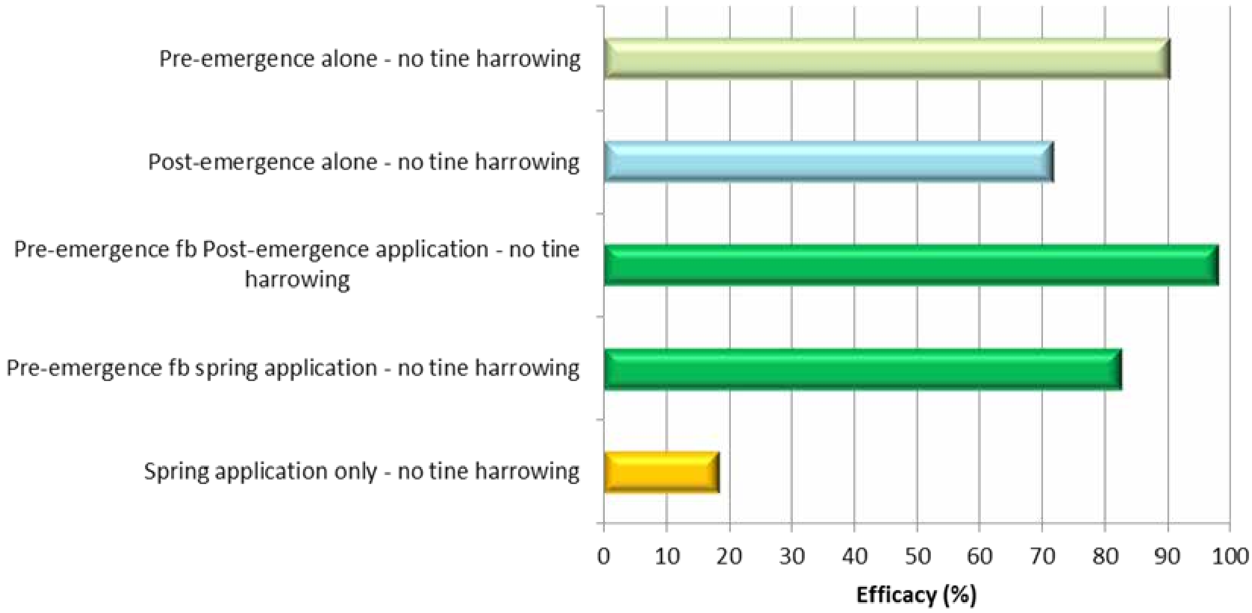

Figure 5 - Strategies without mechanical weed control.

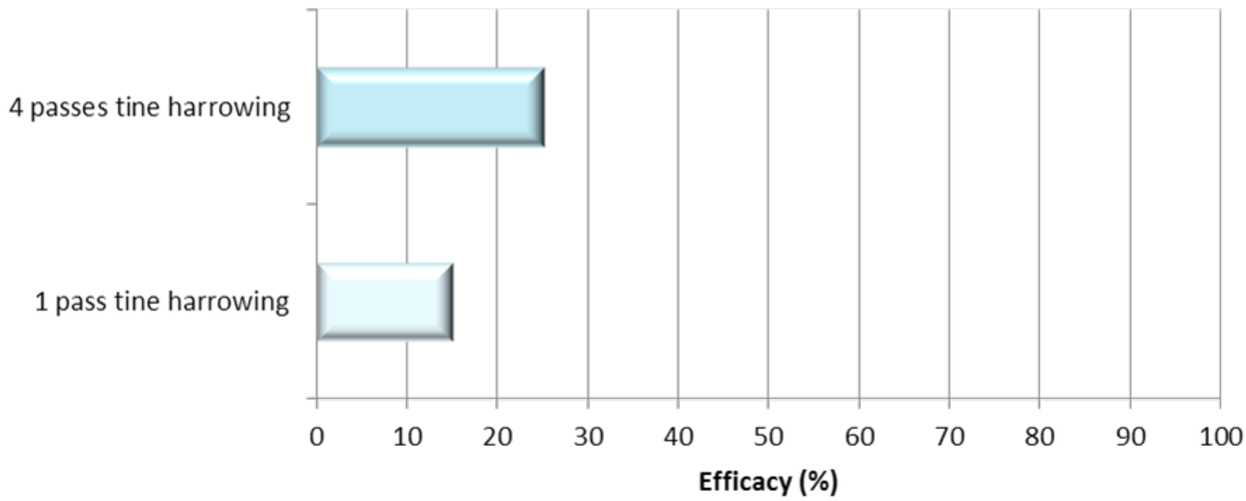

Figure 6 - Comparison of the efficacies of tine harrowing, in one pass or four passes, on ryegrass.

(approximately 700 pl/m²).
Table 15 describes the strategies studied in the trial and dates of application/machinery passes. Unfortunately, it was impossible to perform tine harrowing in autumn due to wet conditions. However, autumn applications on a high ryegrass population with mechanical weeding were clearly superior (Figure 5). Pre-emergence treatment alone was 90% effective, while post-emergence alone was 72%.
On the other hand, the autumn strategy achieved a very good performance with 98% efficacy, followed by spring application, which allowed a gain of 11% compared to post-emergence alone. The resistance status of this population has not been confirmed by tests, but it would appear from these results that these ryegrass weeds are resistant to the HRAC A group of herbicides. Obviously, spring application alone has low efficiency on this kind of population, with only 18% final efficacy.
Mechanical weeding methods alone were ineffective (Figure 6). With only 15% and 25% efficacy, these two methods are at the level of spring application alone, whose low efficacy was probably due to the resistance of ryegrass. We can give a couple of explanations for the failure of the mechanical weeding methods:
- the high population of weeds: historical trials of mechanical weeding have shown that these weeds

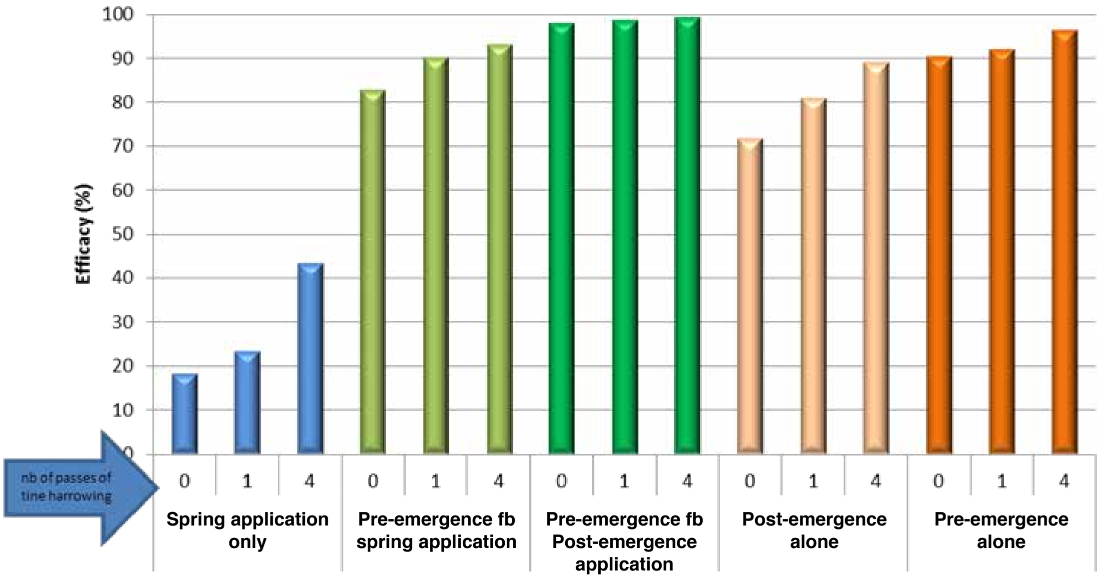

Figure 7 - Comparison of mixed strategies (herbicides + tine harrowing) with one pass or four passes and standard herbicide programmes alone.

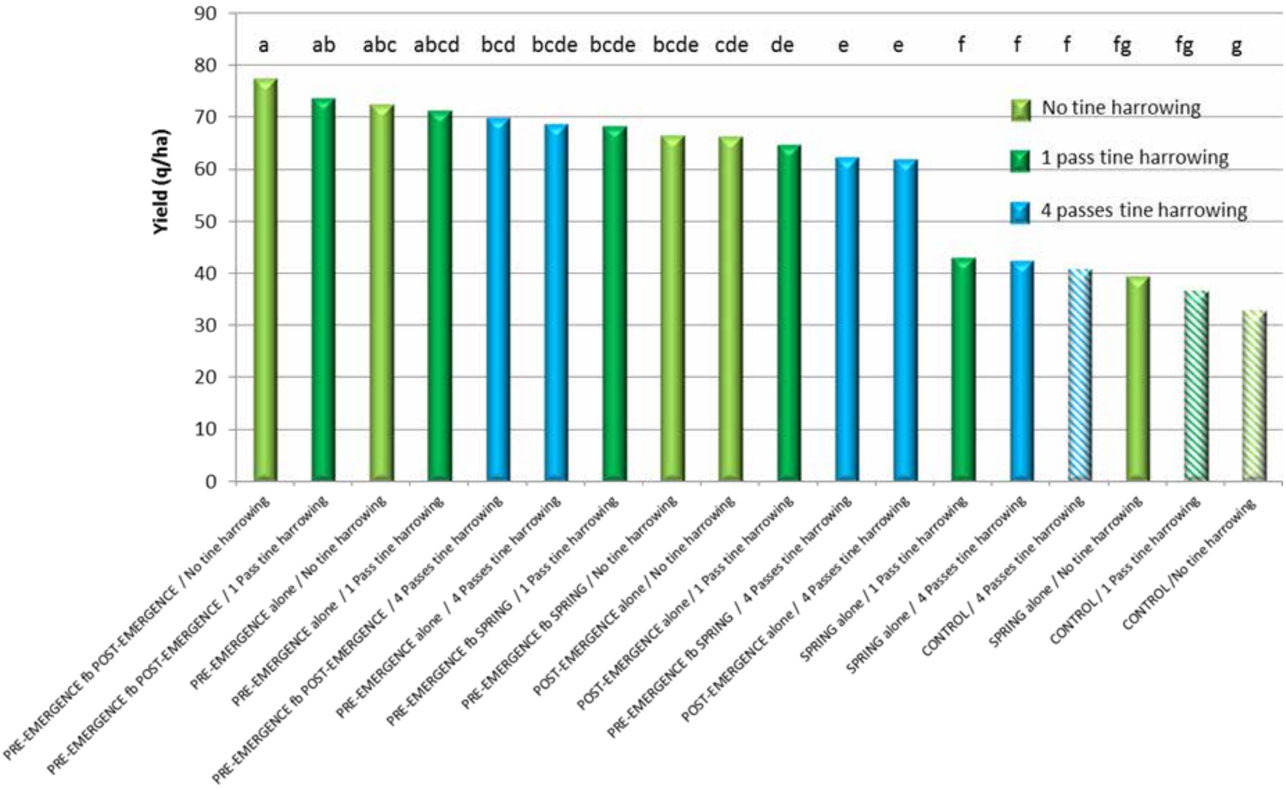

Figure 8 - Comparison of yield between strategies (in light green with no tine harrowing, in dark green with one pass of the tine harrow, and in blue with four passes of the tine harrow). Yields are in q/ha.

are more difficult to control than broadleaf weeds, especially at high densities;
- the intervention period: this was late due to the autumn conditions, which were not at any time favourable for harrowing.

Mixed strategies provided better efficacies, as shown in Figure 7. Nevertheless, it seems difficult to improve the effectiveness of herbicide programmes, which are already at a high level. The benefit of mechanical weeding is visible when the efficacy of

herbicides is low.
Efficacy was reflected in the final yields (Figure 8). Strategies with multiple passes of the harrow produced lower yields when compared to 0 passes or one pass of the tine harrow, even when they used the same herbicide programme. These multiple passes probably impacted the crop, as the yields were lower but not significantly different. These results are finally in line with what has already been observed in grassweed control: the main alternative methods are rotation, sowing date and tillage. Mechanical weeding can help, but will be insufficient to control grassweeds on its own.

TRIAL 2 – BOIGNEVILLE: TINE HARROWING IN WHEAT (PARTNER ARVALIS)

A trial on winter wheat was established to support integration of tine harrowing (a fast, economical tool that can respond to the needs of large farms) in weed control strategies. The main objective was to compare herbicide strategies (from light strategies to full autumn programmes) with or without tine harrowing (from 0 to 4 passes). The trial was designed (Table 16) to allow the use of a tine harrow as it is part of a farmer's equipment. Pre-emergence application with no harrowing was the standard strategy (Trt 1). The ryegrass population was very dense and amounted to 600-700 ryegrass plants per m^2. All strategies were established on 26 October 2019.
Second to fourth mechanical weed control passes. The second pass was carried out at a higher speed than the first pass. The third pass was carried out with settings on "aggressive", while the fourth pass was included due to the ineffectiveness of the third pass (Trt 4, 6, 9, 12, 15, 18)
Date: 24 Feb. 2020, 19 Mar. 2020, 21 Mar. 2020
Three strategies had yields similar to the standard strategy (Figure 9): pre-emergence herbicide application followed by one spring pass with the tine harrow in February (Trt 5); and pre-emergence herbicide application followed by post-emergence application with or without one pass of the tine harrow (Trt 10 and 11). Additional tine harrowing decreased the yield slightly (Trt 6 and 12). Omitting

Herbicide strategy	Mechanical weed control (tine harrowing)
"Trt" is the order of treatments in the graphs from left to right Herbicide rates are in grams of active ingredient per hectare Control (Trt 2, 3, 4) (NoHerb) PreEm: Pre-emergence application (prosulfocarb 2400 g + diflufenican 60 g + pendimethalin 600 g) (Trt 1, 5, 6) Date: 30 Oct. 2019 PostEm: Post-emergence application (prosulfocarb 2000 g + flufenacet 200 g + diflufenican 100 g) (Trt 7, 8, 9) Date: 19 Nov. 2019 PreEm + PostEm: Pre-emergence fb* Post-emergence application (prosulfocarb 2400 g + diflufenican 60 g + pendimethalin 600 g) fb* (flufenacet 240 g + diflufenican 120 g) (Trt 10, 11, 12) Date: 30 Oct. fb* 19. Nov. 2019 PostEmSp: Post-emergence fb* spring application (prosulfocarb 2000 g + flufenacet 200 g + diflufenican 100 g) fb* (pinoxaden 60 g) (Trt 13, 14, 15) Date: 30 Oct. fb* 14. Feb. 2020 Sp: Spring application (pinoxaden 60 g) (Trt 16, 17, 18) Date: 14 Feb. 2020 *fb: followed by	"Trt" is the order of treatments in the graphs from left to right First mechanical weed control pass Settings on "aggressive". (Trt 3, 4, 5, 6, 8, 9, 10, 11, 12, 14, 15, 17, 18) Date: 24 Feb. 2020 Second to fourth mechanical weed control passes. The second pass was carried out at a higher speed than the first pass. The third pass was carried out with settings on "aggressive", while the fourth pass was included due to the ineffectiveness of the third pass (Trt 4, 6, 9, 12, 15, 18) Date: 24 Feb. 2020, 19 Mar. 2020, 21 Mar. 2020

Table 16 - Description of strategies in Boigneville trial.

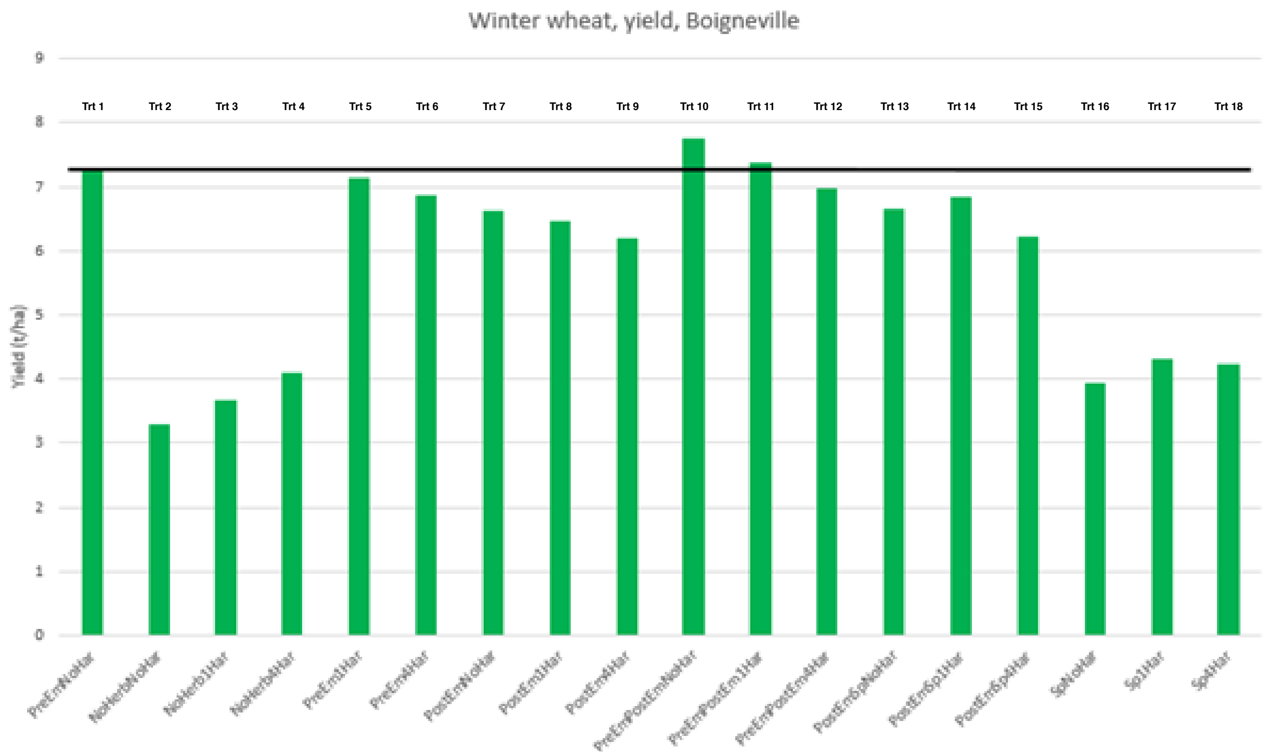

Figure 9 - Yield of winter wheat with different strategies at the Boigneville location in France in season 2019/2020. The horizontal black line indicates the yield level for the standard strategy. The standard strategy was a strategy with only pre-emergence herbicide application.

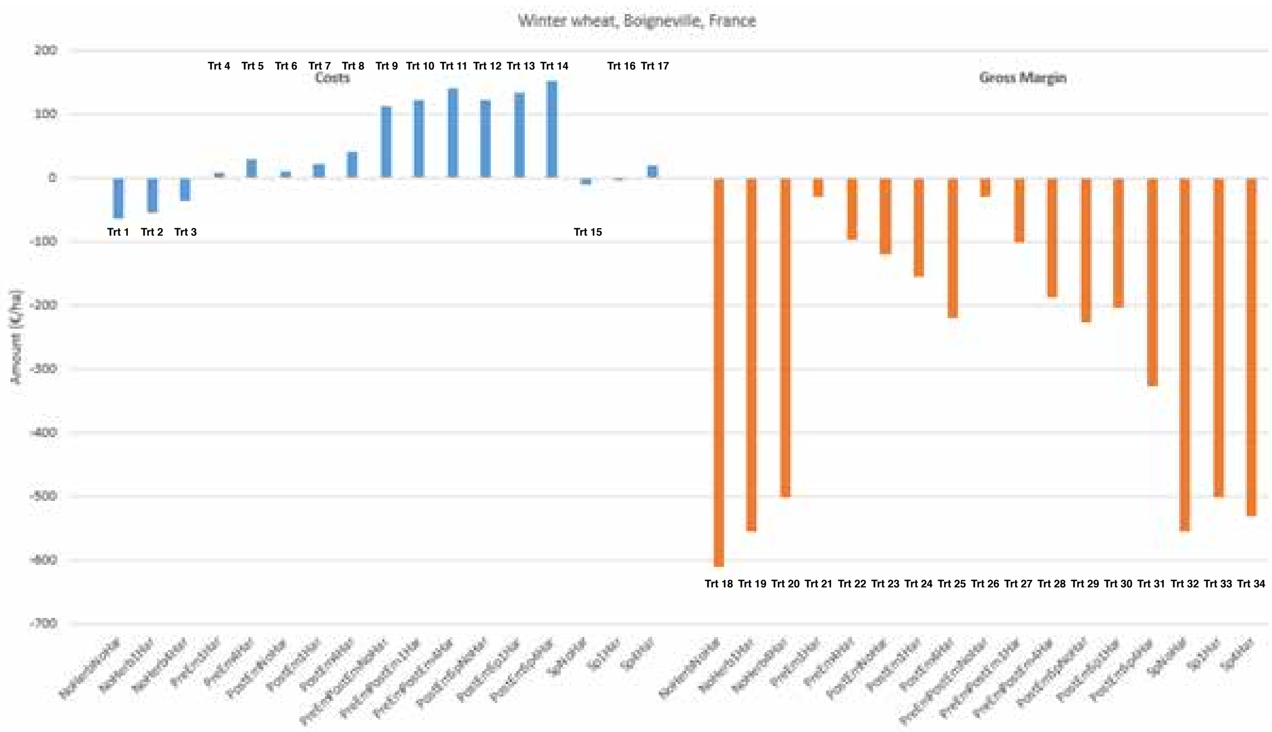

Figure 10 - Differences in costs and gross margin for alternative strategies in winter wheat compared to the standard strategy at the Boigneville location in France in season 2019/2020. The standard strategy involved only pre-emergence herbicide application.

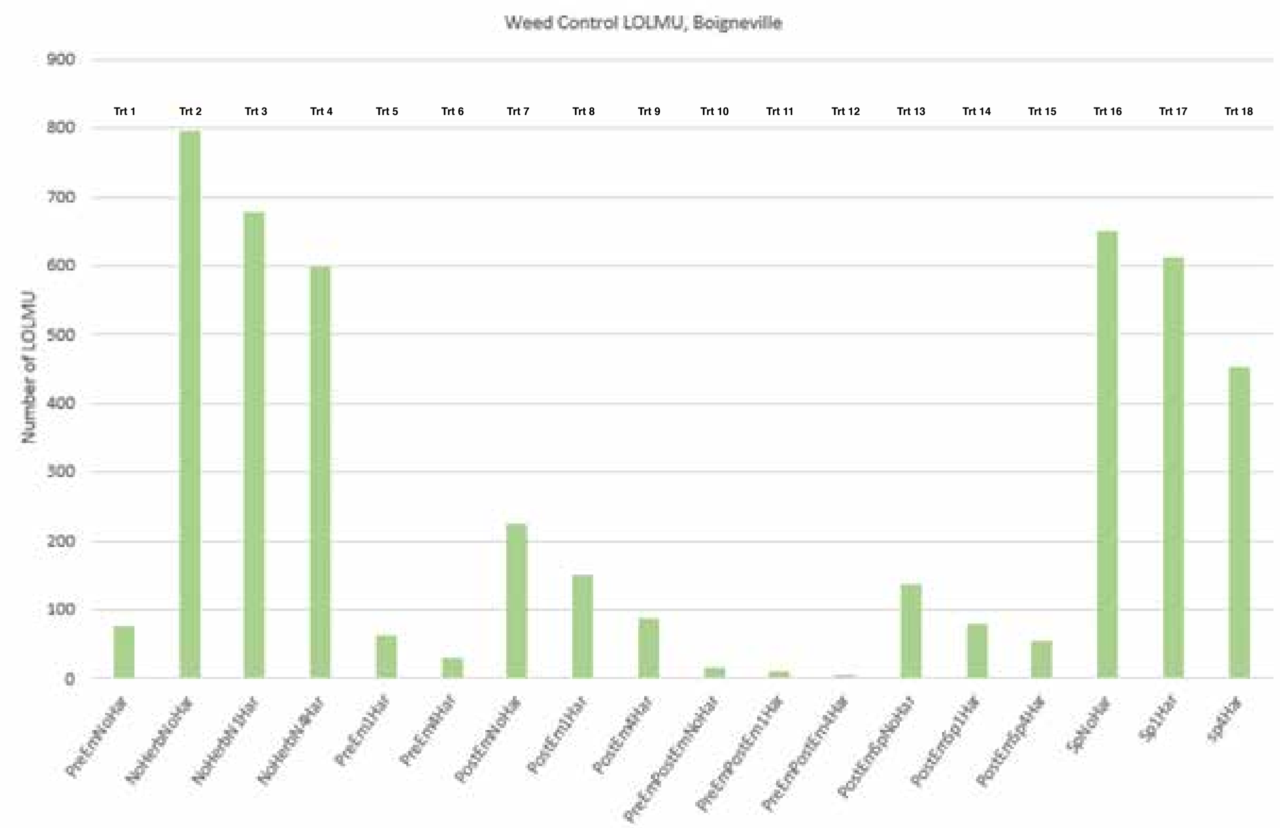

Figure 11 - Number of ryegrass plants in winter wheat at the Boigneville location in France in season 2019/2020.

the pre-emergence herbicide application generally decreased yield, and the strategies with no herbicides provided the lowest yields. The low yields of the strategies without herbicide application decreased the gross margin below that of the standard strategy, even if the costs were lower (Figure 10). None of the alternative strategies had a gross margin as high as the standard strategy, but pre-emergence herbicide application followed by one spring pass with the tine harrow in February (Trt 5) and pre-emergence herbicide application followed by post-emergence application without one pass of the tine harrow (Trt 10) were only marginally lower.

The lower yield of strategies without herbicides and the strategies with only spring application of herbicides and tine harrowing can be explained by a substantially higher number of ryegrass plants in these strategies (Figure 11). The strategies with only post-emergence herbicide application generally had a higher amount of ryegrass plants. Adding tine harrowing to the strategy decreased the number of ryegrass plants, and four passes produced lower numbers than one pass, but this did not increase yield. The reason may be that the late tine harrowing damaged the crop plants.

TRIAL 3 – BOUTIGNY: CHEMICAL + MECHANICAL IN WHEAT (PARTNER CHAMBRE D'AGRICULTURE D'ÎLE-DE-FRANCE)

In this trial, we sought to remove the herbicide treatment applied in pre-emergence for cereals by replacing it with mechanical tillage in autumn. Table 17 below summarises the chosen protocol. Depending on the situation, this protocol changed significantly due to the continuous rains in autumn, causing delayed sowing and making mechanical and chemical passes impossible. Faced with the impossibility of carrying out the initial protocol (Table 17), a simpler protocol was put in place in spring to adapt to the situation.

The protocol was completely modified and broken down into two bands of differentiated herbicide programmes: Band 1 with pre-emergence herbicide treatment, and Band 2 without pre-emergence and with early post-emergence.

Different mechanical passes were carried out perpendicularly according to the following table: no pass (pas d'application), one pass (un passage) and two passes (deux passages), with three different tools: tine harrow (herse étrille), rotoweeder (roto-étrille), and rotary hoe (houe rotative) on two different dates (Figure 12).

Context: wheat after sugarbeet, sown on 22/11/2019 in silty-clay soil, ryegrass density between 40 and 450 ryegrass/m² (high density). Difficult climatic conditions: accumulation of 65 mm of rain 10 days before sowing and return of the rain after sowing. We observed that the soil became extremely hard very quickly after a rainy episode because of the wind, but the pass of the rotary hoe allowed to "uncrust" the soil (17/03/2020). The other passes were made in good conditions: dry and sunny weather, easterly wind (17/03/2020 and 26/03/2020).

	Band 1	**Band 2**
Treatment	Post-sowing / pre-emergence (PS-PE) Chlortoluron 1800g/ha + flufenacet 120 g/ha + pendimethalin 600 g/ha	Early post-emergence Prosulfocarb 1800 g/ha + clodinafop-propargyl 25 g/ ha + cloquintocet -mexyl 6 g/ha
Date	25/11/2019	24/01/2020
Wheat	Not developed	3 leaves
Ryegrass	Not developed	2-3 leaves

Table 17 - The Boutigny trial protocol.

Protocole

Modalités	17/03/2020 Herse étrille	17/03/2020 Rotoétrille	17/03/2020 Houe rotative	26/03/2020 Herse étrille
1	2	-	-	1
2	-	2	-	1
3	1	-	1	1
4	-	1	1	1
5	2	-	1	1
6	-	2	1	1
7	-	-	-	1
8	1	-	2	1
9	-	1	2	1
10	2	-	2	1
11	-	2	2	1
12	-	-	-	1

- : Pas d'application
1 : Un passage
2 : Deux passages

Figure 12 - Setup of mechanical passes in Boutigny.

Results
Heterogeneity of the infestation of ryegrass in the field; ryegrass too developed (> 3 leaves).
Efficacy of PS-PE herbicides. Efficacy of mechanical passes, visible at T+3, but not acceptable at the end.

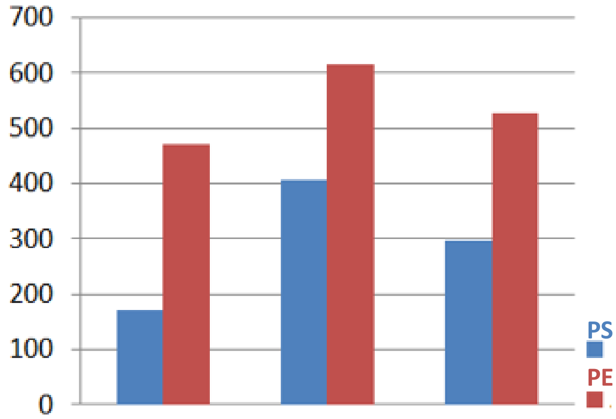

Figure 13 - Ryegrass /m² (left to right: control, 2 rotoweeders + 2 rotary hoes; PS, 2 tine harrows + 2 rotary hoes: PS = Post-sowing; PE = Post-emergence).

2020/2021 SEASON

Two demonstration trials were set up in France in 2020-2021, as described in Table 18 below. The aim of these trials within the IWMPRAISE project was to implement and optimize mechanical tools in winter wheat. As previously described, delaying the sowing date is a powerful lever for weed control, therefore a strategy including sowing date was also introduced into these trials. Unfortunately, the Normandy trial had to be abandoned due to a lack of weeds, coupled with autumn conditions unfavourable for the use of mechanical tools.

Crop	Trial site	Main objective	Method studied
Winter wheat	Lunery	Optimise mechanical tools in wheat (tine harrowing)	Mechanical weed control + herbicides + delayed sowing
Winter wheat	Normandy	Optimise mechanical tools in wheat (hoeing)	Mechanical weed control + herbicides

Table 18 - Trials in France for experimentation on cereals in 2020/2021.

	Sowing date	Pre-emergence	Post-emergence	Tine harrowing 1st pass	Tine harrowing 2nd pass	Spring application	Tine harrowing 3rd pass	Weeds (pl/m²)
Reference	17/10/20	22/10/20	04/11/20	-	-	19/02/21	-	Blackgrass 359 pl/m²
Mechanical 1	17/10/20	22/10/20	04/11/20	20/11/20	-	19/02/21	-	
Several mechanical	17/10/20	22/10/20	04/11/20	20/11/20	27/11/20	19/02/21	25/02/21	
Delayed sowing	10/11/20	12/11/20	14/12/20	-	-	19/02/21		Blackgrass 106 pl/m² (-70%)

Table 19 - Details of weed-management strategies in the winter wheat trial in Lunery (2020/2021).

TRIAL – LUNERY: OPTIMISE MECHANICAL TOOLS IN WHEAT (TINE HARROWING) (PARTNER ARVALIS)

The trial setup in Lunery (Berry) and its implemented strategies are presented in the following table.
For each strategy, a range of herbicide programmes was used, from “intensive” to “low”. These are described in Table 20.
The first pass of the harrow was carried out in good conditions (dry soil surface) at the 3-leaf stage of the crop. The second pass, carried out seven days later in order to disturb the weeds, was also carried out in good conditions, even though the soil was cool on the surface (but not wet). The last pass, at the end of winter, benefited from correct conditions (surface cool but not wet) (Table 19).
The first assessment of weeds (18/11/2020) showed high densities of blackgrass (359 pl/m²). The main results are presented below in Figures 14 and 15. The effect of mechanical weeding was very limited (Figure 14). With only 12% efficacy, the tine harrow did not contribute to weed control. Its effect is, however, more visible on the herbicide strategies with lower

Strategy	Products – Application stage	Doses
CONTROL	CONTROL	-
LOW autumn	DEFI + CODIX pre-emergence	3 L + 1.5 L
STANDARD autumn	DEFI + FOSBURI 1-2 leaves	2.5 L + 0.5 L
INTENSIVE autumn	DEFI + CODIX pre-emergence / FOSBURI 1-2 leaves	3 L + 1.5 L / 0.6 L
PROGRAM	DEFI + FOSBURI 1-2 leaves / ARCHIPEL DUO + H + ACTIMUM tillering	2.5 L + 0.5 L / 1 L + 1 L + 1 L
LOW spring	ARCHIPEL DUO + H + ACTIMUM tillering	1 L + 1 L + 1 L

Table 20 - Details of herbicide strategies in the winter wheat trial in Lunery (2020/2021).

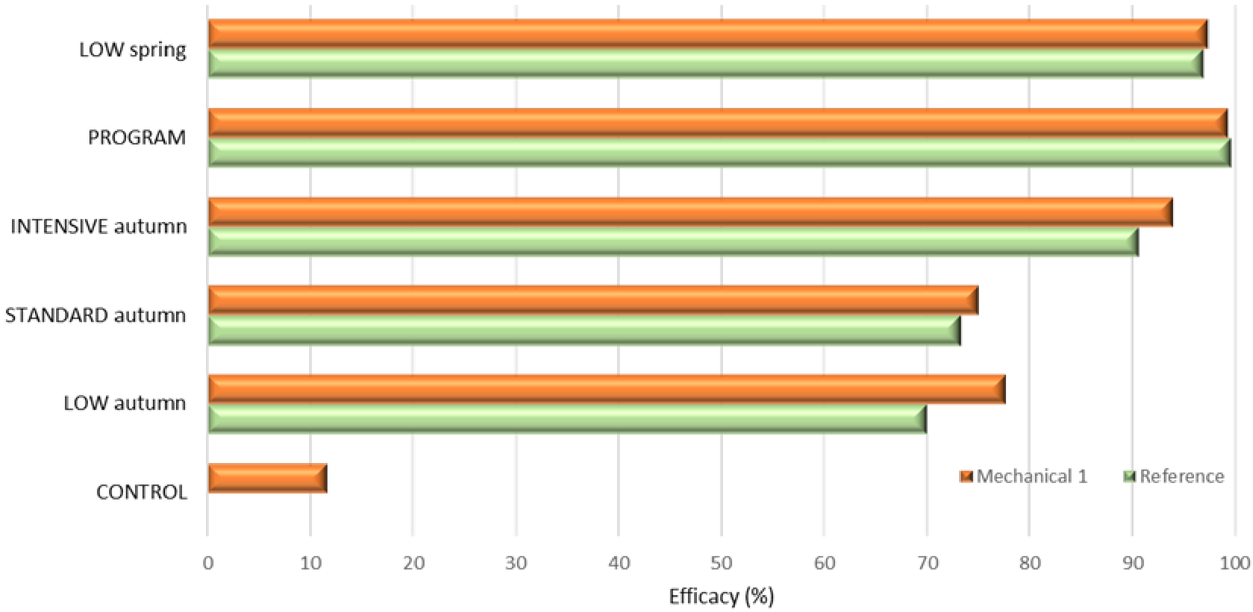

Figure 14 - Efficacy of the Reference strategy compared to “Mechanical 1” with various herbicide strategies.

efficacies, such as “LOW autumn”, when the gain was in the order of 7 percentage points.
The efficacies of the delayed sowing strategy, with various herbicide intensities, was found to be equivalent or even superior to the strategy with several tine harrowing passes. The latter strategy was superior to the strategy with only one tine harrowing pass. This again shows, in the adapted local context, that a delayed sowing-date strategy with a light herbicide programme for blackgrass control, is equivalent to early sowing with an intensive programme.
This trial was presented at an open field day on 11/06/2021. Farmers showed great interest in delayed sowing strategies, especially when blackgrass or ryegrass were present. Nevertheless, the main objection was feasibility in relation to climatic conditions. Tools to reassure farmers about delaying the sowing date seem to be worth developing.

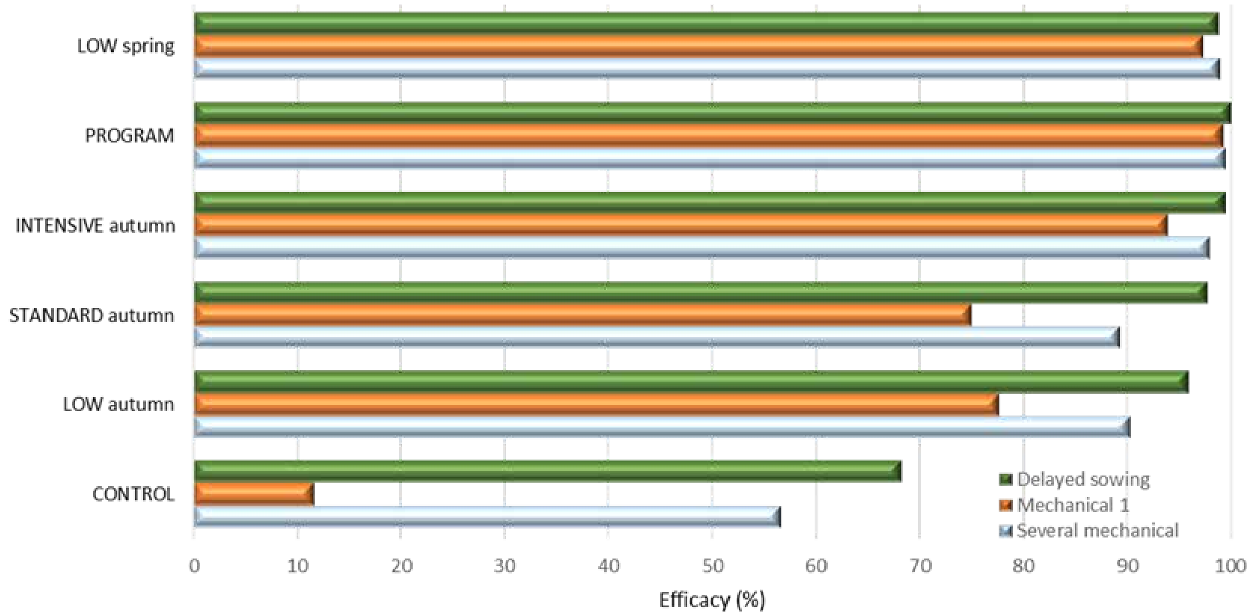

Figure 15 - Efficacy of the Delayed sowing, Mechanical 1 and Several mechanical pass strategies with various herbicide strategies.

Figure 16 - Lunery trial fields.

EXPERIMENTATION ON INTERCROPPING PERIOD

Two demonstration trials were set up in France in 2020-2021 by partner Terres Inovia, as described in Table 21 below.

2020/2021 SEASON

As in the previous season, two trials were set up in July/August 2020 before oilseed rape sowing in a bid to compare strategies to control weeds without glyphosate during the intercropping period. Descriptions of the trials and strategies are presented in Tables 21, 22, 23 and 24 below.

TRIAL 1 - SUBDRAY (BERRY)

Besides tools for weeds management, the only difference for "bis" strategies was the second pass with a disk cultivator. "Bis" strategies were much more infested than the strategies without the second pass with a disk cultivator (Figure 17). This second pass acted as a retardant on seeds and delayed emergence of barley volunteers, which emerged after oilseed rape sowing. The most infested strategy was 4bis (glyphosate + 2nd pass of a disk cultivator). The glyphosate application controlled seedlings of barley volunteers, but did not act as a false seedbed (like Strategies 1/2/3/1bis/2bis/3bis).
The highest biomasses were obtained in the "non-bis" modalities, with the exception of the disk modality (Strategy 1). In October, the opposite was observed: the "bis" modalities were more vigorous and developed than the others (was there an earlier stop in growth?).
The stand results were consistent with those of the dry biomass, with the "non-bis" modalities having more plants, except for the disk modalities. The mid-July tillage may have dried out the soil a little.
The residual post-harvest coolness allowed tillage operations to be carried out under satisfactory conditions (deep tillage possible). Moreover, these operations offered an optimal seedbed for weed emergence (barley re-growth). During intercropping, the pass with a disk cultivator on the "bis" part made it possible to destroy the first emergence of weeds. However, the lack of precipitation after the pass of tools did not allow a second "false seeding".

Crop	Trial site	Main objective	Method studied
Intercropping period	Subdray	Control of weeds during the intercropping period without glyphosate	Mechanical weed control
Intercropping period	Dijon	Control of weeds during the intercropping period without glyphosate	Mechanical weed control

Table 21 - Trials in France in 2020/2021.

	Weeds	Soil type	Previous crop	Sowing date (OSR)
Subdray (Berry)	Barley volunteer	Sandy clay loam	Winter barley	12/08/20
Dijon (Burgundy)	Barley volunteer	Clay	Spring barley	12/08/20

Table 22 - Description of trials during the intercropping period.

Strategy	1	2	3	4	1bis	2bis	3bis	4bis
Harvest date (previous crop)	Classic				Classic			
Between harvest and 25-30 July	Shallow soil tillage				Shallow soil tillage			
15 days after 1st pass	-				Destruction of emerged weeds with disk cultivator			
Before sowing (the day before sowing)	Independent disk cultivator (shallow=5 cm depth)	Rotative harrow (shallow=5 cm depth)	Vibro-cultivator (shallow=5 cm depth)	Glyphosate (=reference)	Independent disk cultivator (shallow=5 cm depth)	Rotative harrow (shallow=5 cm depth)	Vibro-cultivator (shallow=5 cm depth)	Glyphosate (=reference)

Table 23 - Detail of weed-management strategies during the intercropping period in Subdray.

Seeding conditions were relatively good. In some modalities, the management of crop residues was a problem for seeding. This was the case with the vibrocultivator and the glyphosate modality (blockages, raking of the straw in front of the sowing units).
The accumulation of rain between 8 and 15 August allowed a quick and homogeneous emergence of the crop, as well as barley re-growth. Finally, the "bis" modalities were largely more invaded by re-growth, due to the "delayed" false seeding effect (in the rapeseed) of the disk pass on 16 July.
On oilseed rape, there was faster growth in the "bis" modalities. At the start of winter, the growth of rapeseed in the "classic" methods caught up with that of the "bis" methods.
When tools for destroying volunteers were compared, it seems that the vibrocultivator and disks (especially the vibrocultivator) were slightly more effective than the rotary harrow. The glyphosate dose must also be high enough to destroy all barley volunteers. In addition, emergence could continue in rapeseed (including in the glyphosate modality), despite good destruction just before sowing.

TRIAL 2 – DIJON (BURGUNDY)

Unfortunately, there were no weeds before oilseed rape sowing, so the glyphosate application was postponed (it is considered in results as "control") (Table 24). The very dry conditions in summer 2020 resulted in delayed emergence of barley volunteers in the crop, so their absence at sowing did not allow tools and glyphosate to be assessed. Oilseed rape emergence was also quite late. The rapid development of barley re-growth, shortly after

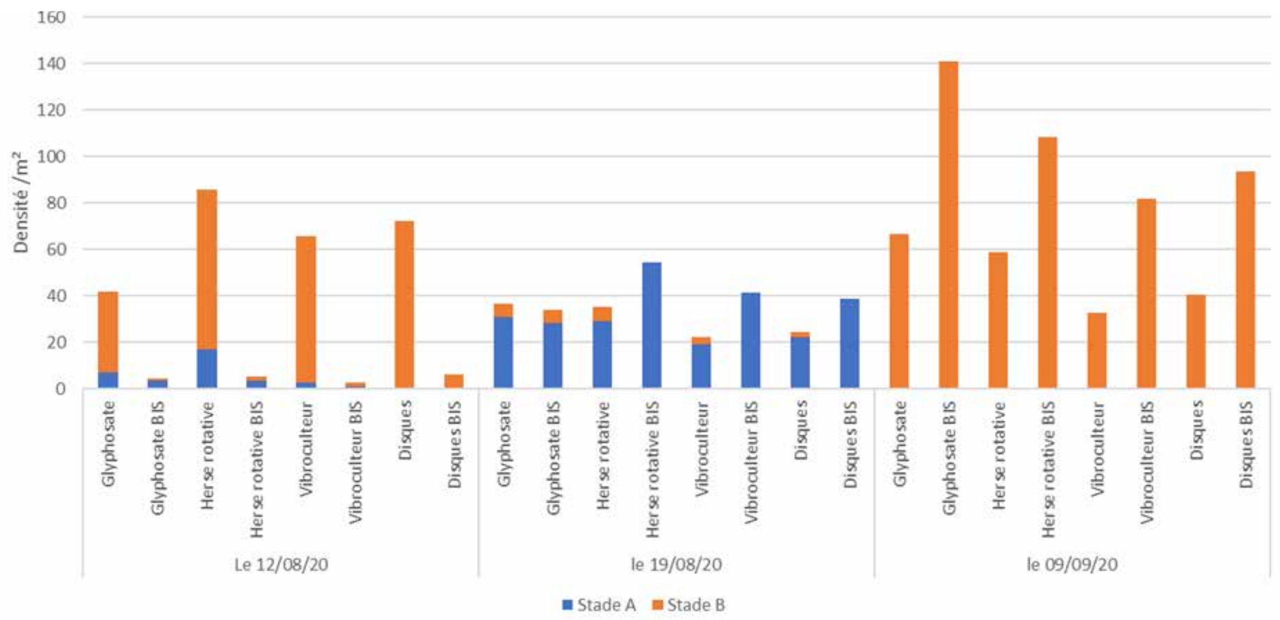

Figure 17 - Densities of barley volunteer, at three dates, between strategies. Stage of barley is mentioned as A (seedlings) and B (2 leaves and more).

sowing, seems to have "smothered" oilseed rape re-growth. In addition, the poor soil-seed contact of the rape could have made it less competitive in terms of development. The Lemken tool seems to have favoured the emergence and development of rape (despite many more angled pivots than the other two methods), as well as barley re-growth (Figure 18).

Strategy	1	2	3
Harvest date (previous crop)	Classic		
between harvest and 25-30 July	Shallow soil tillage		
Before sowing (the day before sowing)	Disk cultivator (cover crop)	Vibro-cultivator (dents) (Lemken Kristall 9)	Glyphosate

Table 24 - Detail of weed management strategies during the intercropping period in Dijon.

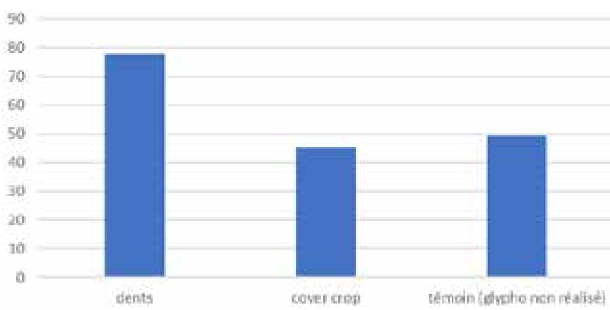

Figure 18 - Densities of barley volunteers between strategies in Dijon.

FRANCE WP4


Mons
Belloy sur Somme
Vallangoiard
St Germain Laxis
St Michel
St Valentin
Dijon
Pusignan
Buros
Montesquieu-
Lauragais

WP4 – EXPERIMENTAL TRIALS IN ANNUALLY DRILLED CROPS IN WIDE ROWS

In the 2020 campaign, two trials were set up in sunflower, one in soybean, three in maize, one in sugarbeet, and one in protein peas by the three partners: Terres Inovia, Arvalis, and Chambre d'Agriculture d'Île-de-France
In the 2021 campaign, only one trial was set up on maize.

EXPERIMENTATION ON SUNFLOWER AND SOYBEAN (Partner: Terres Inovia)

2020 SEASON

The 2020 trials were quite similar to those performed in the previous year. Glyphosate is a big issue for farmers, especially in no-till systems. The related regulation had recently changed, but this was unknown at the beginning of the season. The aim of these trials in sunflower and soybean is to study the impact of tillage tools on weed management during the intercropping period, before drilling, and to avoid glyphosate use.
Four trials were set up (two in sunflower, one in soybean, and one initially in sunflower, later replaced by maize). Due to the difficulty of managing tillage tools in a completely random trial, these trials were designed in strips, with three replicates. Strategies and sites are described in Tables 1 and 2 below.

TRIAL 1 – SAINT MICHEL (BERRY)

All present weeds were destroyed, either by Tool 1 or 2.
In this trial, glyphosate was applied on 21/04/2020 at 3 l/ha. Sowing was carried out on 26/04/2020 with a single seed drill at 60 cm spacing in good environmental conditions. Sowing density was 76,000 seeds/ha. On 29/04/2020, pre-emergence application

Code	Strategy	Description
1	**Management with soil tillage tool**	Tool available on farm
2	**Management with another soil tillage tool**	Use another soil tillage tool available on farm
3	**Glyphosate management**	Use of glyphosate – no tillage

Table 1 - Strategies in sunflower and soybean trials. All strategies were performed during the month before drilling. For Strategies 1 and 2, pick two tools from the following: rotary harrow, stubble cultivator, etc.

Site	Weeds	Soil type	Tool strat 1 (date and depth)	Tool strat 2 (date and depth)	Sowing date (Crop)
St Michel (Berry)	*Mercurialis annua L.* *Polygonum convolvulus L.*	Superficial clay-limestone	Tine cultivator (24/04, 10 cm)	Rotary harrow (24/04, 12 cm)	26/04/20 (sunflower)
St Valentin (Berry)	*Alopecurus myosuroides H.*	Superficial clay-limestone	Tine cultivator (09/04, 10 cm)	Rotary harrow (09/04, 8-10 cm)	17/04/20 (sunflower)
Dijon (Burgundy)	*Alopecurus myosuroides H.* *Polygonum convolvulus L.* *Anagallis arvensis L.*	Clay-loam (50% clay)	Rotary harrow (20/05, 5 cm)	Tine cultivator (20/05, 6 cm)	22/05/20 (soybean) 06/04/20
Montesquieu-Lauragais (West Occitany)	*Lolium sp.* *Bromus sp.* *Vulpia myuros L.*	Rotary harrow (01/04, 4-5 cm)	"Vibroflex" (01/04, 10-15 cm)	Compact disk harrow (02/04, 8 cm)	(sunflower, finally maize)

Table 2 - Trial sites, tillage tools and weeds.

Figure 1 - Rotary harrow in Saint Michel's trial (24/04/2020) performed at 12 cm depth. Soil texture was very fine.

was carried out on the entire trial with S-metolachlor 1,248 g/ha (Mercantor gold 1.3 l/ha). Post-emergence herbicides were applied twice: tribenuron-methyl 15 g/ha + adjuvant (Trend 90 0.1 l/ha) on 20/05/2020 and 02/06/2020.
Observations are reported in Figure 2 below.
Weather conditions in the first ten days of April were similar to those observed in 2019: very low rainfall, maximum temperatures that could reach and exceed 20°C, and regular presence of wind. These conditions were not favourable for a major emergence of weeds.

Before the mechanical or chemical destruction that precedes sowing, there were weeds at the cotyledon stage, which were not identifiable.
On 18/05/2020, before the application of the post-emergence herbicide tribenuron, it was noted that the rotary harrow strategy was slightly more infested with *Polygonum* and *Mercurialis*. The glyphosate strategy was less infested with *Mercurialis* than the other two strategies. At the last observation, there was no difference between the three strategies since the weed pressure was relatively similar.
It was difficult to draw conclusions on this trial because of the relatively low weed infestation. The shape of sunflower roots were also observed and were similar between strategies.

TRIAL 2 – SAINT VALENTIN (BERRY)

Following wheat in 2019, ploughing was carried out at a depth of 15 cm in December 2019. After winter, the first soil tillage was performed under optimal conditions during March 2020 with a tine cultivator at a depth of 10-12 cm.
The soil in the tine cultivator strategy was less refined than in the rotary harrow strategy. However, both types of tillage allowed sunflower to be sown in good conditions and all of the weeds present to be controlled.
Glyphosate was applied at 2.5 l/ha on 8/04/2020, in good conditions. Sowing was carried out with a single-seed drill at 60 cm spacing on 17/04/2020 under optimum conditions. The sowing density was 75,000 seeds/ha. On 19/04/2020, pre-emergence

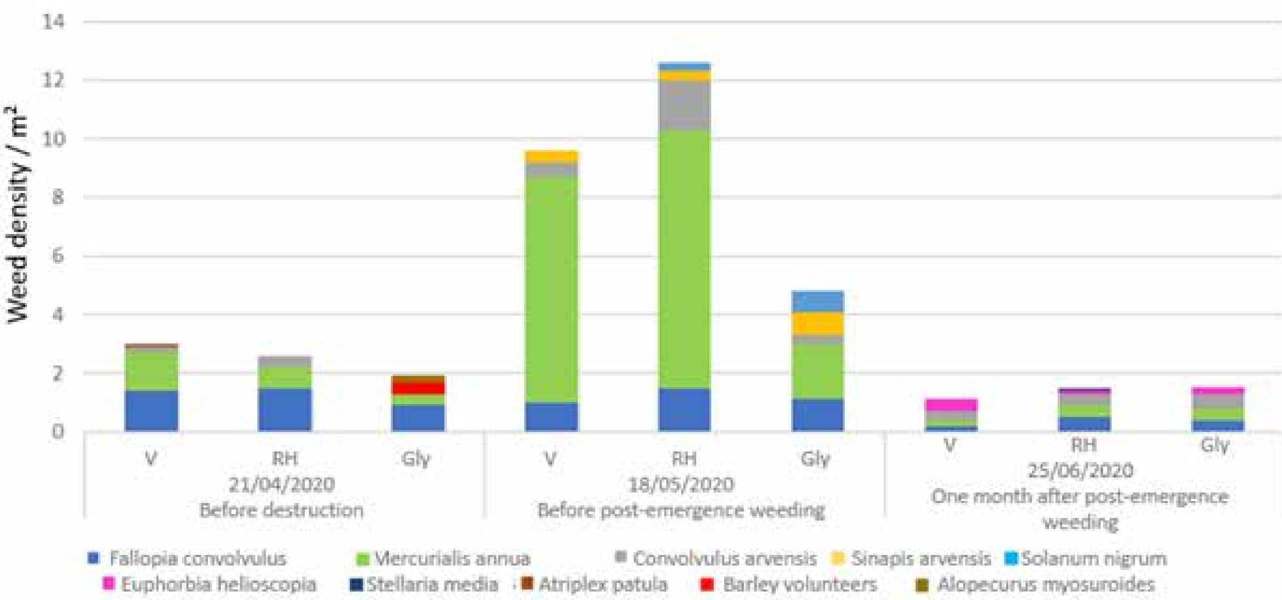

Figure 2 - Weed density in Saint Michel trial (pl/m²). V = vibrocultivator, RH = rotary harrow, Gly = glyphosate. Only *Mercurialis annua* and *Polygonum convolvulus* were homogeneous in the trial.

herbicide weeding was carried out over the entire trial with aclonifen 1200 g + pendimethalin 800 g (Challenge 600 2 l/ha + Prowl 400 2 l/ha). There was no post-emergence application. There were no weeds in the pre-destruction count and in the sunflower observed at B4 stage. Observations are reported in Figure 3.
At the last observation, the infestation was fairly low, with mainly young *Linaria*, *Centaurea* and *Senecio* species. The blackgrass was present at stages C to E of sunflower, suggesting an earlier emergence or poor destruction of a few plants (random observations on the plot).
When the trial was set up, there were no weeds on any of the three strategies. Weather conditions at the end of March and in the first ten days of April were not favourable for weed emergence. The primary soil tillage therefore did not allow a real false seedbed. Temperatures were quite low and rainfall relatively low.
At the last observation carried out on 22/06/2020, there was a slight difference between the glyphosate strategy and the two tillage strategies. In the glyphosate strategy, there was no blackgrass, while in the other two it was present, although density was low. The glyphosate strategy, combined with pre-emergence herbicide, may have controlled weeds in this situation, particularly the blackgrass.
The seedling quality was poor for all strategies (no more than 40% of straight pivots) and the glyphosate strategy seemed to have more curved pivots.

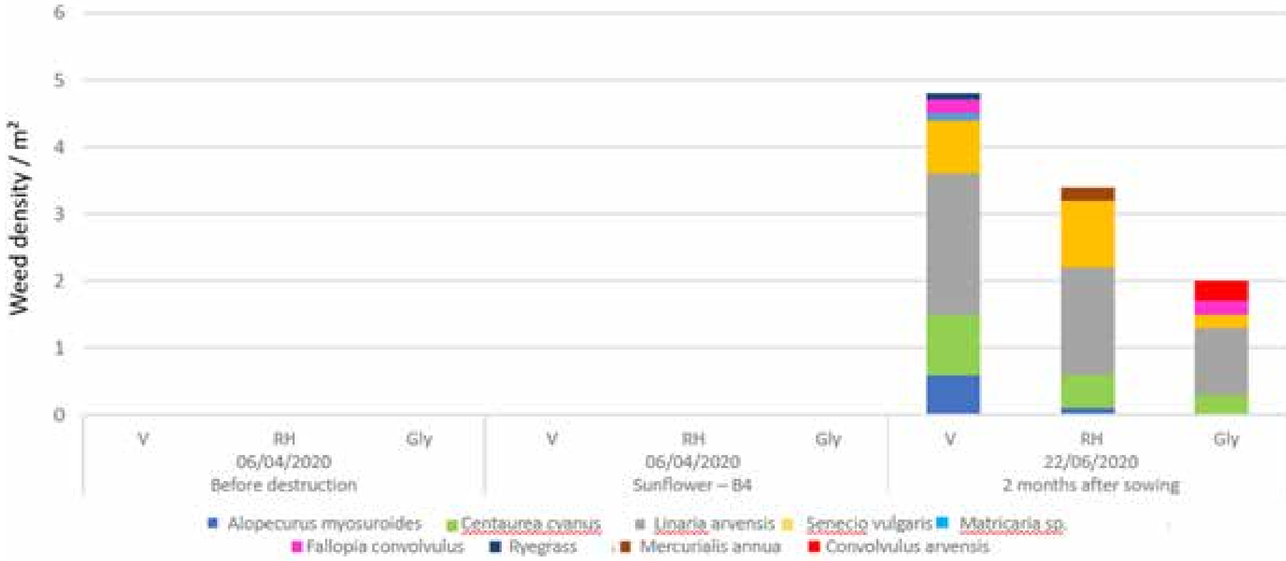

Figure 3 - Weed density in the Saint Valentin's trial (pl/m²). V = vibrocultivator, RH = rotary harrow, Gly = glyphosate.

Figures 4 and 5 - Pictures taken from the last observation on sunflower (22/06/2020).

TRIAL 3 –DIJON (BURGUNDY)

After wheat cultivated in the previous season, ploughing was carried out at a depth of 25 cm on 20/10/2019, followed by a rotary harrow at 10 cm. Primary tillage at the end of winter was carried out on 10/03/2020 in good conditions with a flat harrow at 10 cm depth. Soil tillage strategies were performed on 20/05/2020, whereas glyphosate was applied on 25/05/2020 at 1080 g/ha (2.4 L/ha) after sowing, in pre-emergence of soybean. Sowing was carried out with a single seed drill on 22/05/2020 at a depth of 4 cm.

On 25/05/2020, pre-emergence herbicide was applied on all plots of the trial with pendimethalin 500 g + S-metolachlor 960 g (Prowl 400 1.25 L/ha + Mercantor gold 1 L/ha) and glyphosate. Post-emergence application was made on 09/07/2020 at the R1-R2 stage of soybean on the plots of the trial with bentazon 411 g + adjuvant + imazamox 19 g (Basagran SG 0.4733 kg/ha + Belize 0.4733 L/ha + Pulsar 40 0.4733 L/ha).

Very dry conditions in March did not favour weed emergence. These meteorological conditions resulted in late broadleaf weed emergence (cotyledon stage observed in May) and few weeds emergence would have been induced in winter.

Figures 6 and 7 - Rotary harrow (on the left - Strategy 1) and tine cultivator (on the right - Strategy 2). Pictures taken on 26/05/2020. In Strategy 1, the soil was friable with rare clods of 8 cm in diameter. It was moist at a depth of 2 cm. In Strategy 2, the soil was friable, but it was more cloddy, and moisture was found at a depth of 2 cm. The average size of the clods was 6 cm in diameter and the largest were 16 cm long.

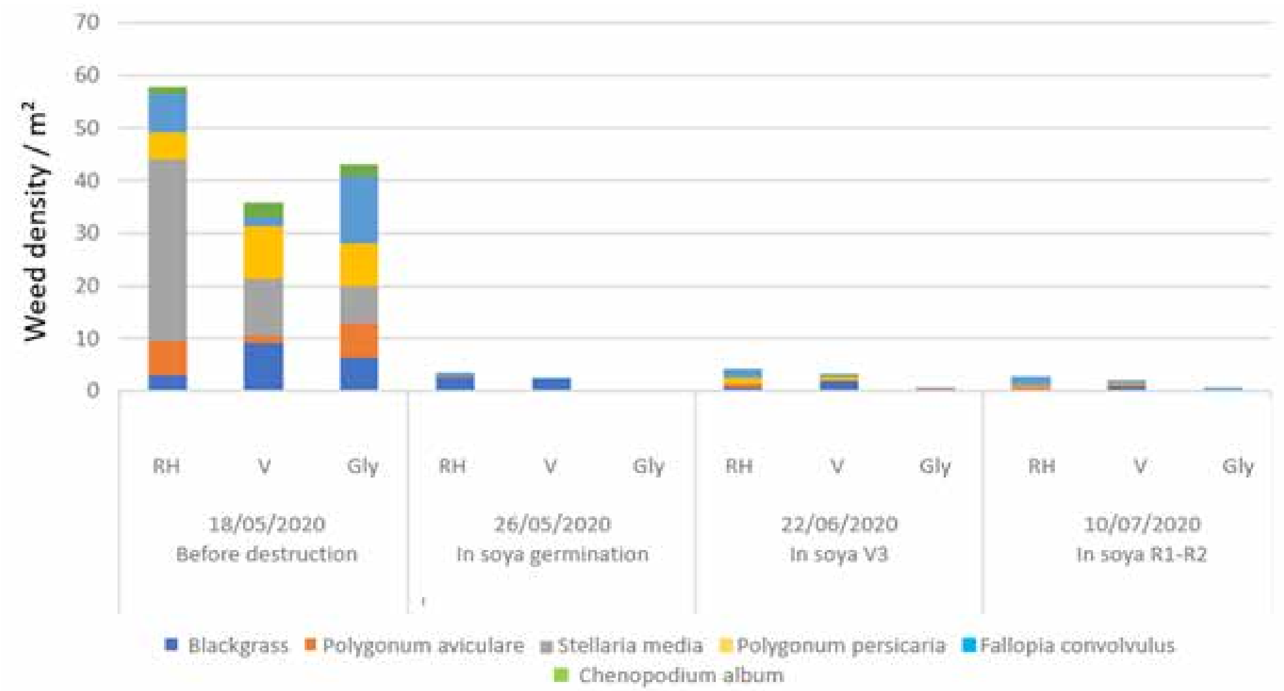

Figure 8 - Weed densities in Dijon's trial (pl/m²). V = vibrocultivator, RH = rotary harrow, Gly = glyphosate.

Figures 9, 10 and 11 - From left to right: Strategy 1 (rotary harrow), Strategy 2 (tine cultivator) and Strategy 3 (glyphosate). Pictures taken on 22/06/2020.

The drought period between March and May made it impossible to find a trial with a heavy infestation of blackgrass. The emergence of broadleaf weeds in the trial was largely induced by the April rains.
Observations on 26/05/2020, reported in Figure 8, showed the rotary harrow to be slightly effective on blackgrass. In addition, the rotary harrow was effective on *Polygonum convolvulus* at all stages. On the other hand, the tine cultivator was more effective on blackgrass from 1 leaf to the tillering stage, but it was not very effective on blackgrass in later stages. The glyphosate strategy was not observed immediately after sowing because the herbicide had not yet finished working.
In Strategies 1 and 2, blackgrass could be found at the heading and seedling stage on 10/07/2020, but in small densities; these were undoubtedly blackgrass plants that were poorly destroyed mechanically before sowing soybean.
The glyphosate treatment was effective on blackgrass, even in later stages, unlike the rotary harrow and tine cultivator. The herbicide treatments of 25/05/2020 had an impact on blackgrass (count on 22/06/2020) but were not sufficient to eliminate it in the mechanical strategies, where it was found in the more advanced stages (tillering and heading). However, blackgrass was finally controlled in all strategies.

EXPERIMENTATION ON MAIZE

(Partners: Terres Inovia, Arvalis)

2020 SEASON

TRIAL 1 – MONTESQUIEU-LAURAGAIS (WEST OCCITANY)

This trial was initially to be sown with sunflower, but a maize trial was set up in the end (see Table 2). A cover crop (faba bean) was sown on 15/20/2020 with a tine pneumatic cereal seeder (Kuhn Megant 600) between 3 and 5 cm. On 24/03/2020, the cover crop was at flowering stage. Biomass was produced on three plots of 1 m² each; on average the dry biomass was 5.23 t/ha.
The field bean was destroyed on 24/03/2020 with a FACA roller in the direction of the slope for the trial and across the slope for the rest of the plot (Figure 12). This difference is very important because it would be noticed later that the pass of the independent disc harrow across the FACA roller cut the bean stems into pieces at a maximum length of about 20 cm.

Figure 12 - Destruction of the cover crop (faba bean) on 24/03/2020 with a FACA roller.

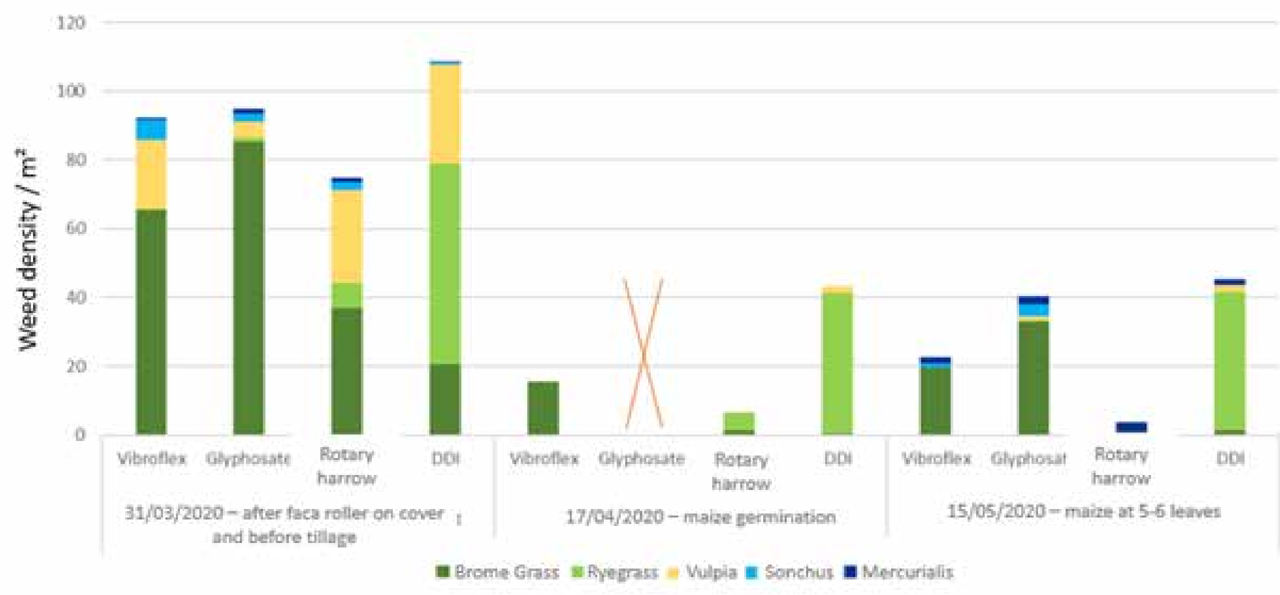

Figure 13 - Density of weeds (pl/m²) at three dates and for all modalities. "DDI" is compact disk harrow.

Figures 14 and 15 - Assessment of weeds in maize on 15/05/2020. Rotary harrow strategy on the left: maize is more robust and homogeneous. It is at the 7-12 leaves stage and the plot is fairly clean. Glyphosate strategy on the right: maize is not as developed as in the other plot and more weeds are present.

Figures 16 and 17 - Assessment of weeds in maize on 15/05/2020. Vibroflex strategy on the left: maize is heterogeneous with a lack of plants due to residues of faba beans. A lot of weeds are present. Compact Disk Harrow strategy on the right: the maize stand is heterogeneous and ryegrass has suppressed the maize.

A third strategy of soil tillage was included in this trial (compact disk harrow) and all strategies were carried out on 01/04/2020 and 02/04/2020. Glyphosate was applied at 720 g/ha (Agave at 2 l/ha) on 10/04/2020. Maize was sown on 06/04/2020 with a "classic" precision seeder (Kuhn-Nodet Planter 2 - 7 rows at 60 cm spacing). The sowing speed was identical for all strategies, i.e. 3.5 km/h. The sowing density was 77,000 grains per hectare of PR9234 variety.
Pre-emergence treatment was carried out on 14/04/2020 and was similar for all programmes: mesotrione 100 g/ha + S-metolachlor 1000 g/ha + DMTA-P 648 g/ha (Camix 2.5l + Isard 0.9 l).
Before the pass of tillage tools or glyphosate, weed infestation was quite high under the canopy of the cover crop and weeds could not be destroyed properly by the FACA roller; bromegrass, ryegrass and Vulpia were especially present.
On 17/04/2020, at the emergence of maize, the glyphosate strategy was still in action and was not evaluated. We could see that the bromegrass had been destroyed rather well by the tillage tools, but perhaps a little less in the "Vibroflex" strategy. On the other hand, ryegrass had been poorly destroyed by tillage tools, persisting particularly in the compact disk harrow strategy. This ryegrass remained present in this strategy later in the trial (Figure 13).
Observations on 15/05/2020 took place approximately one month after pre-emergence treatment. We assessed that the herbicide programme showed poor efficacy because the two applied herbicides had a grassweed spectrum, whereas there was a lot of grass on the Vibroflex, Glyphosate and Compact Disc Harrow strategies. The weed stage was probably too mature for the herbicides to show satisfactory efficacy. The bromes present on the Vibroflex and Glyphosate strategies were both in an advanced stage (C or even D), and therefore were poorly controlled, or in new emergence (Stage B), which occurred in maize. Ryegrass in the Compact Disk Harrow strategy was essentially at an advanced stage (Stages C and D), so the plants had been poorly destroyed. Only the rotary harrow strategy showed satisfactory control of grasses, although a few grasses did remain in the plots (1 or 2 pl/m²).
Results can be extrapolated to sunflower. For a very high faba bean cover crop (around 5 t/ha), the destruction work prior to the establishment of the cash crop will have a very significant impact. The use of a FACA roller was essential. Seedbed preparation was best done with disks. Anything with tines caused clogging of the soil tillage tool. For disk tools, it was essential that the pass was perpendicular to the pass of the FACA roller, in order to reduce the length of the stems. The rotary harrow gave good results, both in terms of maize development and weed control, even though too many blockages occurred when sowing the maize. It was still necessary to aim for a fairly significant working depth (4-5 cm) in order to destroy the grasses. This trial confirms the harmfulness of ryegrass and bromegrass in maize.

TRIAL 2 – BELLOY SUR SOMME (PICARDY) - FORAGE MAIZE

Protocol and strategies are described in Tables 3 and 4.
Crop selectivity was assessed on 16/07/2020 and all modalities were similar, i.e. no effect of herbicides or hoeing was observed. Results for efficacy (assessment on 16/07/2020) are presented in Figures 18, 19 and 20. Chemical references 1 and 2 provided good results overall, in-row and inter-row. As seen in the previous season, alternatives strategies can achieve the same results, as in this trial with strategies ALT 1 or ALT 3. Strategy ALT 2 seems less efficient, essentially due to the herbicide pre-emergence being less efficient on this flora (especially on *Polygonum convolvulus*, as described in Figure 20). Strategies ALT 1 and ALT 3 provided the same results as the references, with only 31% of the area treated (25 cm width out of 80 cm between rows). These observations also revealed that, under the conditions in which this trial was carried out, inter-row efficiency was perfectly controlled, sometimes even better than in-row, due in particular to the good efficiency of the hoeing carried out in dry favourable conditions.

The crop used in this trial was forage maize. Results of yield (dry matter in t/ha and in %) are presented in Figure 21. A decrease in vigour, a reduction in plant size and a yellowing of the leaves were observed in the control, due to strong competition from weeds that tended to suppress the crop. The dry matter for the different strategies varied only slightly, ranging from 32.6% to 35.5%.
An analysis of variance, accompanied by various statistical tests, was carried out on the variable of forage yield (t DM/ha). Associated tests showed that this trial had no suspicious residues (Grubbs method) and that the residual standard deviations showed comparable variability (Bartlett test). In addition, the additivity test did not reveal any interaction between the blocks and the herbicide treatments. Chemical references were superior, with a significant difference between them and Strategies ALT 1 and ALT 3, which were the most effective of the alternative modalities. Hoeing probably reduced weed damage, but also disrupted the crop. No differences were observed between alternative strategies ALT 1, 2 or 3. On dry

Strategy code	T1 (pre-emergence)	T2 (post-emergence)	T3	T4
CONTROL	-	-	-	-
CHEM reference 1	Adengo Xtra 0.44 L/ha			
ALT 1	Adengo Xtra 0.44 L/ha (in row)	Hoeing		Hoeing
ALT 2	Camix 2.5 L/ha (in row)	Hoeing		Hoeing
ALT 3	Adengo Xtra 0.44 L/ha (in row) + Isard 1.2 L/ha (in row)	Hoeing		Hoeing
CHEM reference 2	Adengo Xtra 0.44 L/ha (in row)		Capreno 0.2 L/ha + actirob B 1.5 L/ha	

Adengo Xtra = thiencarbazon 90 g/l + cyprosulfamid 150 g/l + isoxaflutole 225 g/l
Camix = mesotrione 40 g/l + S-metolachlor 400 g/l + Benoxacor 20 g/l
Capreno = Thiencarbazon 68 g/l + tembotrione 345 g/l + isoxadifen-ethyl 134 g/l
Actirob B = esterified oilseed rape 842 g/l

Table 3 - Protocol set up in Belloy sur Somme in maize on four blocks adapted for machinery passes.

Variety & sowing date	T1 (pre-emergence) date	T2 (post-emergence) date	T3 date	T4 date	Weeds (density in pl/m²)
LG31259 (16/04/2020) at 110 pl/m², and 80 cm row width	24/04/2020	20/05/2020 at 4 leaves. Hoeing with Monosem machinery (3 km/h, 4 cm depth)	20/05/2020 at 4 leaves	15/06/2020 at 8 leaves. Hoeing with Monosem machinery (4 km/h, 12 cm depth)	*Chenopodium album* (27 pl/m²), *Polygonum convolvulus* (65 pl/m²). Assessment on 20/05/2020

Table 4 - Details of trial in Belloy sur Somme.

matter, no significant differences were observed between strategies and control.
In this trial, alternative methods (hoeing) achieved significant levels of efficacy, sometimes equivalent to the references, with 69% less herbicide. Nevertheless, yields obtained by forage maize suggest that these mechanical passes had an impact on the crop, with dry matter losses of about 3 t/ha.

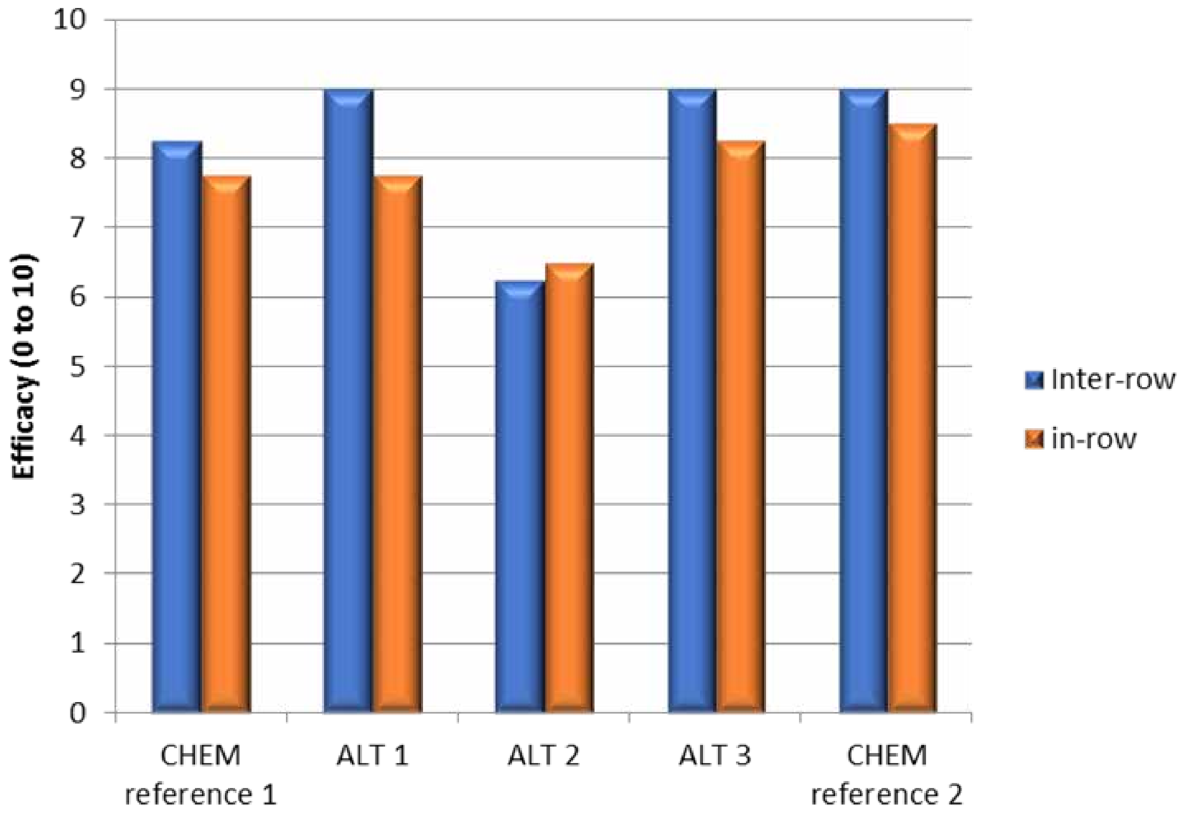

Figure 18 - Global efficacy, inter-row and in-row, in the Belloy sur Somme trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

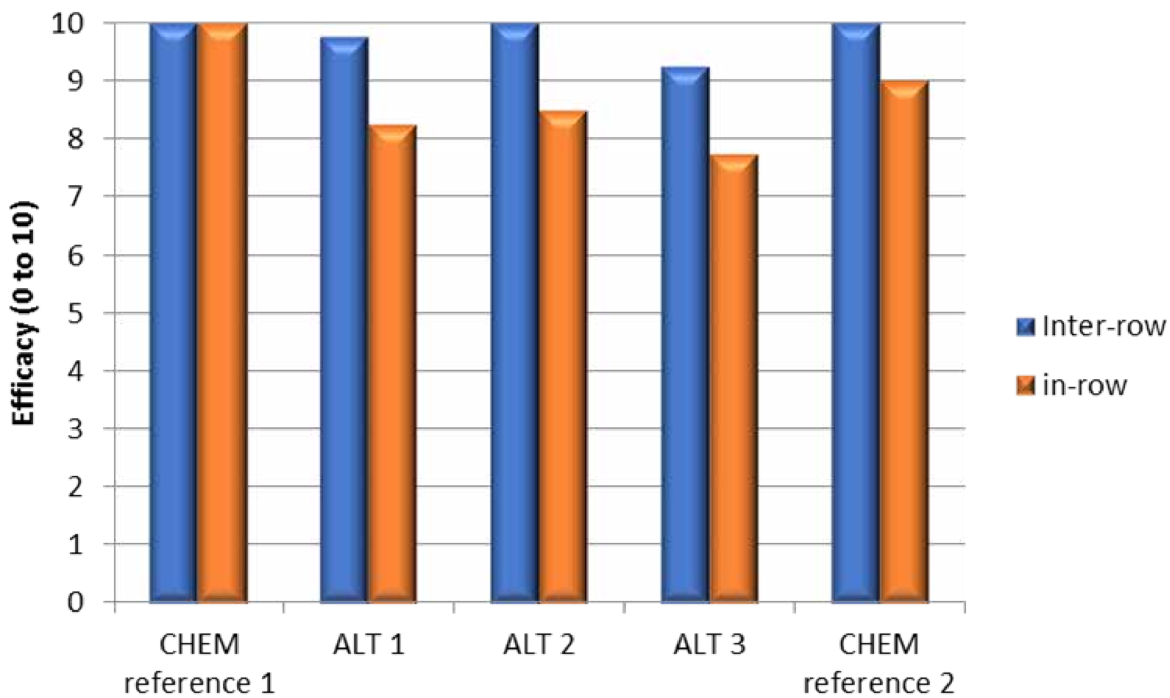

Figure 19 - Efficacy on *Chenopodium album*, inter-row and in-row, in the Belloy sur Somme trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

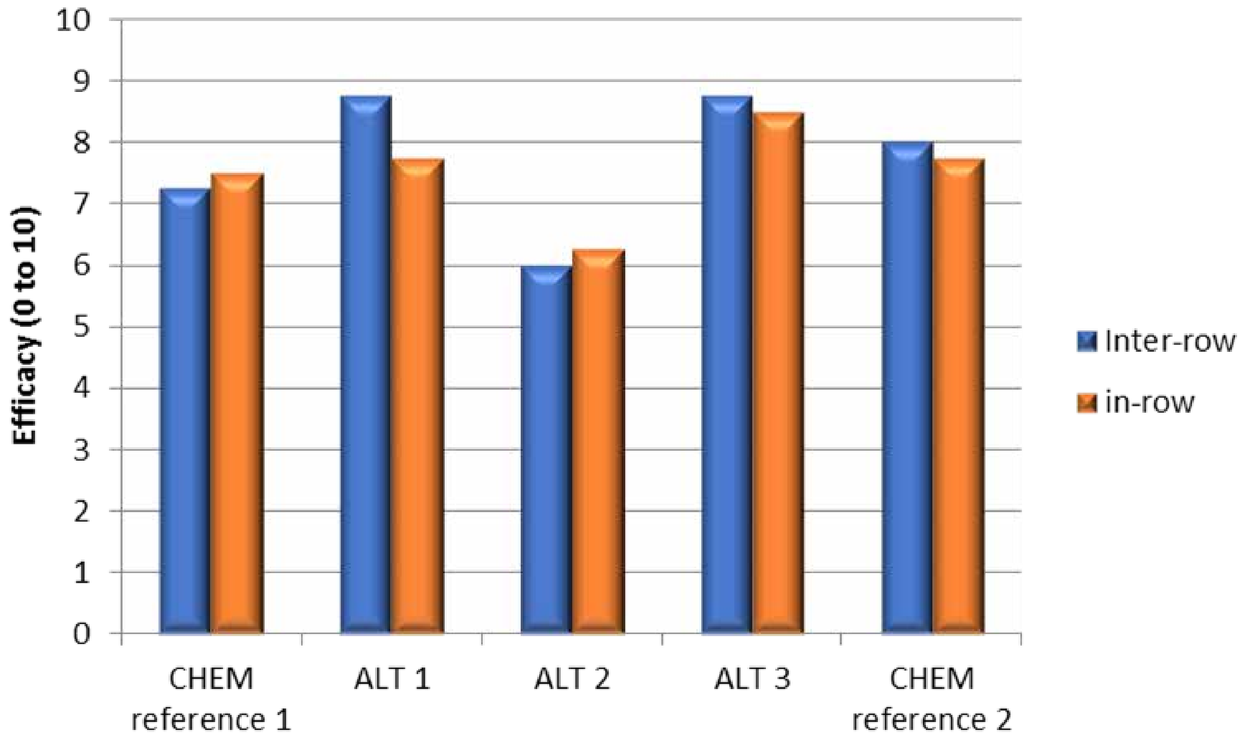

Figure 20 - Efficacy on *Polygonum convolvulus*, inter-row and in-row, in the Belloy sur Somme trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

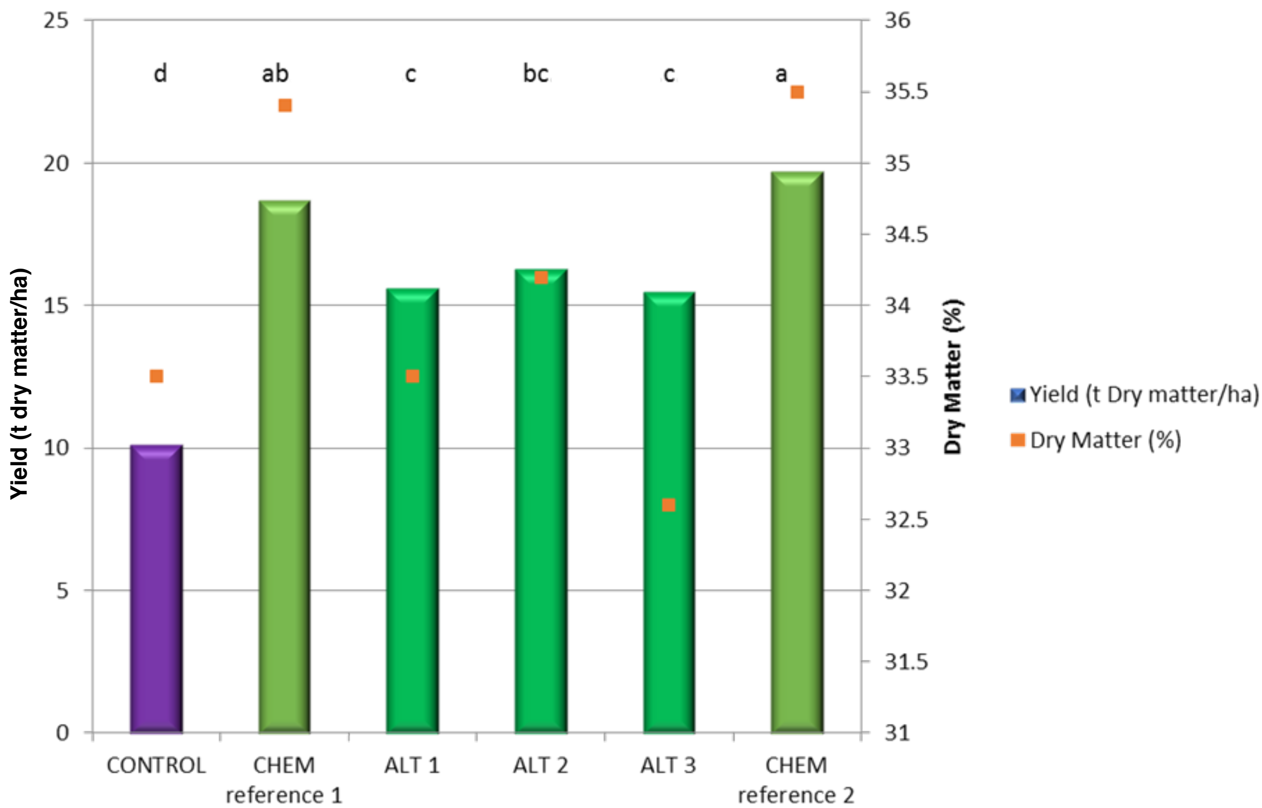

Figure 21 - Yield (in tonnes of dry matter/ha) and percentage of dry matter. Comparison of references to control and alternative strategies in the Belloy sur Somme trial.

TRIAL 3 – MONS (PICARDY) - FORAGE MAIZE

The strategies implemented in forage maize are simpler, being based on farmers' usual practices. In this case, the reference is a pre-emergence only, with Adengo Xtra at 0.44 L/ha. All strategies are detailed in Table 5.

The alternative strategies were based on a localised application and/or complementary hoeing. The part applied locally was 25 cm wide (on 80 cm inter-row), which means a 69% reduction in the quantities applied when compared to a full application. The weeds present in the trial were *Chenopodium album* and *Polygonum convolvulus*.

The efficacy results are presented in Figures 22 and 23 below. The efficacy of the alternative strategies on *Chenopodium album* (lamb's quarter), in the row, were below the references, but at an acceptable level (> 7). In the inter-row, these strategies were very close to the references. Results contrasted more on *Polygonum convolvulus*, with Strategies ALT 1 and ALT 3

Herbicides	Strategy
CONTROL	CONTROL
(T) AdengoXtra 0.44	CHEM reference 1
(Tloc/B2/B4) AdengoXtra 0.44 / Hoeing (x2)	ALT 1
(Tloc/B2/B4) Camix 2.5 / Hoeing (x2)	ALT 2
(Tloc/B2/B4) AdengoXtra 0.44 + Isard 1.2 / Hoeing (x2)	ALT 3
(Tloc/T3) AdengoXtra 0.44 / Capreno 0.2 + Actirob B 1.5	CHEM reference 2

Adengo Xtra = thiencarbazone 90 g/l + isoxaflutole 225 g/l + cyprosulfamid 150 g/l
Camix = S-metolachlor 400 g/l + mesotrione 40 g/l + benoxacor 20 g/l
Capreno = thiencarbazone 68 g/l +tembotrione 345 g/l + isoxadifen 134 g/l
Isard= dimethenamid-P 720 g/l
Actirob B = esterified oil 842 g/l

Table 5 - Strategies implemented in the Mons trial.

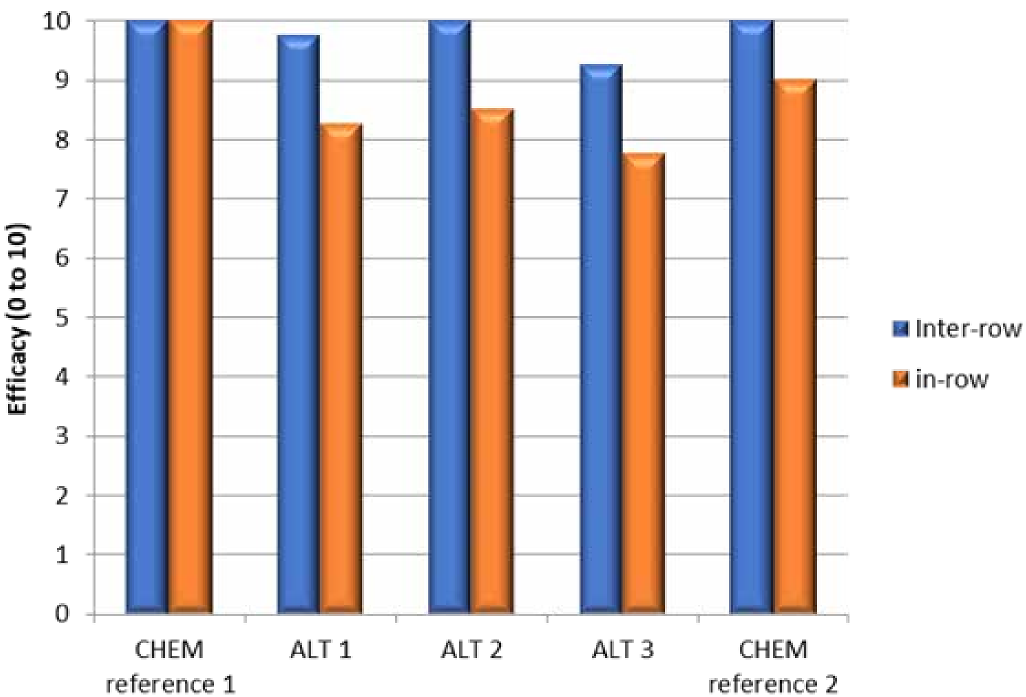

Figure 22 - Efficacy on *Chenopodium album.*

being equivalent/superior to the references. This is due to the herbicide bases used (Adengo Xtra + Isard) on *Polygonum convolvulus*, and especially to the hoeing in the inter-row, which controlled staggered emergence.
The forage yield is reported in Figure 24. The yield measurements showed that the reference modalities were statistically superior to Strategies ALT 1 and ALT 3. These differences can be explained by the competition from goosefoot, which is not well-controlled by these strategies. Strategy ALT 2 was similar to CHEM Reference 1, but statistically inferior

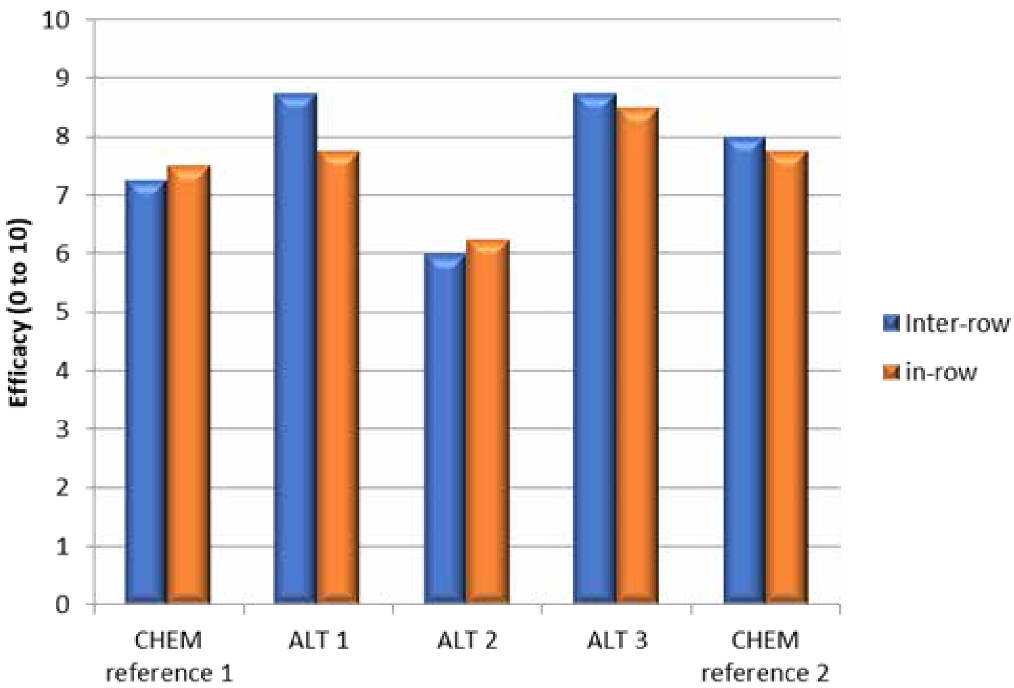

Figure 23 - Efficacy on *Polygonum convolvulus.*

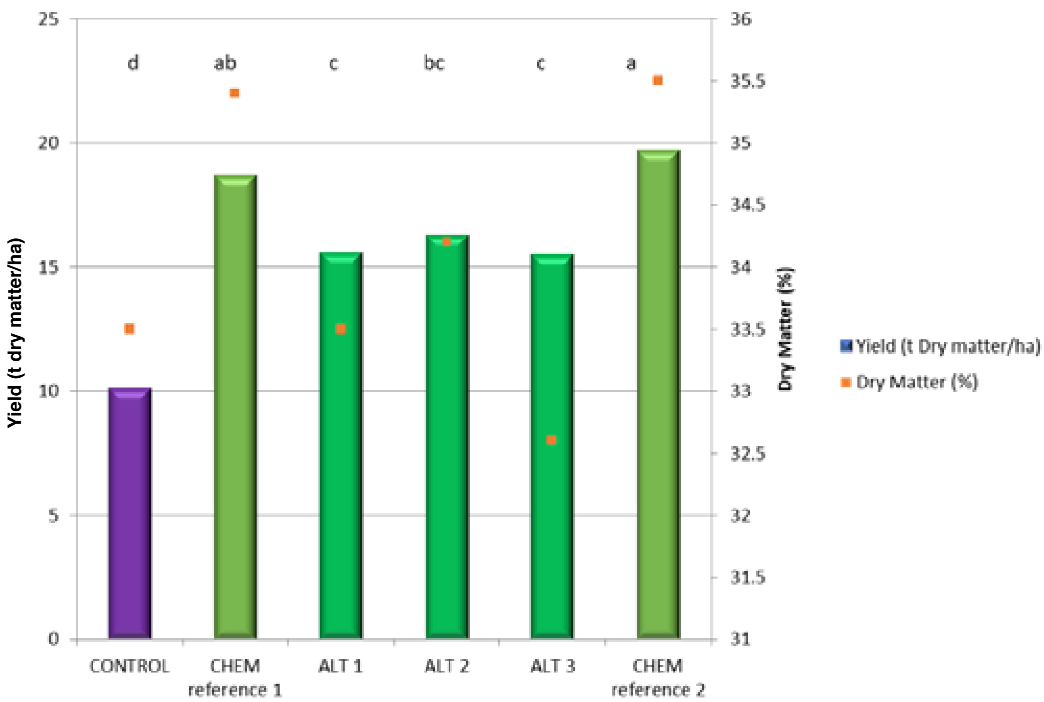

Figure 24 - Yield in tonnes of dry matter and % of dry matter in forage maize for each strategy.

to CHEM Reference 2. The alternative strategies showed interesting effects in efficacy terms in the inter-row (on *Polygonum convolvulus*, in particular), but they were impacted by the lack of control of weeds close to the row. These weeds penalised the maize yield.

TRIAL 4 – BUROS (BEARN) - SEED MAIZE

The second trial was set up on seed maize. This crop is grown in a similar way to grain maize, but producers require better weed control as weeds harm the breeding lines. Moreover, the yield levels are difficult to compare with those of grain maize because part of the area is devoted to the male breeding line, which is not harvested, and the

Strategy code	T1 (pre-emergence)	T2 (post-emergence)	T3 (post-emergence)
CONTROL	-	-	-
CHEM Reference 1	Dual Gold S 2.1 L/ha + Merlin Flexx 1.7 L/ha (in row)	Capreno 0.17 L/ha + ActB 1 L/ha	Laudis WG 0.2 kg/ha + ActB 1 L/ha
ALT 1	Dual Gold S 2.1 L/ha + Merlin Flexx 1.7 L/ha (in row)	Hoeing	Laudis WG 0.2 kg/ha + ActB 1 L/ha
CHEM Reference 2	Isard 1.2 L/ha + Merlin Flexx 1.7 L/ha (in row)	Capreno 0.17 L/ha + ActB 1 L/ha	Laudis WG 0.2 kg/ha + ActB 1 L/ha
ALT 2	Isard 1.2 L/ha + Merlin Flexx 1.7 L/ha (in row)	Hoeing	Laudis WG 0.2 kg/ha + ActB 1 L/ha
CHEM Reference 3	Dual Gold S 2.1 L/ha + Merlin Flexx 1.7 L/ha	Capreno 0.17 L/ha + ActB 1 L/ha	Laudis WG 0.2 kg/ha + ActB 1 L/ha
ALT 3	(in row)	Hoeing	Laudis WG 0.2 kg/ha + ActB 1 L/ha

Dual Gold S = S-metolachlor 915 g/l + benoxacor 45 g/l
Merlin Flexx = isoxaflutole 44 g/l + cyprosulfamid 44 g/l
Isard = DMTA-P 720 g/l
Capreno = thiencarbazon 68 g/l + tembotrione 345 g/l + isoxadifen-ethyl 134 g/l
Laudis WG = tembotrione 44 g/l + isoxadifen-ethyl 22 g/l
Actirob B = esterified oilseedrape 842 g/l

Table 6 - Protocol set up in Buros in seed maize, on four blocks. Each reference can be compared to the equivalent one with hoeing. Moreover, Chem 1/Alt 1 can be compared to Chem 3/Alt 3 to evaluate the effect of Isard 0.6 l/ha.

Variety & sowing date	T1 (pre-emergence) date	T2 (post-emergence) date	T2 (post-emergence) date	T3 (post-emergence) date	Weeds (density in pl/m²)
DF 12 (08/05/2020) at 9.9 pl/m², and 80 cm row width	12/05/2020	27/05/2020 at 3 leaves. Hoeing with Ribouleau machinery (3.5 km/ha, 3 cm depth)	28/05/2020 at 3 leaves	03/06/2020 at 6 leaves	*Echinochloa crus-galli* (25 pl/m²), *Digitaria sanguinalis* (74 pl/m²), *Solanum nigrum* (65 pl/m²), *Chenopodium album* (44 pl/m²). Assessment on 03/06/2020

Table 7 - Trial conditions and details of the applications and hoeing in Buros.

harvested female breeding lines are not a hybrid, and their density is limited.
This trial in Buros is a comparison of the traditional herbicide programmes in seed maize (three types of programme) with their equivalent, but one application was replaced with a hoeing pass. Details of the trial are described in Tables 6 and 7.
This trial was set up to study the value of pre-emergence herbicide on the maize row in seed production and the introduction of post-emergence hoeing. It allows us to compare two strategies after pre-emergence localised on the row, i.e. a double

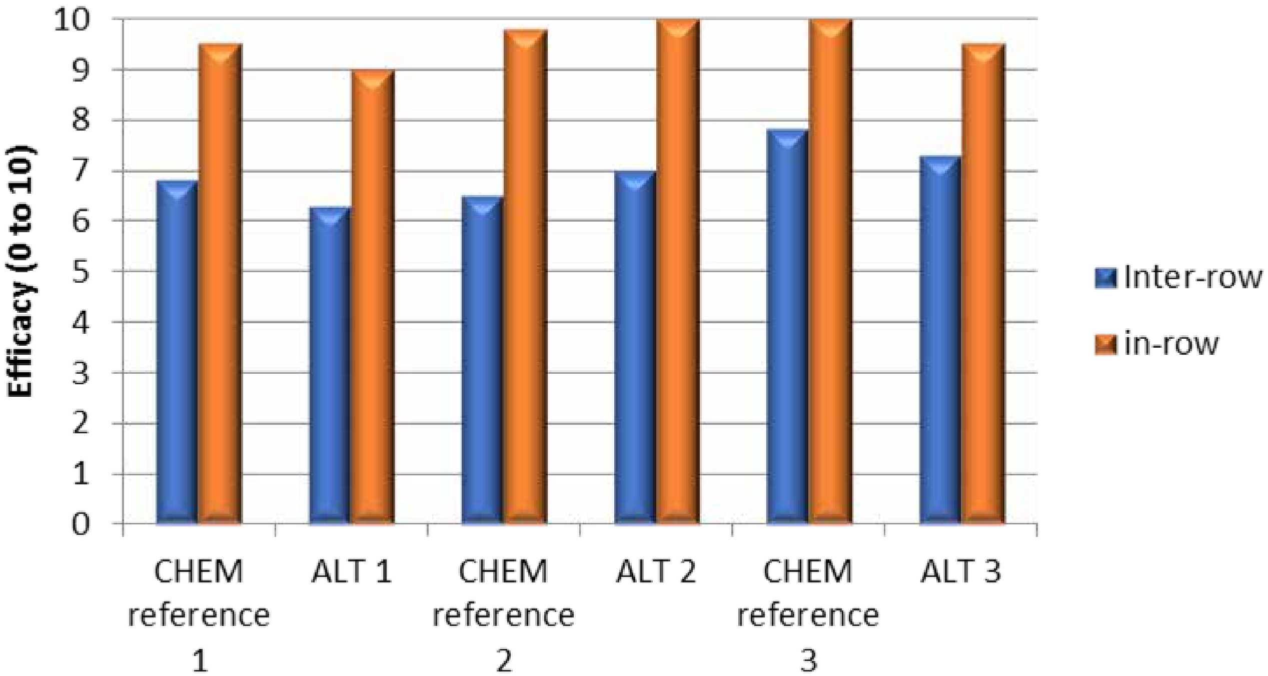

Figure 25 - Global efficacy, inter-row and in-row, in the Buros trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

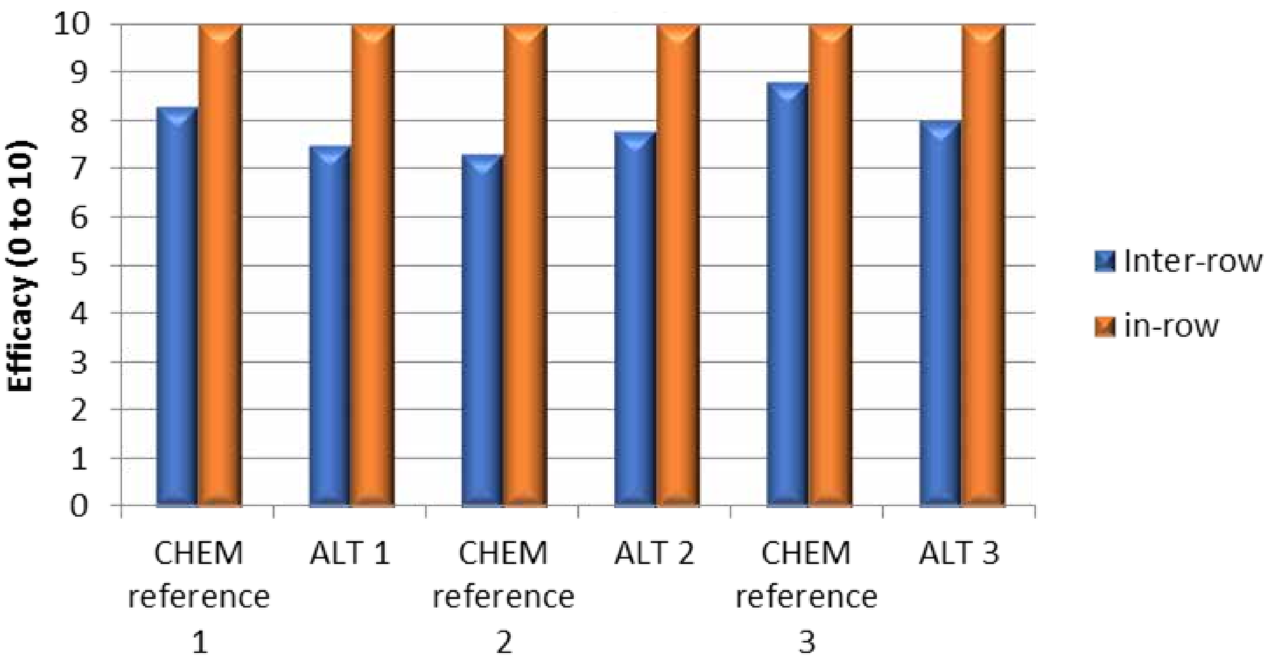

Figure 26 - Efficacy on *Echinochloa crus-galli*, inter-row and in-row, in the Buros trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

Date	Weed	Stage	Density (pl/m²)
6/9/2020	*Echinochloa crus-galli*	2 leaves	25.0
6/9/2020	*Digitaria sanguinalis*	1 leaf to 1 tiller	74.0
6/9/2020	*Solanum nigrum*	6 leaves	65.0
6/9/2020	*Chenopodium album*	6 leaves	44.0

Table 8 - Weeds in the Buros trial.

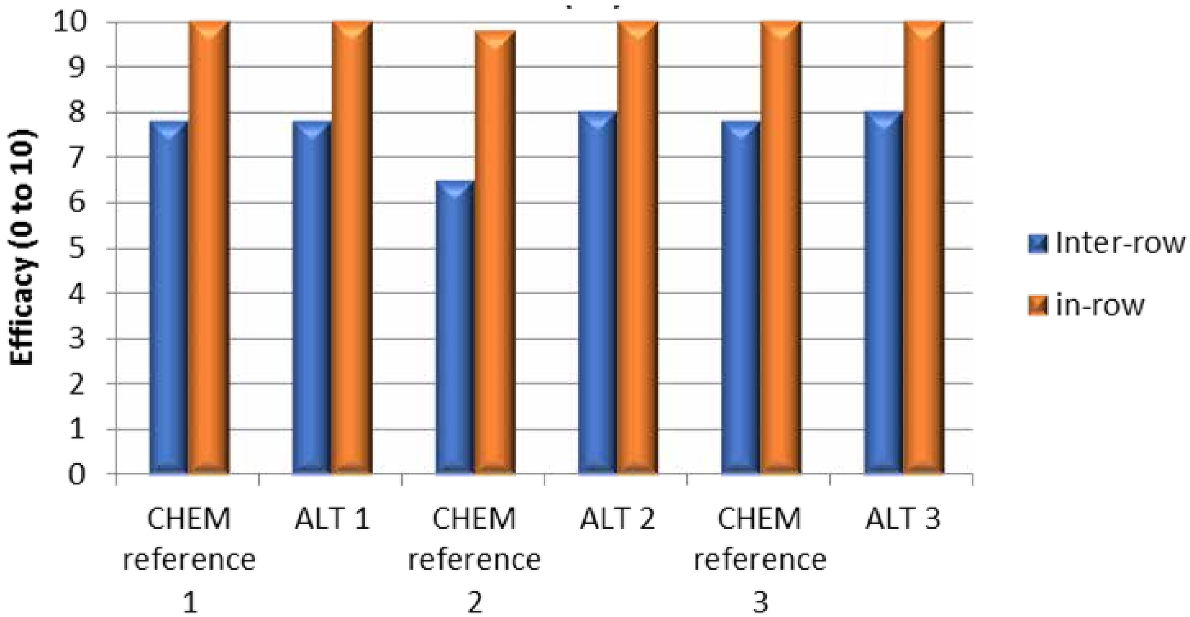

Figure 27 - Efficacy on *Digitaria sanguinalis*, inter-row and in-row, in the Buros trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

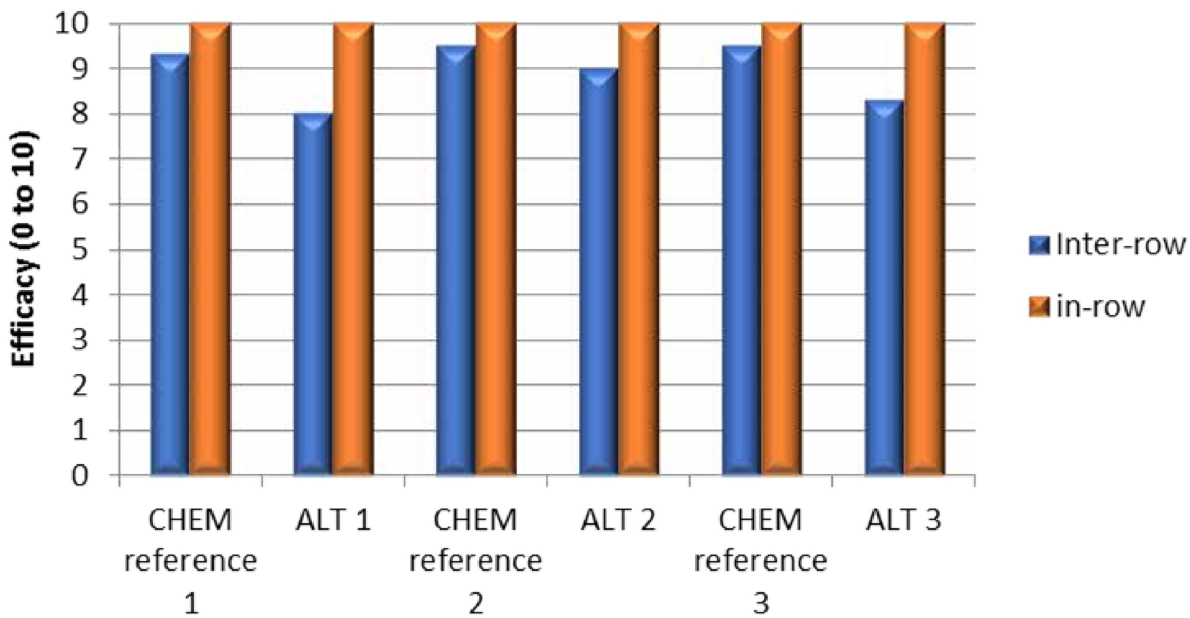

Figure 28 - Efficacy on *Solanum nigrum*, inter-row and in-row, in the Buros trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

post-emergence chemical strategy on the one hand and hoeing followed by a chemical strategy on the other. The treatments, both chemical and mechanical, were carried out in conditions favourable to efficacy. The flora of the plot was relatively dense, with about 100 grasses per m² and about a hundred diversified broadleaved weeds (Table 8). At 13 leaves of the crop, results showed an equivalent efficacy for all strategies (Figures 25, 26, 27, 28 and 29). In all cases, the row was generally cleaner than the inter-row, for the benefit of the localised pre-emergence treatment. In 2020, the conditions for hoeing were favourable to efficacy, which makes it an equivalent intervention in efficacy terms to a chemical strategy carried out at the same stage.
The trial field was harvested and yields varied between

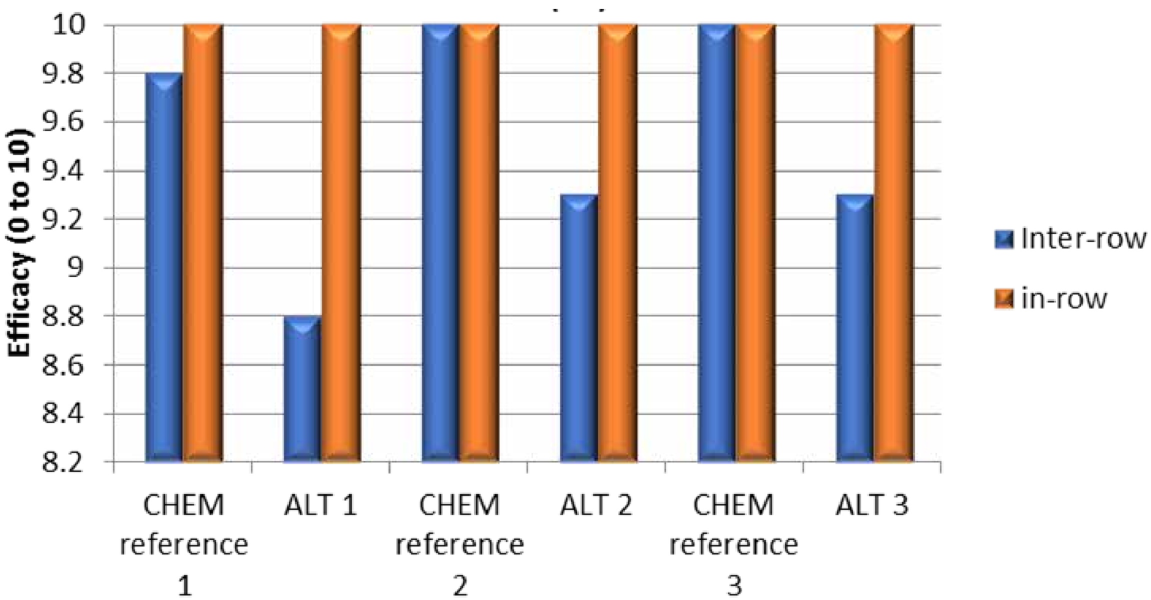

Figure 29 - Efficacy on *Chenopodium album*, inter-row and in-row, in the Buros trial. Efficacy is evaluated from 0 (as control) to 10 (no weeds).

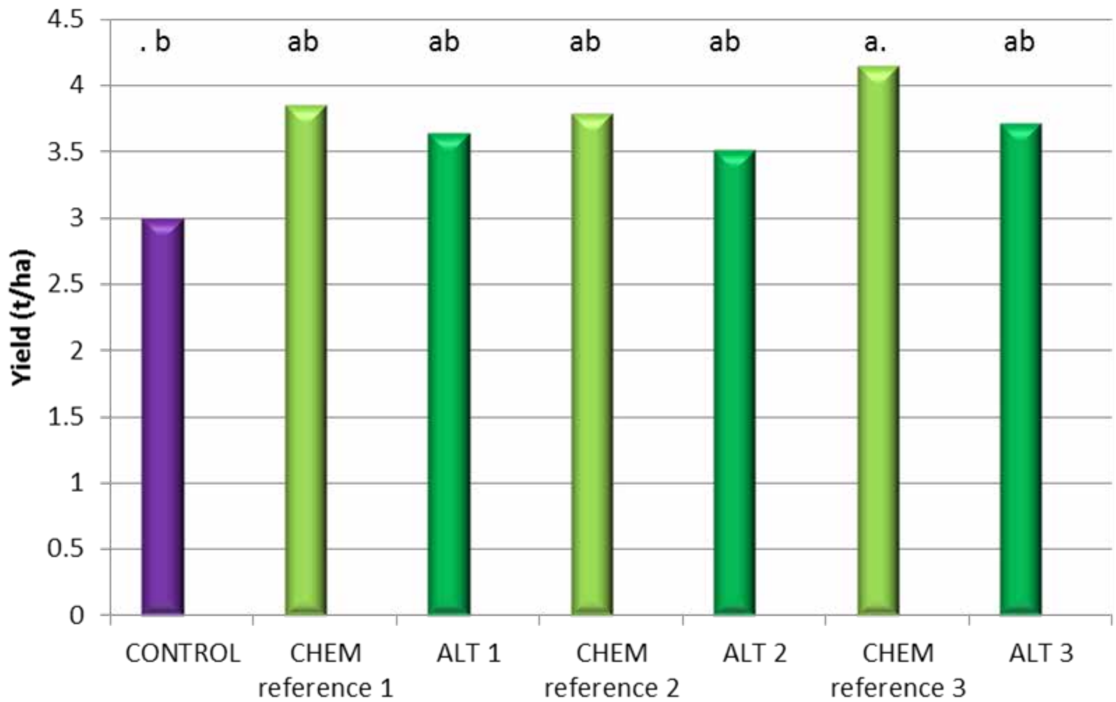

Figure 30 - Yield (in t/ha). Comparison of references with control and alternative methods in the Buros trial.

3.5 and 4.1 q/ha, with no significant difference between strategies (excluding the control) (Figure 30). The alternative strategies showed levels of efficacy and selectivity (an important notion for seed producers) equivalent to the herbicide references. These elements can provide seed producers with an incentive to integrate hoeing in a safe way. However, further trials need to be conducted to ensure the repeatability of these results.
On this high-value crop, weed competition can be very damaging. Therefore, weed control practices are essentially based on herbicides, but with one major limitation: selectivity, because the variety strains are quite sensitive to herbicides. Farmers must therefore find the right compromise between efficacy and selectivity. Alternative methods such as hoeing and localised application are very interesting for this type of crop.
The Reference strategy is based on a localised application in pre-emergence (dimethenamid + S-metolachlor combination) followed by an application at 4 leaves (thiencarbazone + tembotrione) and a last one at 6 leaves (tembotrione). The alternative strategies are based on the integration of hoeing at T2 (4 leaves) to replace a thiencarbazone + tembotrione combination. Each reference herbicide modality is based on different localised pre-emergence treatments. The weeds present in the trial are presented in Table 8.
The efficacy results showed that Strategies ALT 2 and ALT 3 are lower, but close to the chemical references. On yield, the CHEM 3 reference was significantly higher than the control, by 1.15 t/ha. This was the only difference in the trial, as all the alternative strategies were statistically identical to their chemical counterparts. The difference can be explained by better control of weeds, with a herbicide programme better adapted to the them.

2021 SEASON

TRIAL – PUSIGNAN (RHÔNE-ALPES) - GRAIN MAIZE

Following the 2020 trials, a grain maize trial was set up in Pusignan (Rhône-Alpes). The strategies

STRATEGY	Pre-emergence	5-6 leaves of maize	5-6 leaves of maize	11-12 leaves of maize
	14/04/2021	20/05/2021	26/05/2021	11/06/2021
CONTROL				
CHEM REF 1	ADENGO_XTRA 0.44	-	-	-
CHEM REF 2	ADENGO_XTRA 0.33 + ISARD 1 on row	PAMPA 0.5 + PREDOMIN 0.2 + ACTIROB_B 1		
CHEM REF 3	ADENGO_XTRA 0.44 on row	CAPRENO 0.2 + ACTIROB_B 1.5	-	-
ALT 1	ADENGO_XTRA 0.44 on row	-	Hoeing	Hoeing
ALT 2	ADENGO_XTRA 0.44 + ISARD 1 on row	-	Hoeing	Hoeing
ALT 3	CAMIX 2.5 on row	-	Hoeing	Hoeing
ALT 4	ADENGO_XTRA 0.33 on row	ISARD 0.8 + PAMPA 0.5 + PREDOMIN 0.2 + ACTIROB_B 1 on row	Hoeing	Hoeing

Adengo Xtra = thiencarbazone 90 g/l + isaxaflutole 225 g/l + cyprosulfamide 150 g/l
Camix = S-metolachlor 400 g/l + mesotrione 40 g/l + benoxacor 20 g/l
Isard = Dimethenamid-P 720 g/l
Pampa = Nicosulfuron 40 g/l
Capreno = thiencarbazone 68 g/l + tembotrione 345 g/l + isoxadifen 134 g/l
Predomin = tritosulfuron 250 g/kg + dicamba 500 g/kg
Actirob B = esterifed oil 842 g/l

Table 9 - Strategies implemented in the Pusignan maize trial.

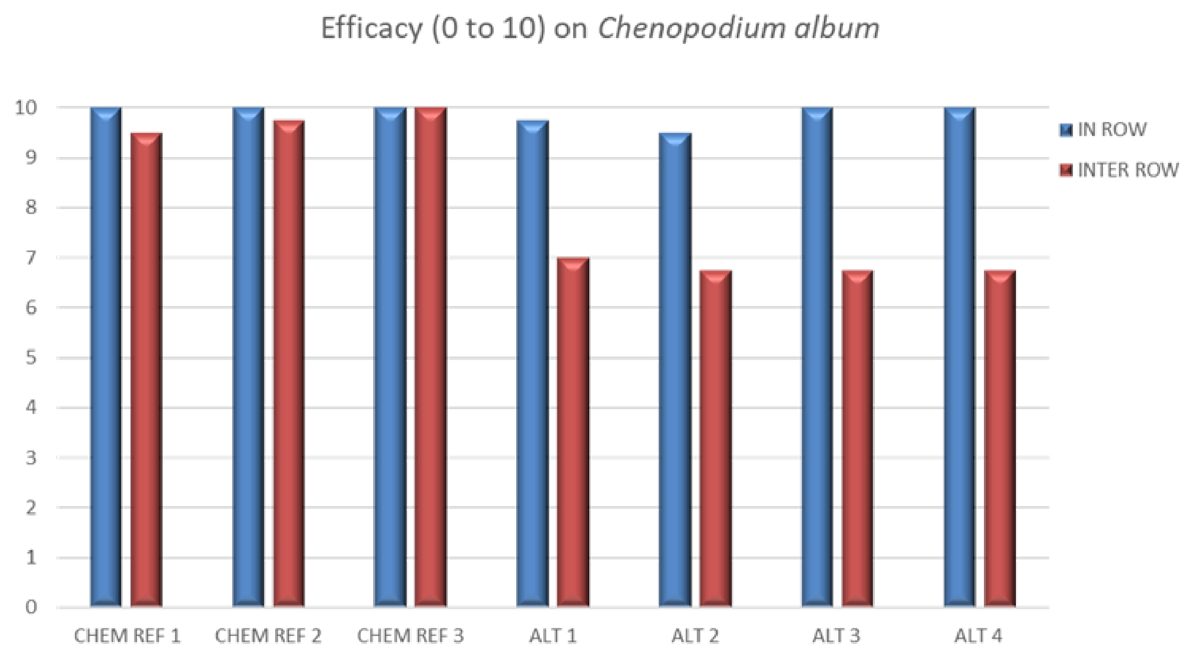

Figure 31 - Efficacy on *Chenopodium album.*

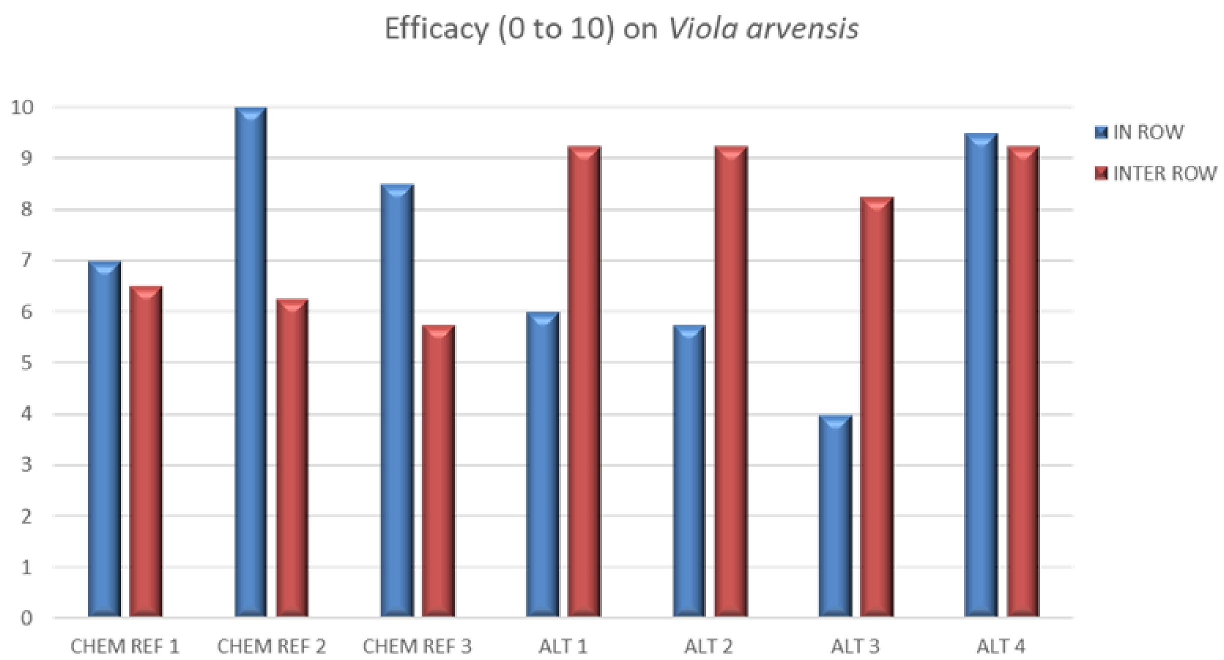

Figure 32 - Efficacy on *Viola arvensis.*

implemented were similar to those of the previous years, i.e. localised pre-emergence weeding, followed by hoeing. A variant was introduced this season, with localised post-emergence treatment.
The details of the strategies, plus date of application/hoeing, are presented in Table 9 below. The trial was sown on 07/04/2021, with variety RGT URBANIXX. The interventions were disturbed by rain, so Strategy ALT 4 was modified: the hoeing planned on 20/05/2021 could not be carried out; the post-emergence application on the row was carried out before it.
The weeds present were *Chenopodium album* (5 to 10 pl/m²), *Viola arvensis* (5 to 10 pl/m²), and *Geranium dissectum* (5 to 10 pl/m²). The efficacy results are presented in Figures 31, 32 and 33 below.
On *Chenopodium album*, the alternative strategies

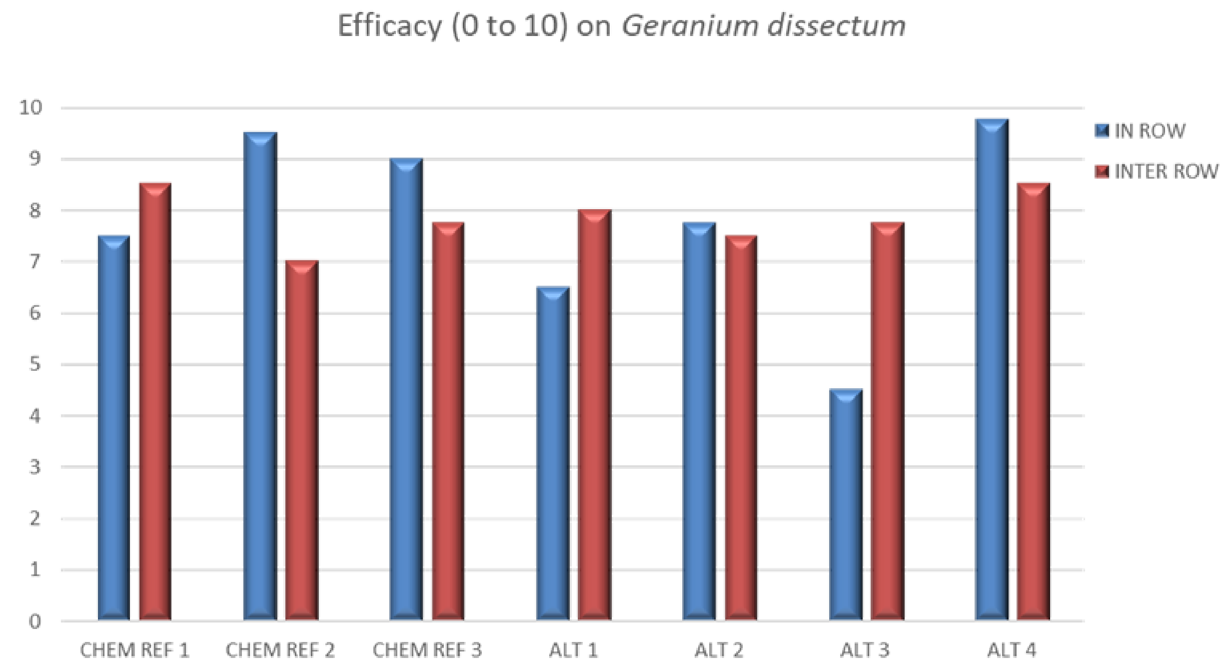

Figure 33 - Efficacy on *Geranium dissectum.*

were less effective in inter-row; on the other hand, they were comparable to the references in the row. On *Viola arvensis*, the efficacies of alternative strategies in-row are lower, except for Strategy ALT 4. The references, with their more complete herbicide solutions, explain these differences. On the other hand, the alternative solutions were more effective in the inter-row. Hoeing control staggered emergence, especially in the climatic context of spring 2021. Strategy ALT 4 was very effective in-row and inter-row. The post-emergence localised application was especially effective on Viola.
On *Geranium*, the differences were essentially based on the herbicides, which were more or less effective on this weed. Thus, Strategy ALT 3 was penalised because Camix does not control *Geranium*. The efficacies in the inter-row were quite similar between strategies. Note the good performance of Strategy ALT 4, with the contribution of the post-emergence localised application on *Geranium* (tritosulfuron was effective in this case).

EXPERIMENTATION ON SUGARBEET

(Partner: Chambre d'Agriculture d'Île-de-France)

2020 SEASON

TRIAL – ST GERMAIN-LAXIS (BRIE)

The objective of this trial was to define the best weed-control strategy by combining chemical treatment and mechanical tillage by hoeing, while limiting the impact on the environment as much as possible.
A mixture of three to four different chemical products was tested in eight programmes. The theoretical impact of these treatments was measured by calculating the herbicide TFI (Treatment Frequency Index linked to herbicides): the maximum considered TFI varied, depending on the method, from 1.4 to 5.5. In addition, for each method, half of the plots only underwent chemical treatment, and the other half was treated with half chemical treatment + mechanical tillage by hoeing.
Context: beets sown on 03/22/2020, on churning silt soil. Rapid and homogeneous emergence, classic low-density flora.
Results (plants/m²): *Solanum nigrum* 12, oilseed rape volunteers 3, *Polygonum aviculare* 1, *Chenopodium album* 0.5.
The herbicide treatments were carried out on 10/04/2020, 17/04/2020 and 04/05/2020. Hoeing was carried out on the mid-length of the plots on

	Code	Chemical (2 to 4 applications)				Herbicide TFI min	Herbicide TFI max
1	**BTGV**	Bettapham	Boxer SC 500	Grizzli VXT	Venzar SC	2.77	5.54
2	**TGV**		Boxer SC 500	Grizzli VXT	Venzar SC	2.50	5
3	**TG0.5V**		Boxer SC 500	Grizzli VXT	Venzar SC	2.65	5.30
4	**T0.3GV**		Boxer SC 500	Grizzli VXT	Venzar SC	2.70	5.40
5	**TGS**		Boxer SC 500	Grizzli VXT	Safari	1.05	2.10
6	**TGSd**		Boxer SC 500	Grizzli VXT	Safari duo active	1.65	2.30
7	**TGSC**	Centium 36 CS	Boxer SC 500	Grizzli VXT	Safari	1.05	2.10
8	**T0.3G0.5V**		Boxer SC 500	Grizzli VXT	Venzar SC	0.70	1.4

Bettapham = phenmedipham
Boxer SC 500 = ethofumesat
Grizzli VXT = metamitron
Venzar SC = lenacil
Safari = triflusulfuron-me
Safari duo active = triflusulfuron-me + lenacil
Centium 36 SC = clomazon

Table 10 - Chemical applications in the St Germain-Laxis trial.

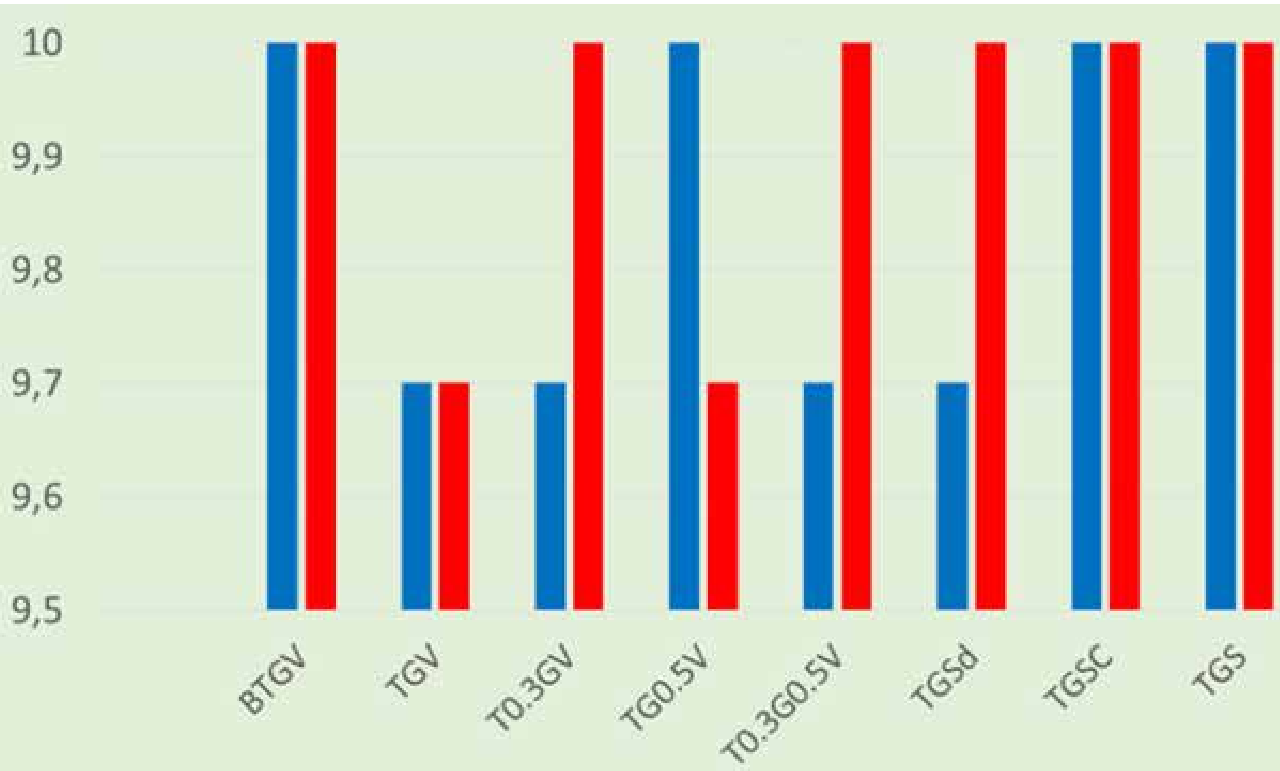

Figure 34 - Efficacy (scale from 0 to 10) on 27/05/2020. Blue with mechanical, red without mechanical.

Figure 35 - Hoeing carried out on the mid-length of the plots on May 14 at 10 sugar-beet leaves in the St Germain-Laxis trial.

14/05/2020 at 10 leaves from the beets stage. The climatic conditions of the year did not require a fourth herbicide pass or additional mechanical pass.

Conclusion

Additional methods are an essential complement to the use of mechanical tools, e.g. false seedbed, shifting of cereal sowing dates and diversification of rotations, as well as any method contributing to reducing weed pressure in the plots.

EXPERIMENTATION ON PROTEIN PEAS

(Partner: Chambre d'Agriculture d'Île-de-France)

2020 SEASON

TRIAL – VALLANGOUJARD (VEXIN)

The Vallangoujard trial is a continuation of the achievements of 2018 and 2019. It was carried out by a farmer who practices no tillage in order to preserve the organic matter, structure and microbiological activity of his soil; he has not tilled his plots for 20 years. Today, he has to deal with an infestation by ryegrass (more than 500 per m²) which penalises his yields.
Several solutions that combine mechanical and chemical treatments were tested:
- Deep tillage [**DT**] every four years (ploughing at 30 cm depth), then superficial tillage with stale seedbeds and sowing combined with tillage (rotary harrow);
- Pseudo-ploughing [**PP**] (15 cm deep) followed by false seedbed [**FSB**] and direct sowing, or sowing combined with tillage (rotary harrow);
- Very shallow but regular tillage (false seedbed) [**FSB**] and direct sowing, or sowing combined with tillage (rotary harrow);
- "No tillage" [**NT**] (only chemical weeding) with direct sowing, with and without cover crop.

In 2018 and 2019, the trial was conducted on winter wheat. In the autumn of 2019, the plot was initially meant to receive a winter pea. The objective was to allow weeding with a different family of herbicides (Kerb Flo) and to free up the plot earlier to carry out more stale seedbeds during the intercropping period, or to establish cover earlier in the conservation agriculture modality.
However, autumn sowing was not possible due to weather conditions (continuous rain) which made the plot inaccessible to machinery. This crop was therefore replaced by a spring pea sown on 23/03/2020. The following table summarises the different methods tested in the Vallangoujard multi-year trial since 2018 and the protocol initially planned for 2020.
For the first year, two sowing dates were carried out to assess the impact of shifting the sowing date on the presence of weeds in the plot.
Context: spring protein peas, sown on 03/23/2020, on loamy clay soil, ryegrass density between 2 and 30 ryegrass/m² (low to medium density), initially > 800 ryegrass/ m² in 2018.
In the results below, the establishments were carried out with a disk seeder for the first four strategies, with a combined rotary harrow and seeder for the last three strategies.
Annual results: the results of the 2020 observations (Figure 37) showed a clear disadvantage to the direct seed drill. However, these results are probably due to the cultivation conditions of the farm, which does not practice direct seeding and therefore does not adapt its herbicide application conditions for weeding. In

direct seeding, the residues of the previous crops and the inter-crop covered the surface of the soil and required the application of root herbicide products in different conditions than in a ploughing or tillage situation. Hence, a bias for the direct seeding conditions in this trial in which the first four strategies were negatively impacted.

Multi-year results: the results of the observations (Figure 38) obtained over the three-year trial revealed disparate situations. In the first year, the ryegrass populations were very high, especially for the “direct sowing without cover” modality, with more than 800 ryegrass/m², and very low for the ploughing strategy, with 2 ryegrass/m². After three years, the differences were still there, and sowing with a combination of rotary harrow and seeder proved to be the most favourable. However, it can be seen that the situation greatly improved, even though ryegrass densities above 10/m² were still too high to no longer have an impact on the productivity of the plots.

We could see the effectiveness of levers, such as ploughing, or pseudo-ploughing, and false seedbeds. It seems that direct seeding makes it more complicated to manage weed problems.

Figure 36 - Aerial view of the Vallangoujard trial.

		1	2	3	4	5	6	7
2018 wheat	Soil tillage	PP + FSB	FSB	NT without cover crop	NT with cover crop	FSB	PP + FSB	DT + FSB
	Sowing	Disk seeder				Rotary hoe		
2019 wheat	Soil tillage	PP + FSB	FSB	NT without cover crop	NT with cover crop	FSB	PP + FSB	FSB
	Sowing	Disk seeder				Rotary hoe		
2020 peas	Soil tillage	PP + FSB	FSB	NT without cover crop	NT with cover crop	FSB	PP + FSB	FSB
	Sowing	Disk seeder				Rotary hoe		

PP = pseudo ploughing, FSB = false seedbed, NT = no tillage, DT = deep tillage

Table 11 - Protocol of the Vallangoujard trial.

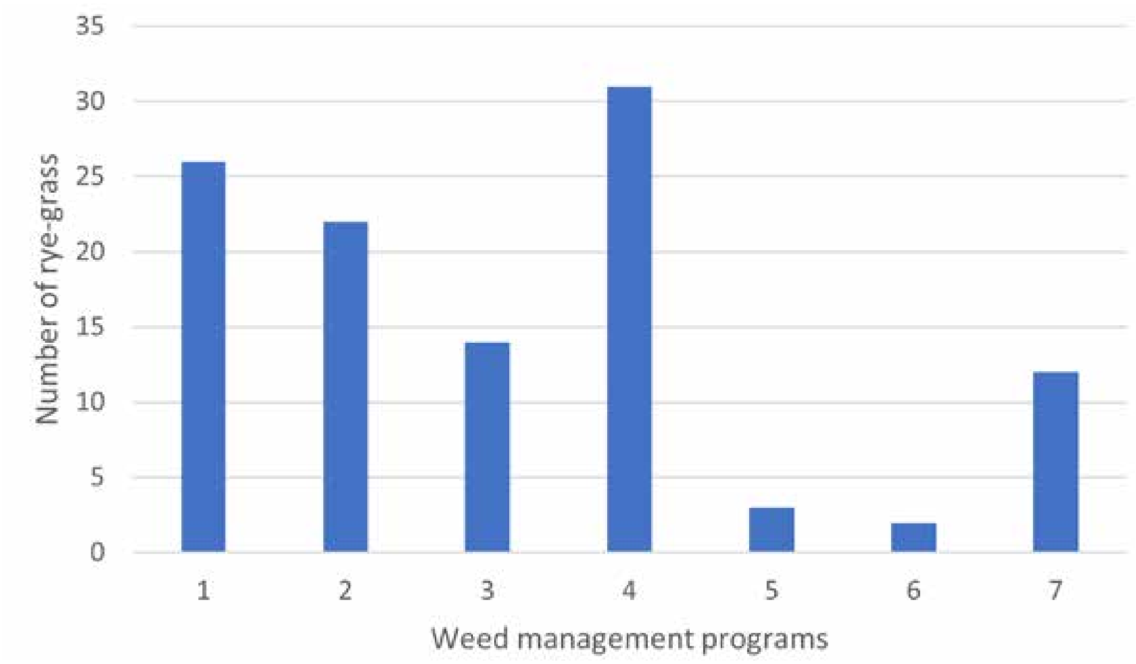

Figure 37 - Population of ryegrass June 2020 in the Vallangoujard trial.

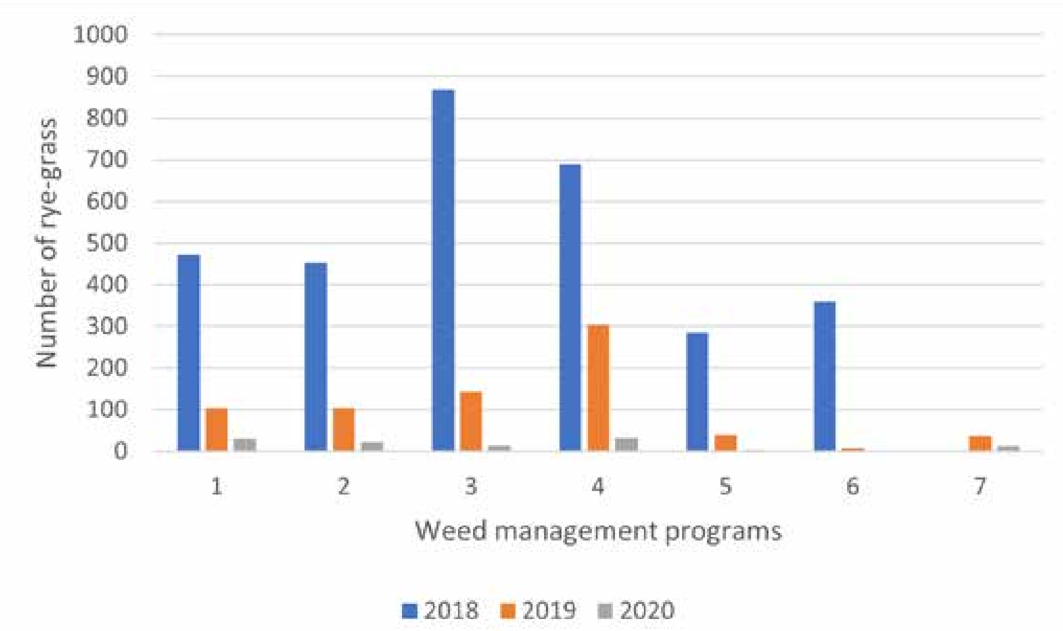

Figure 38 - Population of ryegrass over 3 years (2018 to 2020) in the Vallangoujard trial.

UNITED KINGDOM

EXPERIMENTAL TRIALS AT NIAB

The NIAB Group is the UK's fastest growing crop science organisation, having trebled in size over the past decade through a strategic programme of investment, merger and acquisition. NIAB's headquarters is based in Cambridge, with regional centres across the midlands, eastern England and the South, and has farmer membership across the country. NIAB works with a network of scientific partnerships and collaborates with leading commercial and research organisations in the UK, Europe and globally. IWMPRAISE research has been conducted at NIAB Cambridge and East Malling.

Figure 1 - NIAB's headquarters and Regional Centres.

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93 Lawrence Weaver Road
Cambridge
CB3 0LE, UK
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AN INNOVATIVE APPROACH TO BLACK-GRASS CONTROL IN WINTER BARLEY

Centre: Cambridge

Objectives

- Evaluate ways in which herbicide loading on the crop can be reduced by targeting herbicide application to the crop row;
- Explore how inter-row cultivations can be used to control black-grass in narrow crops.

Summary

- Narrow row widths were associated with lower black-grass head density;
- Herbicides were ineffective, and generally caused an increase in black-grass head density;
- Inter-row cultivation was effective when combined with wider row spacing.

Materials and Methods

This trial began in the spring of 2020 in spring barley (cv. RGT Planet) sown at two different row widths – 16.7 cm and 33.4 cm. Across these, different combinations of herbicide mix, application technique and inter-row cultivations were compared. The main target was *Alopecurus myosuroides* (black-grass). Assessment of black-grass seedling density, black-grass head density and crop ear density was made.

The herbicide treatment was Liberator (0.3 l/ha) + Hurricane (0.12 l/ha) applied pre-emergence of crop and weed.

Treatment	Row Width	Herbicide Application	Inter-row cultivation
1	Narrow	Untreated	None
2		Treated (whole area)	
3		Untreated	1-3 true leaves of the weed
4		Treated (whole area)	
5	Wide	Untreated	None
6		Treated (whole area)	
7		Treated (crop row only)	
8		Untreated	1-3 true leaves of the weed
9		Treated (whole area)	
10		Treated (crop row only)	

Table 1 - List of treatments.

Figure 1 - The nozzle set to spray over the row.

Operation	Date	Relative to drilling date (days after)
Drilling	26/03/2020	0
Pre-em (broad-acre)	30/03/2020	4
Pre-em (on-row)	03/04/2020	8
Inter-row cultivation	14/04/2020	19

Table 2 - Key dates.

Row width	Black-grass density		Estimated black-grass heads per plant
	Seedlings	Heads	
Narrow	71.6	3.5	0.07
Wide	55.2	11.5	0.20

Table 3 - Weed Population in untreated plots (per m²).

Treatment	Row Width	Herbicide Application	Treatment Mean	Mean across Row Width	Mean across Herbicide
1 & 3	Narrow	Untreated	70.9	71.6	59.5
2 & 4		Treated (whole area)	72.3		68.0
5 & 8	Wide	Untreated	48.1	55.1	
6 & 9		Treated (whole area)	63.7		
7 & 10		Treated (crop row only)	53.6		53.6

Table 4 - Weed seedling density (per m²) prior to inter-row hoeing.
A two-way ANOVA indicates that row width was the only significant factor (p= 0.049).

Trt	Row Width	Herbicide Application	Inter-row cultivation	Treatment Mean	Mean across Row Width	Mean across Herbicide	Mean across Inter-row Cultivation
1	Narrow	Untreated	None	3.5	5.1	4.9	11.1
2		Treated (whole area)		6.4		10.3	
3		Untreated	1-3 true leaves of the weed	2.9			6.8
4		Treated (whole area)		7.7			
5	Wide	Untreated	None	12.5	11.5		
6		Treated (whole area)		18.4			
7		Treated (crop row only)		14.7		14.3	
8		Untreated	1-3 true leaves of the weed	0.8			
9		Treated (whole area)		8.5			
10		Treated (crop row only)		14.0			

Table 5 - Black-grass head population (per m²).
A two-way ANOVA indicates that row width was the only significant factor (p= 0.005).

Trt	Row Width	Herbicide Application	Inter-row cultivation	Treatment Mean	Mean across Row Width	Mean across Inter-row Cultivation
1	Narrow	Untreated	None	364.7	361.7	356.9
2		Treated (whole area)		364.7		
3		Untreated	1-3 true leaves of the weed	348.0		382.9
4		Treated (whole area)		369.3		
5	Wide	Untreated	None	374.0	370.4	
6		Treated (whole area)		346.7		
7		Treated (crop row only)		334.7		
8		Untreated	1-3 true leaves of the weed	414.0		
9		Treated (whole area)		430.0		
10		Treated (crop row only)		323.0		

Table 6 - Crop ear population (per m^2).
A two-way ANOVA indicates that herbicide and inter-row cultivation were both significant factors.
The interaction between row width and inter-row cultivation was also significant ($p = 0.006$).

Row Width

The use of wide rows in conventional weed management is uncommon as they reduce the ability for the crop to compete with the weed, increasing relative seed return compared to narrow row set-ups. However, when considering more radical control methods, they become more attractive as they enable a greater area to be cultivated and offer more flexibility in the timing of cultivation. Lower densities of black-grass seedlings were observed in the wide rows (Figure 2), which is an outcome from the overall lower disturbance of soil during establishment. However, with a less competitive crop, the weed has had greater opportunity to tiller and produce seed-bearing heads, as seen in Figures 3 and 4.

Herbicide application

The exciting opportunity with this trial was to look at reducing overall herbicide loading by only applying herbicide to the crop-row. In this example a 12cm band of herbicide was applied over each of the crop rows in the wide row configuration, with an

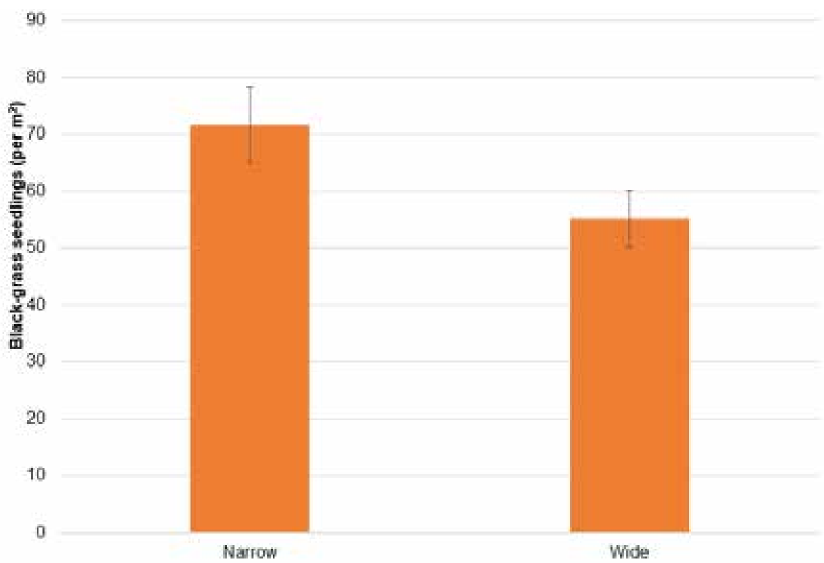


Figure 2 - The effect of crop row width on black-grass seedling density.

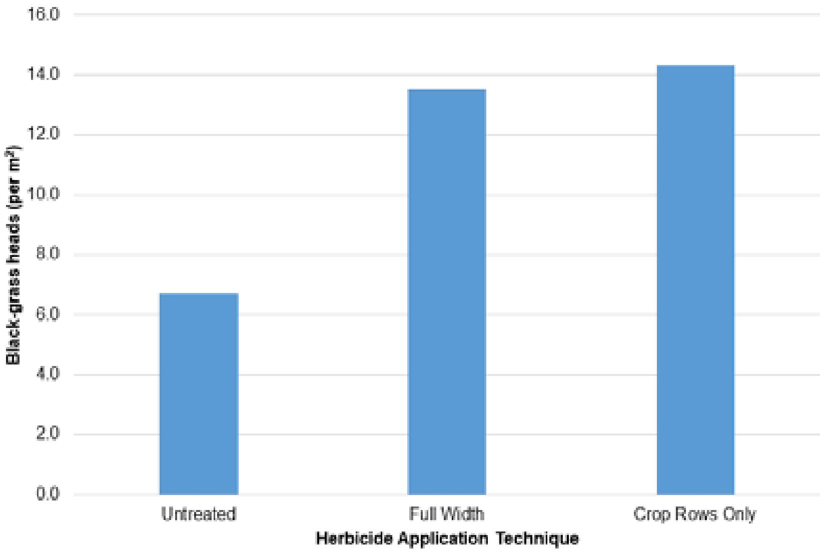


Figure 3 - The control of heads from different herbicide application techniques in wide-row spring barley.

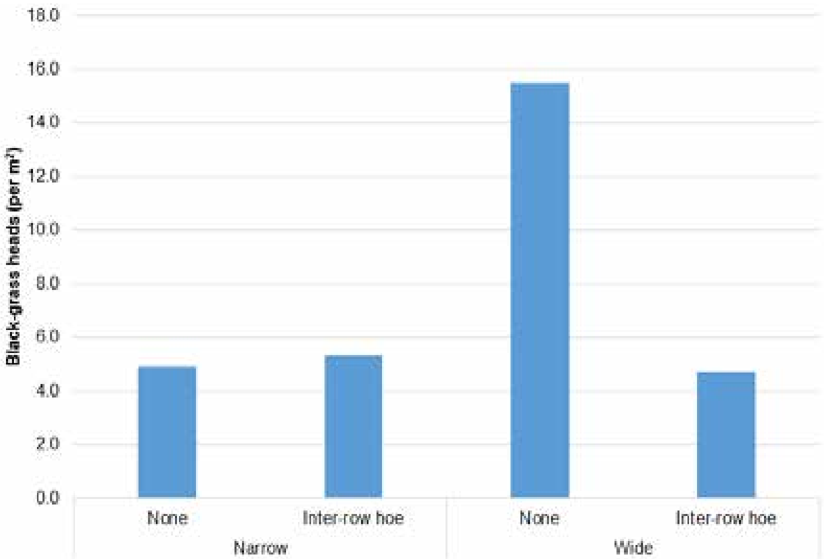


Figure 4 - The effect of row width and the use of inter-row cultivation on black-grass head density.

effective reduction of 64% in herbicide loading. In this example there has been no significant increase in weed burden as a result (see Figure 3). This finding lends further support to minimising the use of any graminicide in spring barley crops.

Inter-row cultivation

In this season, a single pass of the machine was made when the weed was between one and three true leaves, regardless of row width. The machine was set to work at an optimum balance between crop damage and weed control, so that the depth of the A-blades was set at 2-3cm in the narrow rows, and 3-5cm for the wider rows, with an operating speed of 8 kph. In narrow rows, there was no benefit to using inter-row cultivation for weed control, partly as the level of weed was already very low.

When moving to the wide rows, there was a significant reduction in black-grass of 48% when treatments were pooled together. The combination of wide rows, no herbicide and a single cultivation pass gave the best result in the trial, with a reduction to less than 1 black-grass head per m^2. However, across the herbicide treatments, the use of inter-row cultivations in wide rows was only as effective as using narrow rows with no cultivation (Figure 4).

The use of cultivations in combination with the wide rows gave a significant uplift in crop performance,

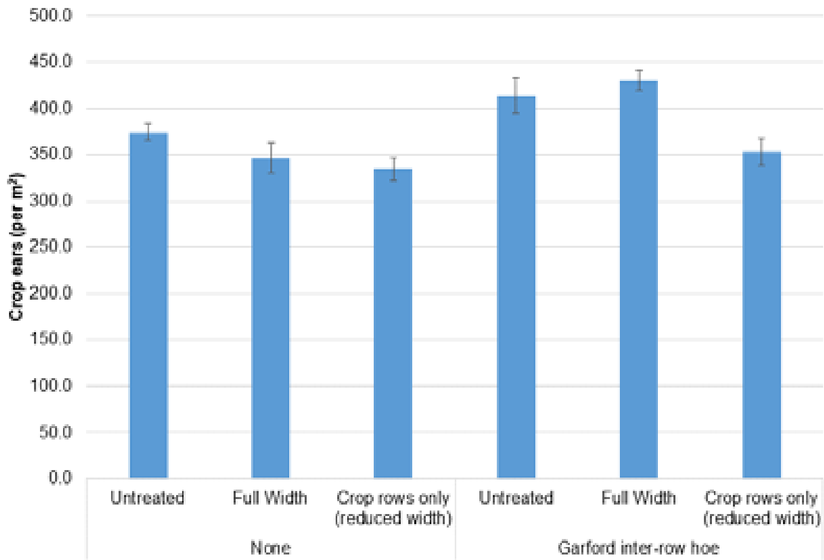


Figure 5 - The effect of a single pass from an inter-row cultivator on crop ears in wide-row spring barley.

with crop ear density used as a proxy for yield. This represents a 15% – or 0.5 t/ha increase in crop yield. It is suggested that in a dry spring, when fertiliser was slow getting to the root zone, the more aggressive cultivation in the wider rows helped to incorporate the fertiliser, whilst simultaneously releasing a small amount of available nitrogen for the crop to take up.

Summary

This initial work is encouraging as it demonstrates that the technology is effective enough in its own right to offer control of black-grass, although it raises sufficient questions to merit further work. The use of wide rows has shown that weed control can be improved, with potential for increasing yields. It is important to evaluate this observation with more purpose and rigour, as it suggests that inter-row cultivation can play a role in reducing pesticide use and the use of artificial fertiliser.

THE EFFECT OF DRILLING DATE ON BLACK-GRASS CONTROL IN SPRING BARLEY

Centre: Cambridge

Objectives

- Evaluate the role that drilling date has in spring barley for black-grass management;
- Demonstrate and quantify the trade-offs between crop productivity, black-grass seed return and herbicide efficiency;
- Evaluate the requirement for pre-emergence herbicides in spring barley crops.

Summary

- The level of black-grass in a spring crop is strongly affected by drilling date, with greater densities found in earlier sown crops. Later emerging black-grass has lower fecundity;
- In this year, higher yields were associated with the later drilling dates. This is a combination of the lower levels of black-grass, and better conditions around establishment;
- Optimum herbicide inputs to spring sown cereals were relatively low at all drilling dates; for spring barley a single application of Liberator (0.3 l/ha) was sufficient at the earliest drilling date, with later drilling dates requiring no graminicide inputs.

Materials and Methods

The experiment was established in the spring of 2020, with spring barley (cv. RGT Planet) sown at three drilling dates. At each drilling date, a range of herbicide treatments consisting of Hurricane (diflufenican), Liberator (flufenacet and diflufenican) or Crystal (flufenacet and pendimethalin) were tested, either in isolation or in combination. The target weed species was *Alopecurus myosuroides* (black-grass), which was assessed at seedling stage and at maturity. The plots were taken to harvest to determine crop yield.

Results

Sowing date was the strongest influence on weed density in this trial, with the latest sowing date having significantly lower weed seedling densities. The relationship between sowing date and black-grass head density at maturity was even stronger, with significant reductions associated with each

Treatments

Trt	Drilling	Herbicide
1	February	Untreated
2		Hurricane (0.25 l/ha)
3		Liberator (0.3 l/ha)
4		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)
5		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)
6	March	Untreated
7		Hurricane (0.25 l/ha)
8		Liberator (0.3 l/ha)
9		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)
10		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)
11	April	Untreated
12		Hurricane (0.25 l/ha)
13		Liberator (0.3 l/ha)
14		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)
15		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)

Table 7 - List of treatments.

Results

Drilling Date	Operation	Date	Relative to drilling date (days after)
Early March	Drilling	05/03/2020	0
	Pre-em	07/03/2020	2
	Post-em	30/03/2020	25
March	Drilling	23/03/2020	0
	Pre-em	30/03/2020	7
	Post-em	10/04/2020	11
April	Drilling	08/04/2020	0
	Pre-em	10/04/2020	2
	Post-em	22/04/2020	14
All	Harvest	22/08/2020	170/152/136

Table 8 - Key dates.

Trt	Drilling Date	Herbicide	Treatment Mean	Drilling date Average	Herbicide Average
1	Early	Untreated	78	104.32 a	83.9
2	March	Hurricane (0.25 l/ha)	107.6		94.0
3		Liberator (0.3 l/ha)	122.8		87.6
4		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	81.2		82.1
5		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	132		106.4
6	Late	Untreated	109.6	100.08 a	
7	March	Hurricane (0.25 l/ha)	106		
8		Liberator (0.3 l/ha)	94		
9		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	89.6		
10		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	101.2		
11	April	Untreated	64	68 b	
12		Hurricane (0.25 l/ha)	68.4		
13		Liberator (0.3 l/ha)	46		
14		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	75.6		
15		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	86		
		LSD	**65.3**	**28.5**	**40.2**
		CV	**43.6**	**42.6**	**46.4**

Table 9 - Weed seedling density (per m^2).
A two-way ANOVA indicates that drilling date was the only significant factor ($p = 0.04$), with herbicide insignificant ($p = 0.74$) and insignificant interactions ($p = 0.84$). For significant factors, different letters indicate treatments that are significantly different from each other.

Trt	Drilling Date	Herbicide	Treatment Mean	Drilling date Average	Herbicide Average
1	Early	Untreated	40	31.04 a	16.5
2	March	Hurricane (0.25 l/ha)	48		21.5
3		Liberator (0.3 l/ha)	18		9.6
4		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	29.2		13.6
5		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	20		12.0
6	Late	Untreated	7.6	11.6 b	
7	March	Hurricane (0.25 l/ha)	14.8		
8		Liberator (0.3 l/ha)	10.8		
9		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	10.4		
10		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	14.4		
11	April	Untreated	2	1.28 c	
12		Hurricane (0.25 l/ha)	1.6		
13		Liberator (0.3 l/ha)	0		
14		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	1.2		
15		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	1.6		
		LSD	**22.6**	**10.2**	**17.9**
		CV	**93.4**	**94.1**	**127.8**

Table 10 - Black-grass head population (per m^2).
A two-way ANOVA indicates that drilling date was the only significant factor (p< 0.001), with herbicide insignificant (p = 0.4334) and insignificant interactions (p = 0.5602). For significant factors, different letters indicate treatments that were significantly different from each other.

Trt	Drilling Date	Herbicide	Treatment Mean	Drilling date Average	Herbicide Average
1	Early	Untreated	5.99	5.93 a	6.69
2	March	Hurricane (0.25 l/ha)	5.67		6.60
3		Liberator (0.3 l/ha)	5.98		6.68
4		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	6.15		6.64
5		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	5.87		6.53
6	Late	Untreated	6.94	6.86 b	
7	March	Hurricane (0.25 l/ha)	7.07		
8		Liberator (0.3 l/ha)	6.97		
9		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	6.67		
10		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	6.66		
11	April	Untreated	7.13	7.08 b	
12		Hurricane (0.25 l/ha)	7.05		
13		Liberator (0.3 l/ha)	7.09		
14		Liberator (0.3 l/ha) + Crystal (2.0 l/ha)	7.09		
15		Liberator (0.3 l/ha) f/b Crystal (2.0 l/ha)	7.05		
		LSD	**0.67**	**0.24**	**0.59**
		CV	**6.12**	**4.81**	**9.33**

Table 11 - Crop yields (t/ha at 15% moisture).
A two-way ANOVA indicates that drilling date was the only significant factor (p< 0.001), with herbicide insignificant (p = 0.864) and insignificant interactions (p = 0.698). For significant factors, different letters indicate treatments that were significantly different from each other.

subsequent sowing date. The combination of lower initial densities, and lower fecundity at a per plant level, has demonstrated that later sowing should be encouraged to maximise weed control.
Later sowing can compromise crop performance, however in this trial the latest sowing was associated with the highest yields. In the UK, weather conditions in the spring can be unpredictable and in this season the soils remained moist for a longer period, enabling better establishment of crops at this time.
Herbicide use was only associated with significant reductions of weed seedlings at the first sowing date. The products used in this trial were residual herbicides which rely on moist soils for optimum performance, and it is clear that conditions were not appropriate for these products in the later sowing dates. This is a strong message, and gives an opportunity to reduce herbicide use, without impacting on overall weed control.

Drilling date

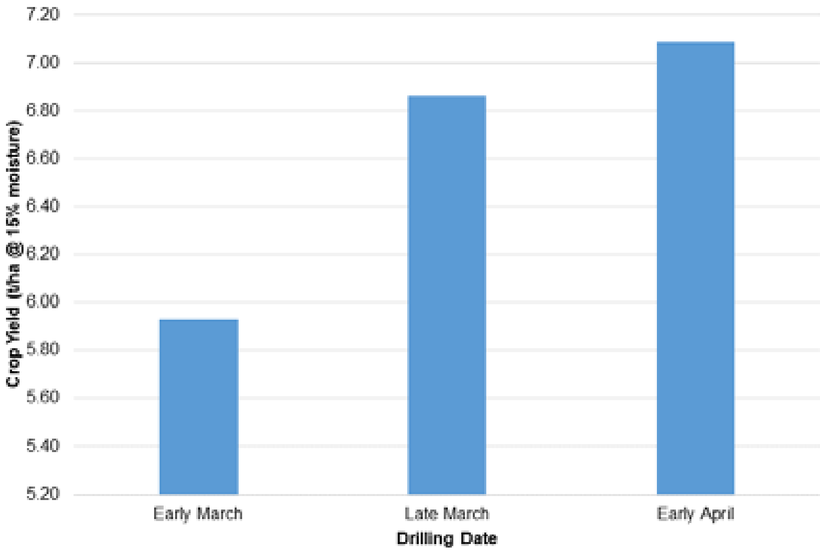


Figure 6 - Overall average response of Crop yields to drilling date. The values are average values across the whole trial.

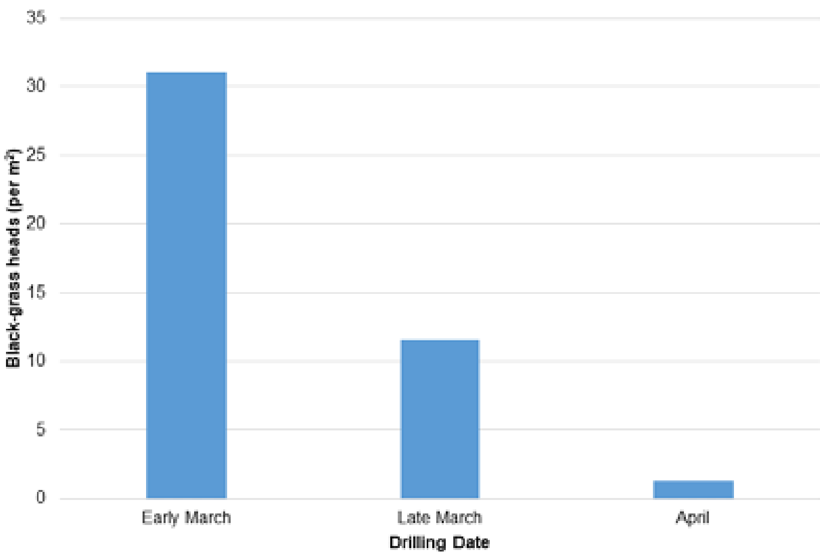


Figure 7 - Overall average response of Black-grass heads per m^2 to drilling date. The values are average values across the whole trial.

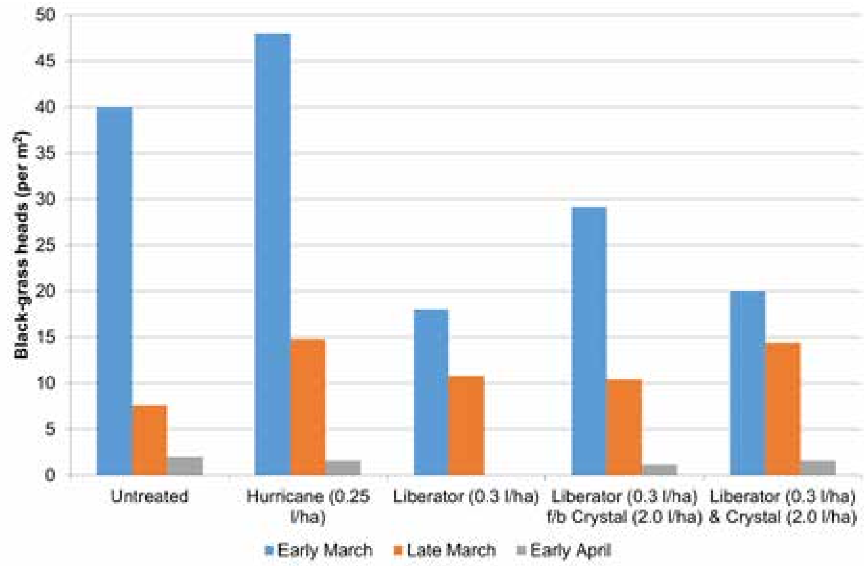


Figure 8 - Overall average response of Black-grass heads per m^2 to each treatment. The values are average values across the whole trial.

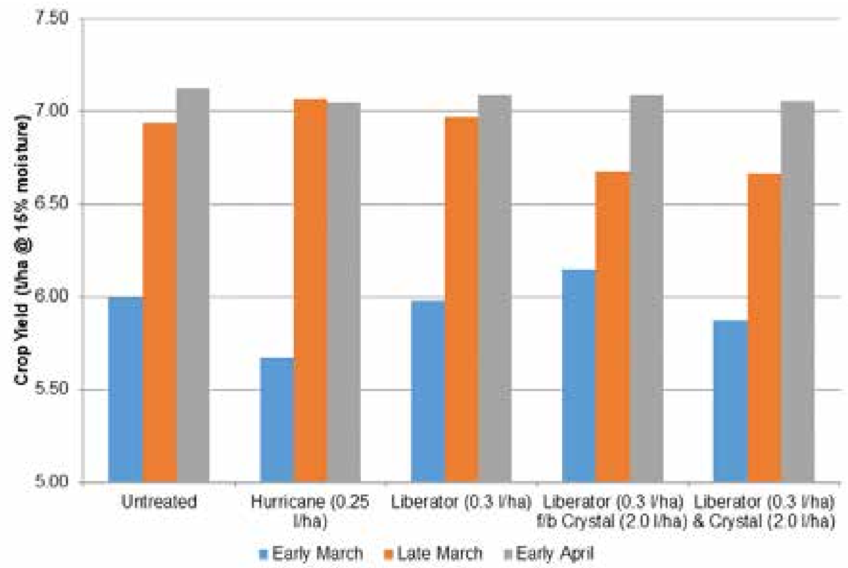


Figure 9 - Overall average response of Crop yield (t/ha) to each treatment. The values are average values across the whole trial.

THE EFFECT OF CULTIVATION AND DRILLING DATE ON BROAD-LEAVED WEED SPECIES

Centre: Cambridge

Objectives

- Demonstrate the speed at which cultivation or drilling date can select for weed species;
- Track these changes over time.

Summary

Trt	Drilling Date	Herbicide	Treatment Mean
1	Autumn	Plough	Untreated
2			Treated
3		Deep Non-Inversion	Untreated
4			Treated
5		Direct drill	Untreated
6			Treated
7	Early Spring	Plough	Untreated
8			Treated
9		Deep Non-Inversion	Untreated
10			Treated
11		Direct drill	Untreated
12			Treated
13	Late Spring	Plough	Untreated
14			Treated
15		Deep Non-Inversion	Untreated
16			Treated
17		Direct drill	Untreated
18			Treated

Table 12 - List of treatments.

Cultivation and time of sowing has the ability to influence the species diversity and density of broad-leaved weeds in cereal crops grown in the UK. Lower cultivation intensity was able to contribute to lower populations emerging. Herbicides remain an effective control strategy, however implementing more holistic measures will be necessary in the future to ensure control remains this way.

Materials and Methods

This trial was established in the autumn of 2019 at a site near Cambridge, UK (cv. KWS Siskin/KWS Chilham). The matrix design enabled a comparison of cultivation prior to establishment and time of sowing on weed density. The target species were broad-leaved weeds, which were assessed four weeks after crop emergence, and at crop maturity. The crop performance was assessed with crop yield.

Drilling Date	Operation	Date	Relative to drilling date (days after)
Autumn	Drilling	31/10/2019	
	Pre-em	07/11/2019	7
	Post-em	18/01/2020	79
Early Spring	Drilling	12/03/2020	
	Pre-em	13/03/2020	1
	Post-em	24/04/2020	43
Late Spring	Drilling	04/04/2020	
	Pre-em	14/04/2020	10
	Post-em	05/05/2020	31
All	Harvest	10/08/2020	284/151/128

Table 13 - Key dates.

Treatments

Plots that received herbicide were treated with Stomp Aqua (pendimethalin, 3.3 l/ha) at pre-emergence of crop and weed, and Zypar (halauxifen-methyl & florasulam, 1.0 l/ha) at post-em. Rates were constant, even in spring crops, where products/rates were not label recommendations.

Results

Introduction

The focus for weed control trials in the UK has understandably been on black-grass, as it is the key species causing greatest yield loss. The study into the most effective chemical control options has been combined with work to determine the effect of different crop establishment systems, which has played a large part in moving forward the conversation on black-grass control. An over-sight of this work is that the reaction of other species, namely broad-leaved species, has not been studied. Currently, control of these species by chemical means is fairly straightforward, with very limited recorded cases of herbicide resistance. However, the seeds of these species are able to maintain viability in the soil for longer periods of time, over one-hundred years in the case of poppy, which means that once a large seedbank has been propagated it may be very difficult to control.
NIAB has a site which has historically been poorly managed for broad-leaved weeds, leaving a large and

Trt	Drilling Date	Cultivation	Herbicide	Average number of weeds (per m²)
1	Autumn	Plough	Untreated	60
2			Treated	0
3		Deep	Untreated	12.8
4		Non-Inversion	Treated	0
5		Direct drill	Untreated	8.6
6			Treated	0
7	Early	Plough	Untreated	32.6
8	Spring		Treated	1.2
9		Deep	Untreated	10.4
10		Non-Inversion	Treated	2.2
11		Direct drill	Untreated	13.2
12			Treated	2.2
13	Late	Plough	Untreated	8.4
14	Spring		Treated	2.2
15		Deep	Untreated	22.6
16		Non-Inversion	Treated	1.2
17		Direct drill	Untreated	17
18			Treated	4.4

Table 14 - A summary of weed densities.

Trt	Drilling	Cultivation	Herbicide	Crop yield (t/ha)
1	Autumn	Plough	Untreated	6.0
2			Treated	6.5
3		Deep	Untreated	6.4
4		Non-Inversion	Treated	6.6
5		Direct drill	Untreated	5.9
6			Treated	6.5
7	Early	Plough	Untreated	2.6
8	Spring		Treated	2.7
9		Deep	Untreated	2.8
10		Non-Inversion	Treated	3.1
11		Direct drill	Untreated	2.5
12			Treated	2.6
13	Late	Plough	Untreated	2.6
14	Spring		Treated	2.7
15		Deep	Untreated	2.7
16		Non-Inversion	Treated	2.7
17		Direct drill	Untreated	2.6
18			Treated	2.8

Table 15 - A summary of crop yield.

diverse soil seedbank. This site will be used to study how over-arching system changes that may come as result of other weed problems can alter the diversity of broad-leaved species, alongside work focussed on specific control measures. The initial part of this work was a matrix of cultural control measures (cultivation x drilling date) to observe the initial weed flora from these species. This trial will be repeated on the same footprint to track the changes if an establishment system is maintained e.g. continuous direct drilling.

Weed Density

In just a single season, immediate differences in the number of species and weed density were observed across the cultivation blocks, with the most dramatic effects seen in the autumn drilled plots.
Plots that were established in the autumn, into a ploughed seedbed, showed greatest species richness, with nine species observed. Poppy (*Papaver rhoeas*), groundsel (*Senecio vulgaris*) and field pansy (*Viola arvensis*) were the most dominant species.

Where deep non-inversion was practiced, a similar number of species was observed, but all at a much lower density. The direct drilled plots had extremely few broad leaved weeds present, reflecting the zero seed return from the previous season. In contrast to the other cultivations, grass weeds, most notably black-grass, were present at a moderate density (10 plants/m²). These were rogued out, so as to maintain the focus of the trial on broad leaved weeds and prevent domination by grassweeds. The herbicide combination used was 100% effective against broad leaved weeds in the autumn. The two spring drilling dates resulted in far more similar weed flora – dominated by field bindweed (*Convolvus arvensis*), with other typical spring germinating weeds, such as Knotgrass (*Polygonum aviculare*) and Fat Hen (*Chenopodium album*), being present at low densities. The same combination of herbicides was less effective, most clearly at the late spring establishment timing, with a combination of dry soil conditions reducing pre-em efficacy and Zypar being found unsuitable for bindweed. In the direct drilled and the non-inversion plots, the numbers of weeds increased as time of sowing was extended, with more

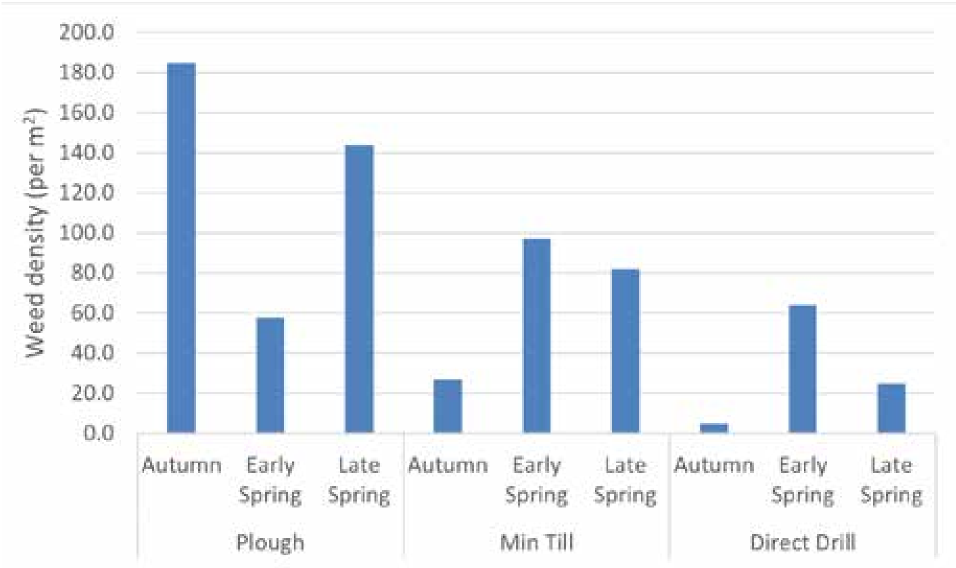


Figure 10 - The average weed density in the herbicide untreated plots for each cultivation x sowing date interaction.

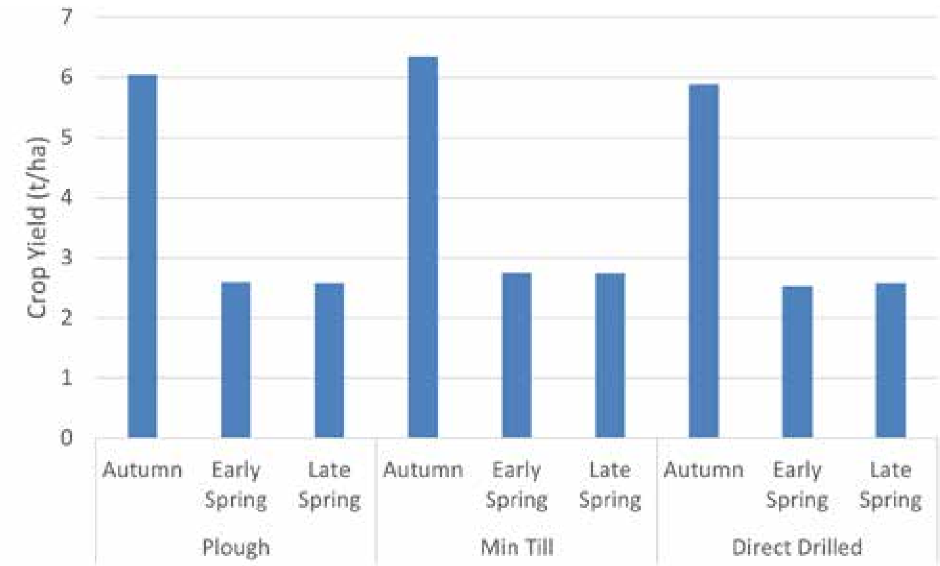


Figure 11 - Average crop yields from the herbicide untreated plots for all cultivation x time of sowing interaction.

weeds observed in the late spring drill plots than in the equivalent ploughed plots.

Yields

Effect of broad-leaved weeds on crop yield has been of little focus so to report these results is of interest. With the multiple species present in the trial, it is difficult to allocate any yield reduction at a species level, so it is appropriate to equally attribute each species' contribution and use total weed number as a measure of weediness.
Table 15 outlines the yields for all treatments.

The use of herbicide was associated with marginally higher crop yields (Figure 12), as a result of reducing weed competition. This was most evident in the autumn sown crops, where weeds were greatest in number. In spring crops, there was no significant difference between the treated and untreated plots, even though there were significant differences in the level of weed. This suggests that although the densities that emerge in these spring crops may be numerous, they are not species likely to cause significant yield damage.

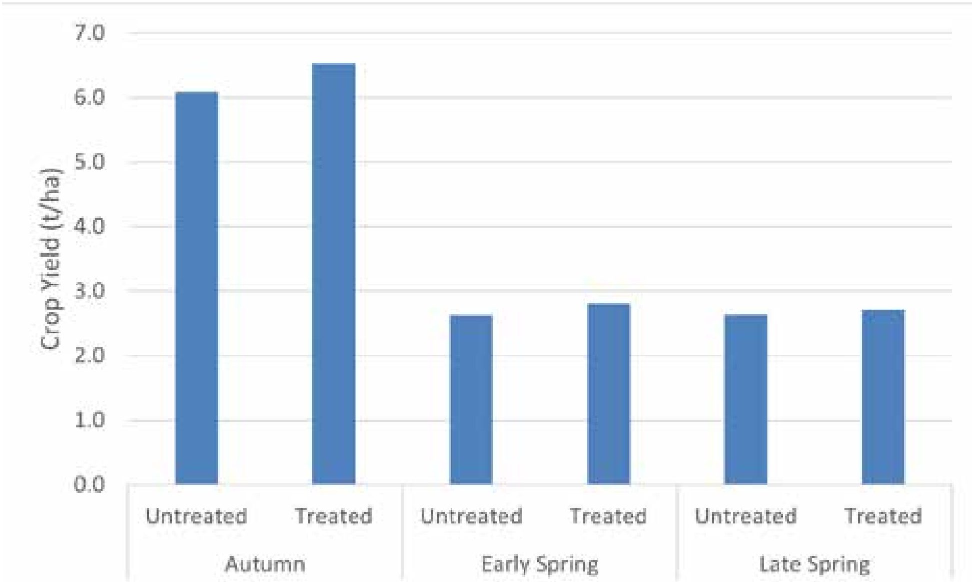


Figure 12 - The average crop yield for the herbicide untreated and treated pairs, by drilling date.

WP6 – EXPERIMENTAL TRIAL ON IWM STRATEGIES IN VINEYARDS

Weed control in the area under the vines (intra-rows) in vineyards is typically achieved through the application of herbicides. However, given the on-going loss of herbicide actives and the increasing popularity of organic produce among consumers there is a need to adopt alternative, non-chemical control methods. One such alternative is the use of mechanical weeders that are mounted onto the back of a tractor and used to physically disrupt and remove the weeds. Their precise mode of action varies, some using a blade and others using a serrated disk or finger weeder with a tilling-like action.
The objective of this experiment was to compare two mechanical weeding methods with a conventional herbicide treatment and a no-treatment control (strimming only), in order to determine whether they could achieve sufficient weed control without jeopardising either vine vegetative growth, grape yield or quality.

Experimental design

This trial was established at NIAB EMR's Research Vineyard in the summer of 2018 and continued until December 2021. It consisted of two rows of each treatment, with 10 blocks of five vines (all Chardonnay clone CH.96 on 3309C rootstock) in each row (Figure 13). The no-treatment control rows were strimmed only (referred to hereafter as the Control treatment), and the grower control rows received regular herbicide applications (referred to as the Herbicide treatment). The two mechanical weeders used in the trial were the blade and the finger disk with finger hoe, both manufactured by Clemens Technologies (Figure 14). The blade weeder was the Radius SL+, which consists of a blade that runs horizontally through the top-soil layers to lift weeds and break up soil aggregates and weed roots in a way similar to tilling. This weeder can be used from April through to September in the UK. The other mechanical weeder used in this trial was the finger disk (roller) in combination with the finger hoe (referred to hereafter as the Disk treatment), which uses a (vertical) serrated disk in combination with a (horizontal) finger roller, which roll through the soil to physically destroy the weeds and also disrupt weed growth. The manufacturers recommend using this weeding tool from April to August in the UK. Both of these mechanical weeders require approximately six passes during the growing season to maintain good weed control.

Assessments

The weeding treatments were applied between April and September in each year of the trial, and the following assessments were conducted at key phenological stages to evaluate their impact on vine performance:

- **Vine vigour**: vine vegetative growth was assessed by LiDAR (light detection and ranging) scans of the canopy to measure row volume several times throughout the growing season.

Figure 13 - Location of the trial (left) and the layout of the weeding trials at NIAB EMR's Research Vineyard (right). It consisted of two replicate rows of 10 blocks of five vines for each weeding strategy, planted at a spacing of 1.1 m, with 2.4 m between rows. Inter-rows were mowed throughout the trial.

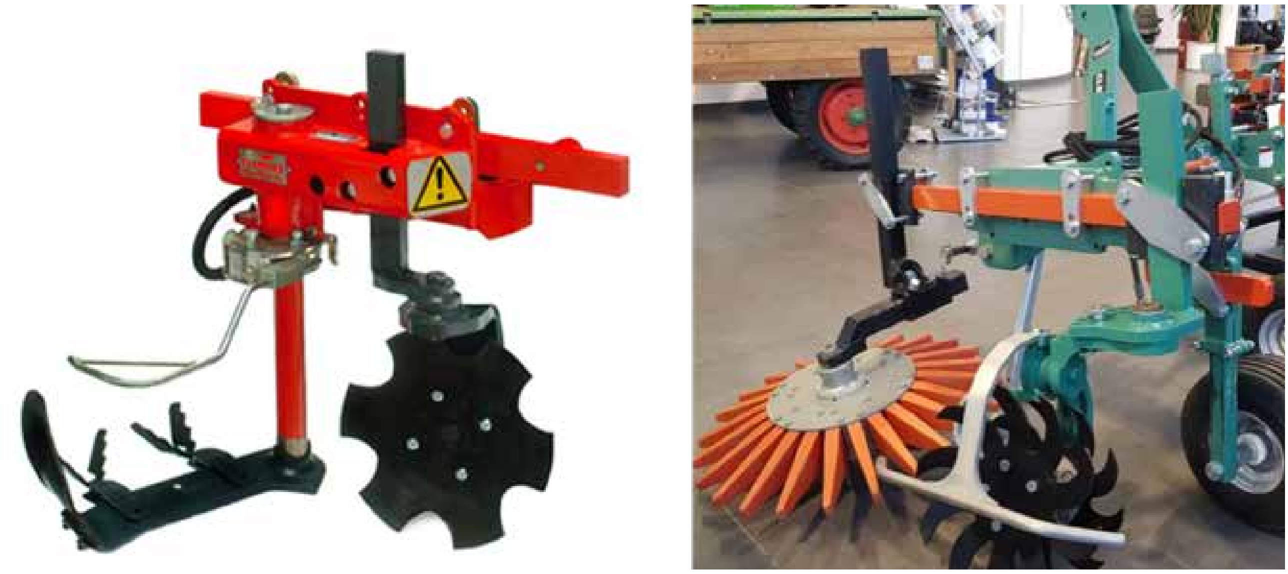


Figure 14 - The blade (left) and the finger disk with finger hoe (right) which were used for the mechanical weeding treatments.

- **Vine nutritional status**: the nutritional status of the vines was assessed using the Dualex instrument which measures the concentrations of leaf compounds based on chlorophyll fluorescence. It measures leaf epidermal phenolics (flavonols and anthocyanins) and leaf chlorophyll content, in addition to the Nitrogen Balance Index (NBI).
- **Inflorescence counts**: Inflorescence counts were recorded at flowering on a subset of vines within each treatment to give an early indication of yield.
- **Vine yield**: the vines produced their first crop for harvesting in 2020, so the yield data is for 2020 and 2021 only. It is reported in tonnes per hectare (t/ha).
- **Grape must quality**: sugars, acids and the concentration of yeast available nitrogen (YAN) in grape must (juice) samples were assessed using the OenoFoss^{TM} instrument.
- **Weed assessments**: Botanical surveys were carried out three times a year to identify weed species and

Figure 15 - Control vines in 2021 (left), and three rows (blade, control and herbicide-treated) in the final year of the trial at NIAB EMR's Research Vineyard (right). Note that vines in the Control row are distinctly smaller and more chlorotic than those in the neighbouring treated (blade and herbicide) rows.

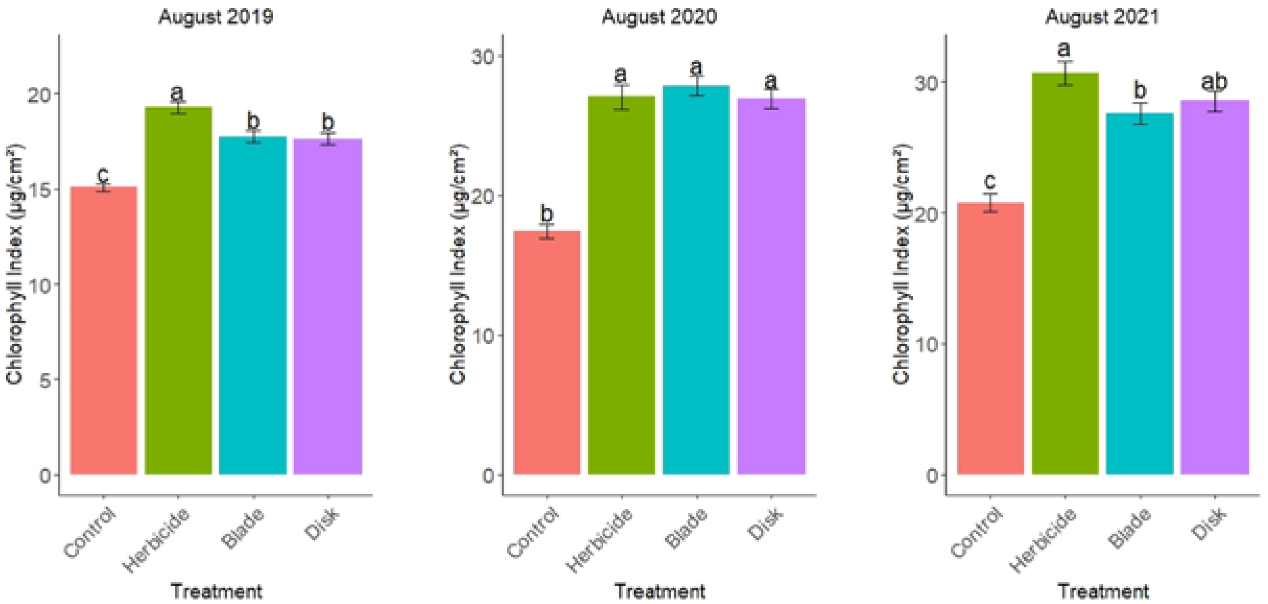


Figure 16 - Chlorophyll index concentrations of vine leaves in each treatment over the course of the experiment. Control vines consistently had lower chlorophyll levels than the treated (mechanically and chemically) vines.

quantify their abundance (number of individuals in a quadrat) and coverage (% of quadrat area covered by each weed species/family).

Final Results

Vine vigour and nutrition

Vines that did not receive mechanical or chemical weed control were visibly chlorotic from the early stages of the trial (Figure 15), with chlorophyll levels being significantly lower in control vines than those in the weed control treatments in 2019, 2020 and 2021 (Figure 16).
The Nitrogen Balance Index (NBI), which is calculated as the ratio of chlorophyll to flavonol epidermal content, revealed a similar trend to that of the chlorophyll index, with Control vines having significantly lower values at véraison when compared to the mechanically and chemically weeded vines (Figure 17).

Over the course of the trial, vines in the mechanical and herbicide weeding treatments consistently had higher vigour than control vines at véraison (July/August), as indicated by row volume (Figure 18). There were also significant differences in vigour earlier in the season at flowering June, however these were less pronounced.

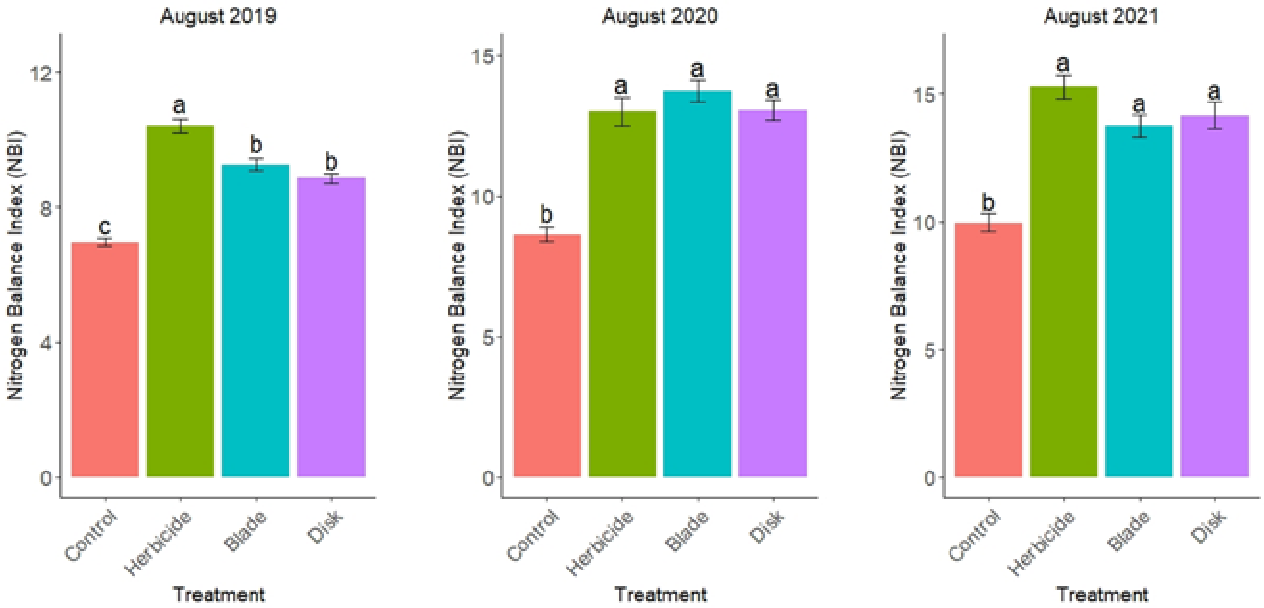


Figure 17 - Nitrogen Balance Index (NBI) of vines during véraison in each year of the trial.

Grape quality and yield

In both harvest years (2020 and 2021), grapes from the control treatment had significantly lower total acidity (Figure 19). However, there were no consistent trends in pH, total soluble solids (TSS) or yeast available nitrogen (YAN) between the two harvest years (Figure 20).
The IWM treatments in the UK trial exhibited consistent trends in yield in the two final years of the trial, with all weed management strategies resulting in significantly higher (>260%) yields in comparison to the control vines (Figure 21). This was also reflected earlier in the season by the average number of inflorescences per vine (Figure 22). There was no difference in yield between the different mechanical and herbicide weed control strategies.

Weed abundance and coverage

Weed abundance (the number of individuals in a quadrat) and coverage (% of quadrat area covered by each weed species) was recorded three times in both 2020 and 2021. Weed coverage dynamics were highly variable between years, with no clear trend in the relationship between weeding method and weed coverage during the trial (Figure 23). However, when comparing the mean total coverage of all weeds under each treatment at each individual timepoint, the control rows were found to have significantly higher total weed cover in November 2020 in comparison to all other weeding treatments (Figure 24). Of the three weeding treatments, the blade mechanical weeder and herbicide treatments were the only methods that resulted in an overall decline in total weed coverage in both years (Table 16). Overall, *Poaceae* and *Asteraceae* were the most abundant weed families. However, there were no significant differences in the total number of any weed family between treatments across all time points. In terms of total coverage across all timepoints, only two families, *Brassicaceae* and *Onagraceae*, differed significantly between weeding treatments, with the herbicide treatment having significantly higher total coverage of both (Figure 25). *Brassicaceae* was significantly higher in the herbicide rows in comparison to the blade-weeded rows (Tukey HSD p=0.04) and control rows (p =0.03), while *Onagraceae* had significantly higher coverage in the herbicide rows when compared to the control (p = 0.02), blade (p = 0.05) and disk (p = 0.02) rows.

Conclusions

The final results from our trial indicate that the mechanical weeding methods employed were able to control the weeds sufficiently without having any detrimental impact on vine vigour, nutritional status or yield when compared to vines in the herbicide-treated rows. Vines in the control rows (mowing only) had significantly lower yields, vine vigour and foliar nutrition in comparison to the mechanical and herbicide treated vines. The findings of this trial therefore demonstrate that mechanical weeding methods are a viable alternative to chemical approaches, without compromising berry yield or quality.

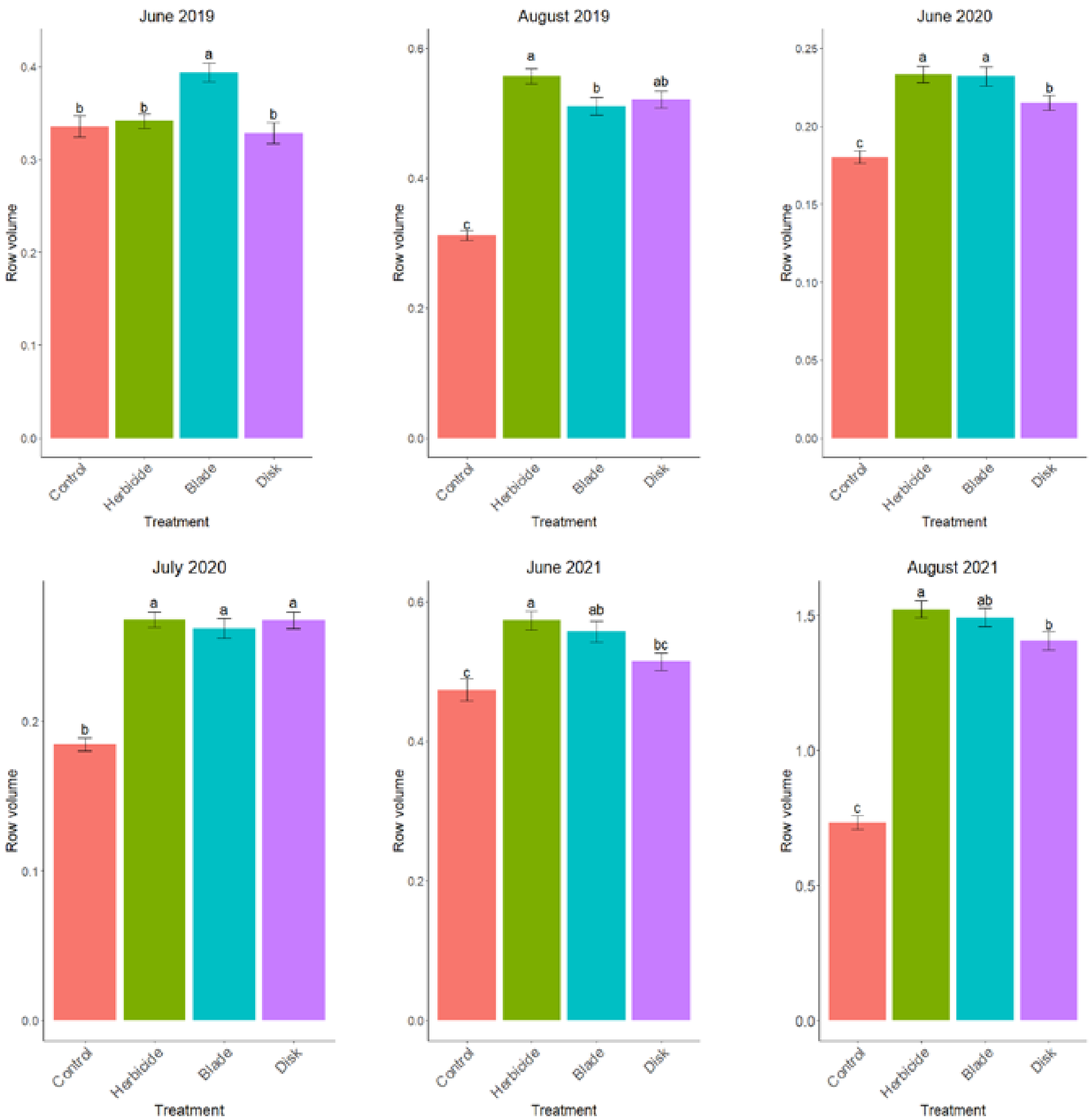


Figure 18 - Vine vigour as indicated by row volume (LiDAR scanning) at flowering time (June) and véraison (July/August) throughout the course of the trial.

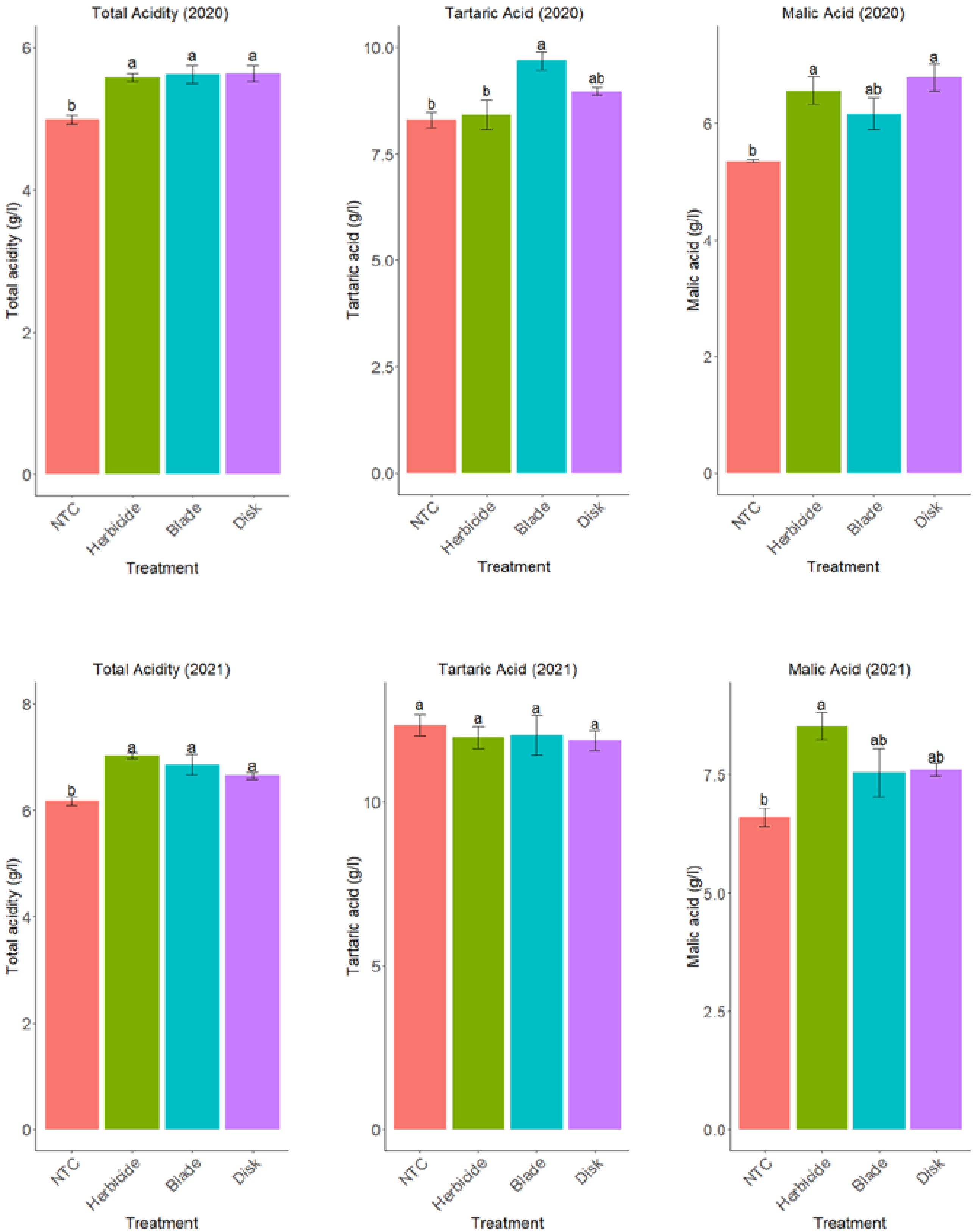


Figure 19 - Grape must (quality) analysis of acid content (total, tartaric and malic) for each of the weeding treatments in the two harvest years.

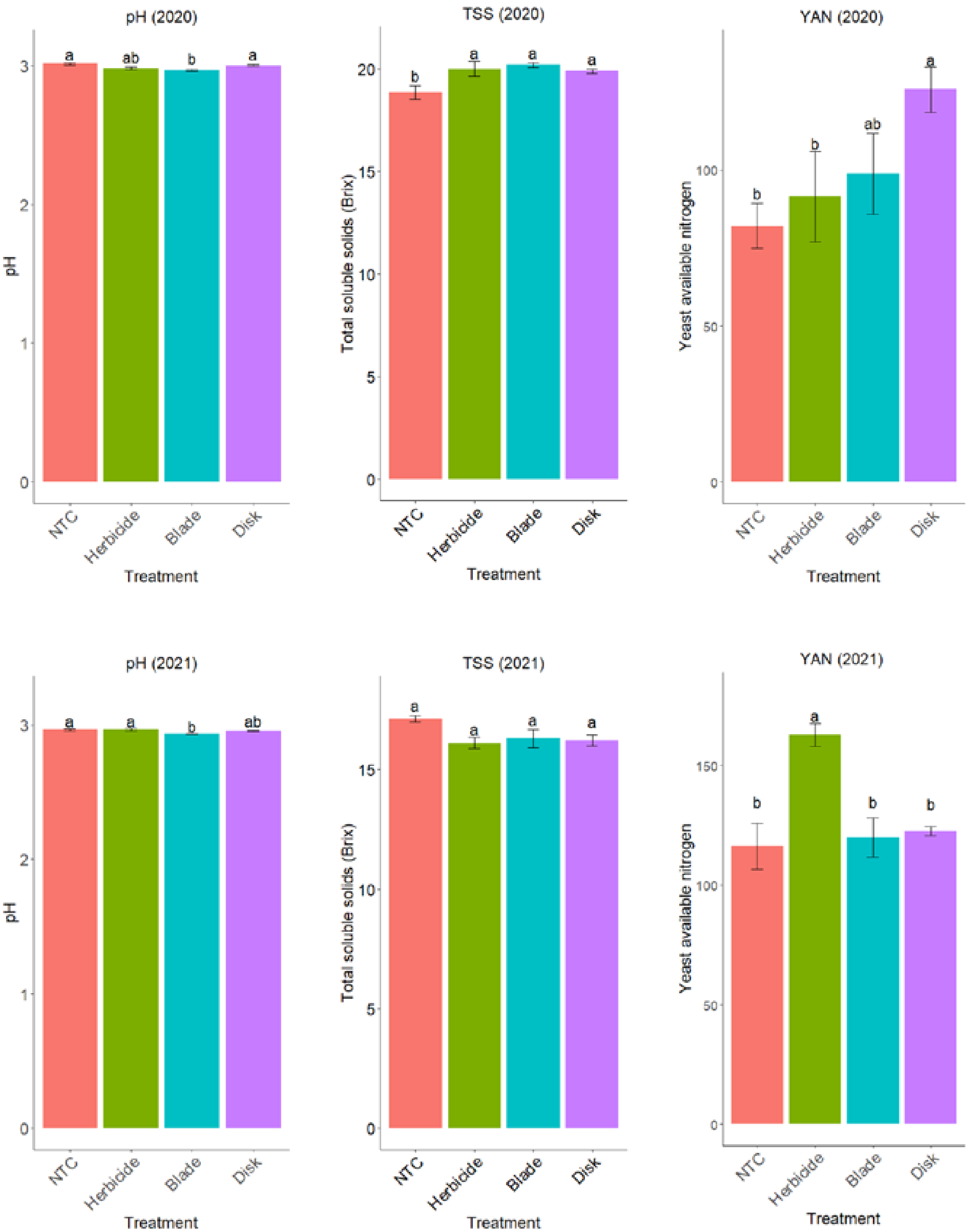


Figure 20 - Grape must (quality) analysis of pH, TSS (Brix) and YAN for each of the weeding treatments in the two harvest years.

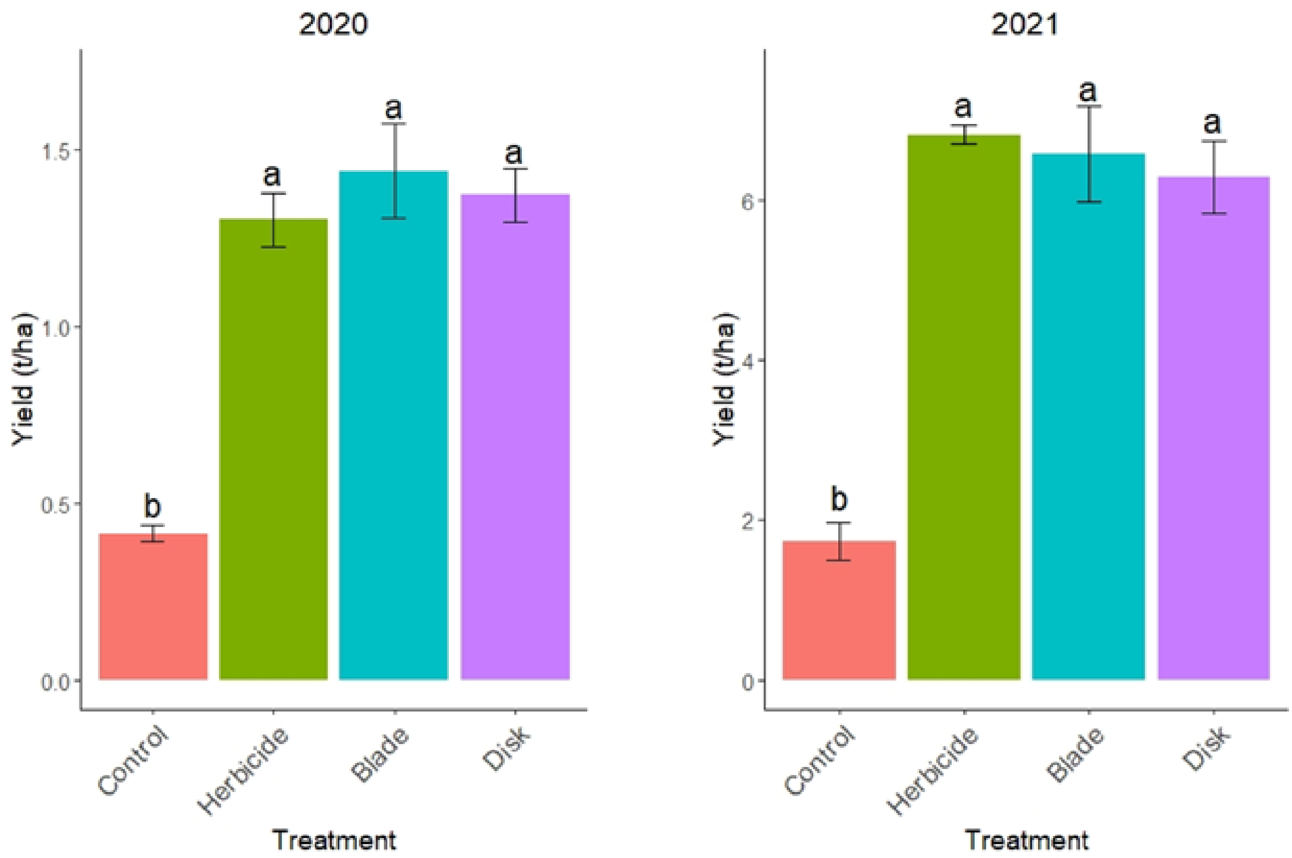


Figure 21 - Grape yield in the final two productive years of the weeding trial (the vines were too young to produce a crop in the first two years).

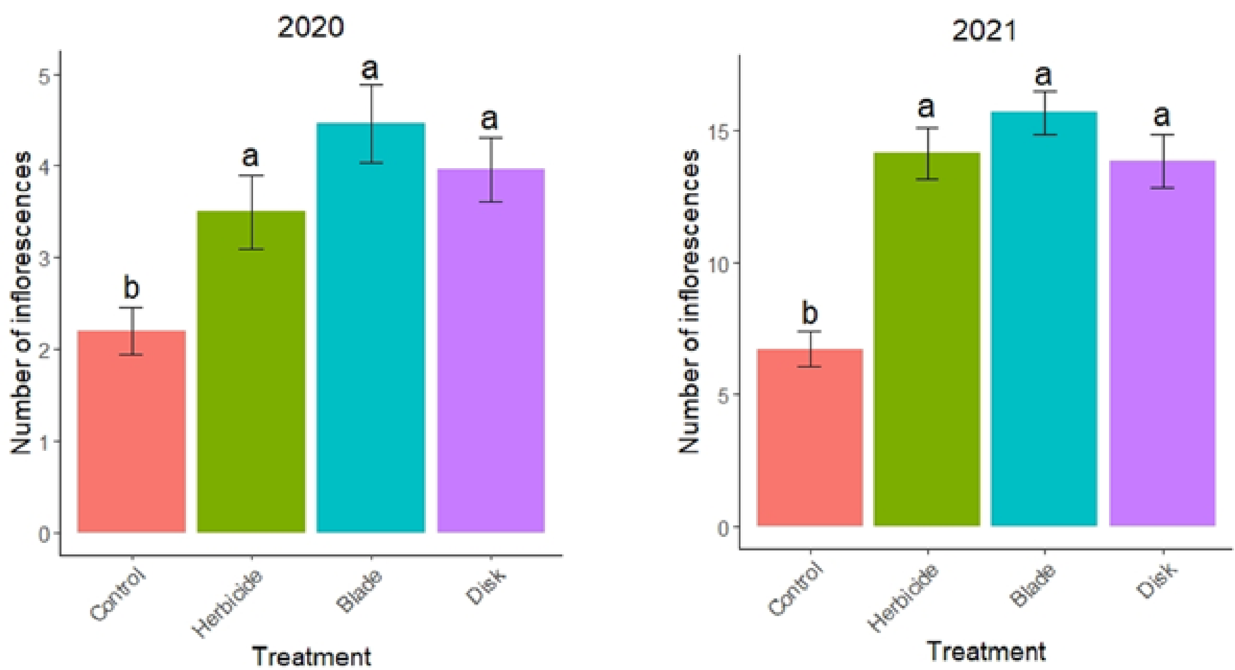


Figure 22 - Inflorescence counts for vines in the different weeding treatments at flowering in 2020 and 2021.

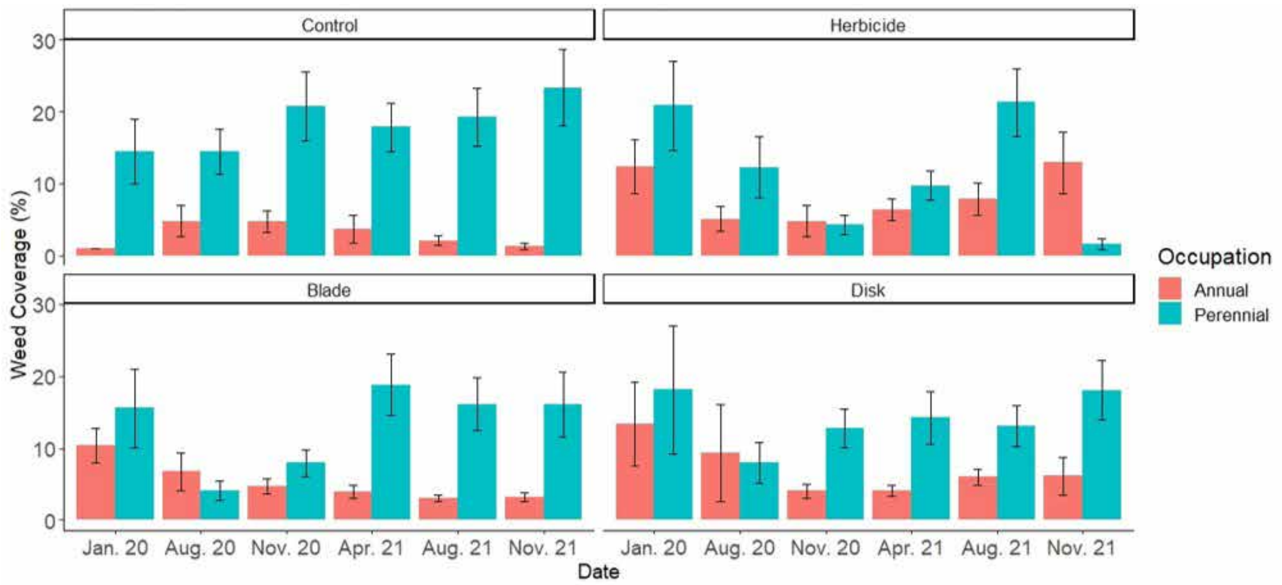


Figure 23 - Mean coverage of annual and perennial weeds in rows under the different weeding treatments at each survey timepoint throughout the trial.

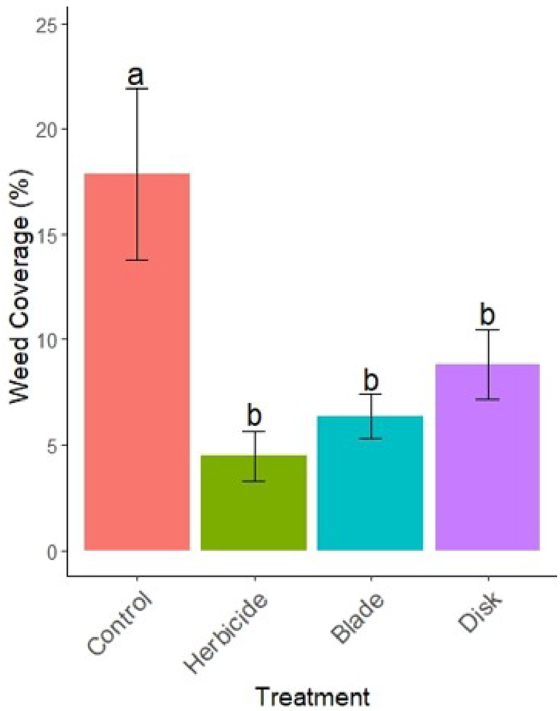


Figure 24 - Average total weed coverage in each treatment in November 2020, which was significantly higher in the control rows.

Survey date		Control	Herbicide	Blade	Disk
2020	January	297	307	357	328
	August	420.5	321	68	200
	November	589.8	134.5	280	371
2021	April	570	466.5	523	416.5
	August	300	528	417.5	415
	November	589.5	264	498	532.5

Table 16 - Total weed coverage for each weeding treatment during the 2020-2021 survey period.

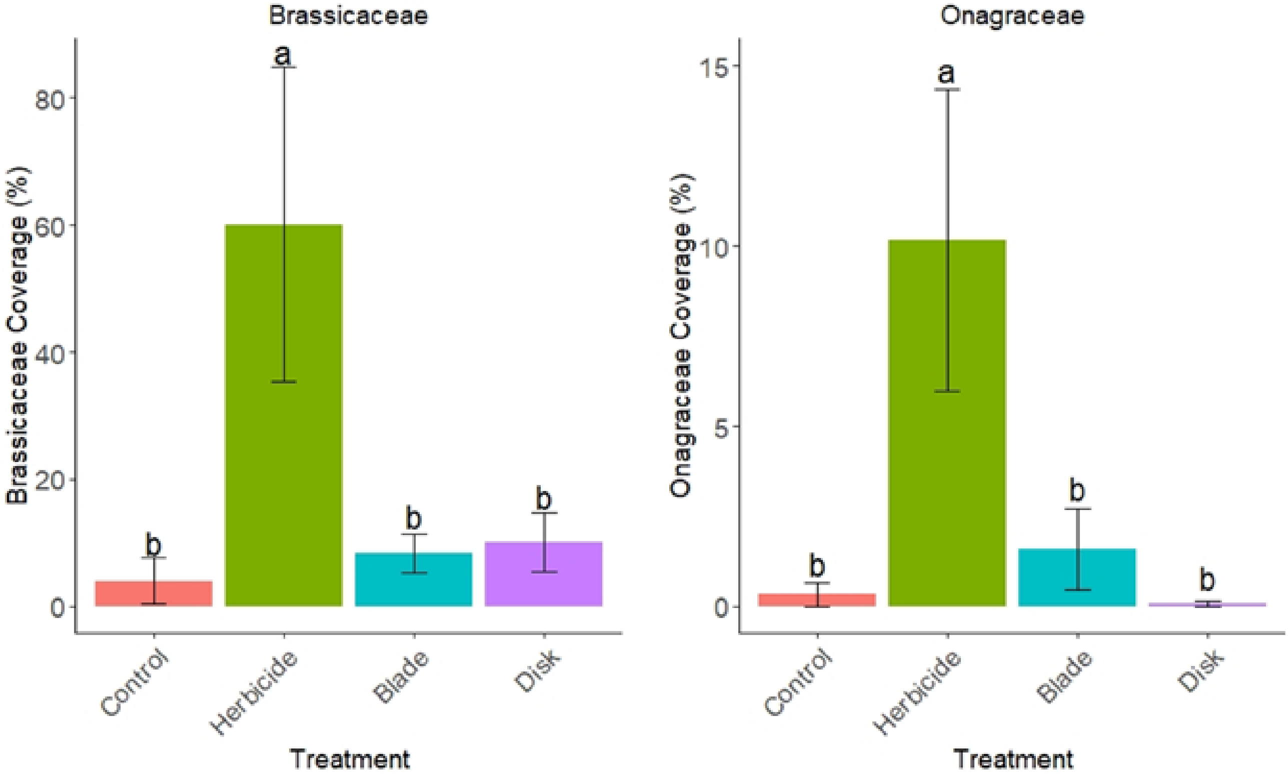


Figure 25 - The mean total abundance of *Brassicaceae* (left) and *Onagraceae* (right) per survey timepoint for each weeding treatment.

Figure 26 - The IWMPRAISE Demo day at NIAB EMR's Research Vineyard in November 2021, held in collaboration with Clemens Technologies.

THE NETHERLANDS

EXPERIMENTAL TRIALS MANAGED BY WAGENINGEN UNIVERSITY & RESEARCH

The IWMPRAISE experimental location is in the polders in the north of the Netherlands; it is one of the experimental farms of Wageningen University and Research (WUR) and is located in Lelystad. It is an arable cropping location, with 700 ha on clay soil, and has the use of several high-tech experimental field tools.

Address:
WUR Experimental Farm
Edelhertweg 1
8219 PH Lelystad – The Netherlands
GPS coordinates: 52°32'23.7"N 5°33'44.9"E
tel. +31 320 291111

For guided visits please contact:
Hilfred Huiting
e-mail: hilfred.huiting@wur.nl
tel. +31 320 291339

Two experiments are in place for the WP4 of the IWMPRAISE project in the Dutch national cluster:
1. Annual row crops- arable & vegetable crops;
2. Annual row crops- maize.
Both trials are located in Lelystad, at the experimental research farm of WUR.

EXPERIMENT ON ANNUAL ROW CROPS – ARABLE AND VEGETABLE CROPS

This experiment was established in the spring of 2018. The IWM framework developed in the IWMPRAISE project (https://doi.org/10.1016/j.eja.2021.126443) was used to design an IWM strategy, and to yearly evaluate and redesign said strategy.
The experiment, depicted in Figure 2, had three replicates. The main goal was to compare the IWM strategy with a conventional reference strategy, considering:

- an eight-year rotation based on the IWM principles (ICM8);
- a conventional four-year rotation, where weed management is based on direct control with herbicides (Ref4).

Two intermediate subsystems were included for comparison:

- an eight-year rotation, in which weed management is based on direct control with herbicides (Ref8);
- a four-year rotation, in which weed management is performed with as little herbicide as possible (ICM4).

The crops in the four-year rotation are potato, seed onion, sugar beet and spring wheat, all common crops in an arable rotation on clay soil in the Netherlands (Table 1). Weed control is predominantly chemical. These crops were also included in the eight-year IWM rotation, but to increase crop diversification, the rotation was extended with winter cover crops, carrot, cabbage and an additional potato crop. Potato has a large economic value in the Netherlands.
With the diversification of the crop rotation through these additional crops, crop management is more variable during the growing season, and growing conditions are more variable for weed species. In both rotations the soil was ploughed. Targeted control tactics included in the IWM rotation were mechanical weeding, thermal weeding, mowing and herbicides, which were applied site-specific in patches or with band-spraying whenever possible, depending on the weed density and crop. In the IWM rotation, weeds were monitored visually (counts) to determine densities and the need for control; based on the growth stage of the weeds and soil conditions, the most suitable weed control methods were chosen. Monitoring was not used in the conventional system to determine the need and type for direct control.

Figure 1 - Aerial photo of the trial fields.

Results

Weeds

Changes in the size and composition of the weed seedbank were used as a parameter for the effects of the IWM system. At the start of the experiment the weed seedbank was determined; the final seedbank will be determined in Spring 2022. The weed density is determined in all crops before harvest and used to compare the effect of the two weed management strategies on the weed density.

Crop Yield

Potato yields in the eight-year IWM strategy (ICM8) and the four-year reference rotation (Ref4) are shown in Figure 3, together with the intermediate strategies (Ref8, ICM4). Yields between IWM and the reference system were not significantly different within years (except for 2018). However, each year's potato yields in IWM were lower when compared to crop yields in the reference system. Cereal yields (Figure 4) were not significantly different between systems. Carrot yields were not significantly different between systems (Figure 5). Onion yields were significantly lower in the IWM strategy (ICM8 and ICM4) when compared to the reference strategy (Ref4 and Ref8) in 2018 and 2019. However, from 2020 the variety was changed to a one with a higher yield potential, and differences were no longer significant in 2020 and only slight lower in 2021 (Figure 6). Sugar beet yields in the eight-year IWM strategy (ICM8) and the four-year reference rotation (Ref4) are shown in Figure 7, together with the intermediate strategies (Ref8, ICM4). Yields between IWM and the reference system were not significantly different within years. However, each year's sugar beet yields in IWM are lower when compared to crop yields in the reference system. Cabbage yields were not significantly different between strategies within years (Figure 8). However, each year's cabbage yields in IWM were lower when compared to cabbage yields in the reference system. Grass clover yields (Figure 9) were not significantly different between systems.

Pillar of IWM framework	Tactic	IWM rotation (ICM8)	Conventional reference (Ref4)
Diverse cropping system	Length of rotation (years)	8 (potato, cabbage, carrot, cereal [spring barley in 2018, winter wheat in 2019-2021], grass/clover, sugar beet, onion)	4 (potato, sugar beet, onion, spring barley in 2018, winter wheat in 2019-2021)
	Cover crops	Yes	No
Cultivar choice and establishment	Cultivar choice	Yes, early soil coverage	No
	Sowing date adjustment	Yes, delayed	No
	Sowing pattern altered	Yes	No
	Seed rate altered	Yes	No
Field/Soil management	Seed bed preparation	Yes	No
Direct control	Pre-emergence herbicides	Yes	Yes
	Post-emergence herbicides	Yes	Yes
	Mowing	Yes	No
	Hand weeding	Yes	Yes
	Patch/Band-spraying	Yes	No
	Mechanical weeding	Yes, harrow, hoe, finger-weeding	Yes, hoeing
	Thermal weeding	Yes	No
Monitoring & Evaluation	Scouting	Yes	No
	DSS	Yes	No
	Sensing technology	Yes	No

Table 1 - Tools and tactics used in the IWM strategy from the five IWM framework pillars and the conventional reference weed management system for an arable cropping system on clay soil in the Netherlands.

Figure 2 - Experimental layout.

LEGEND

Plot	Crop	Plot	Crop
Aa1 8-	Potato 8 year conventional	Aa1 8+	Potato 8 year iwm
Aa 4-	Potato 4 year conventional	Aa 4+	Potato 4 year iwm
Aa5 8-	Potato 8 year conventional	Aa5 8+	Potato 8 year iwm
Gk 8-	grass clover 8 year conventional	Gk 8+	grass clover 8 year iwm
Gr4-	summer wheat 4 conventional	Gr4+	summer wheat 4 year iwm
Gr8-	summer wheat 8 year conventional	Gr8+	summer wheat 8 year iwm
Pn8-	Carrot 8 year conventional	Pn8+	Carrot 8 year iwm
Sb4-	Sugarbeet 4 year conventional	Sb4+	Sugarbeet 4 year iwm
Sb8-	Sugarbeet 8 year conventional	Sb8+	Sugarbeet 8 year iwm
Sk8-	Cabbage 8 year conventional	Sk8+	Cabbage 8 year iwm
Ui4-	Onion 4 year conventional	Ui4+	Onion 4 year iwm
Ui8-	Onion 8 year conventional	Ui 8+	Onion 8 year iwm

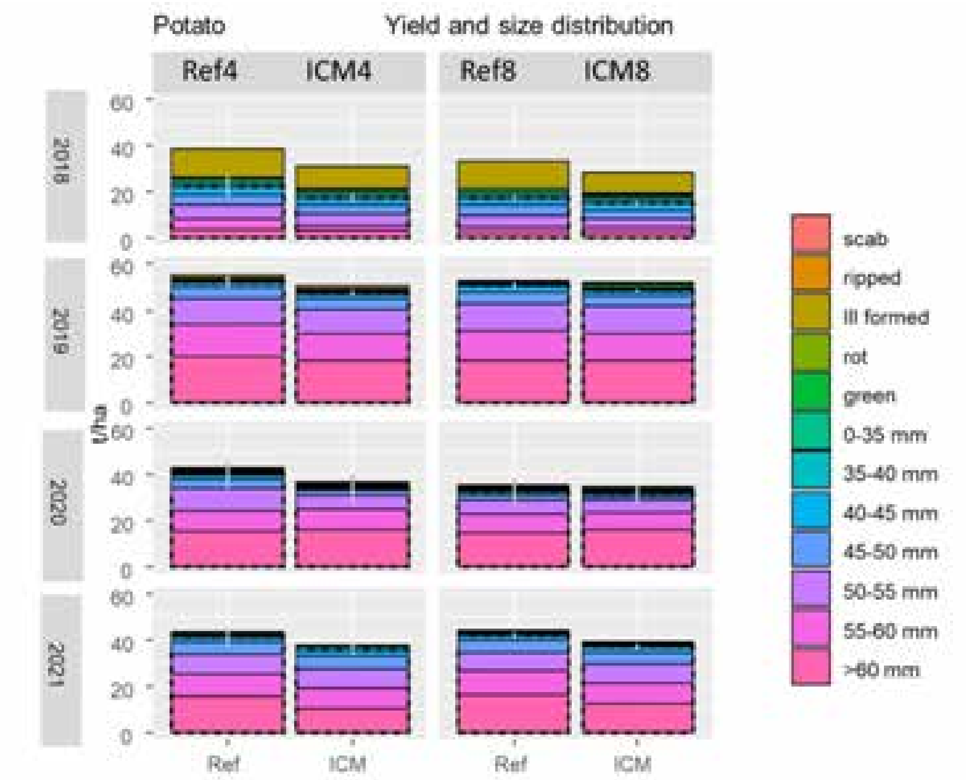


Figure 3 - Potato yields in the four-year reference rotation (Ref4) and the eight-year IWM rotation (ICM8), and intermediate strategies (Ref8 and ICM4).

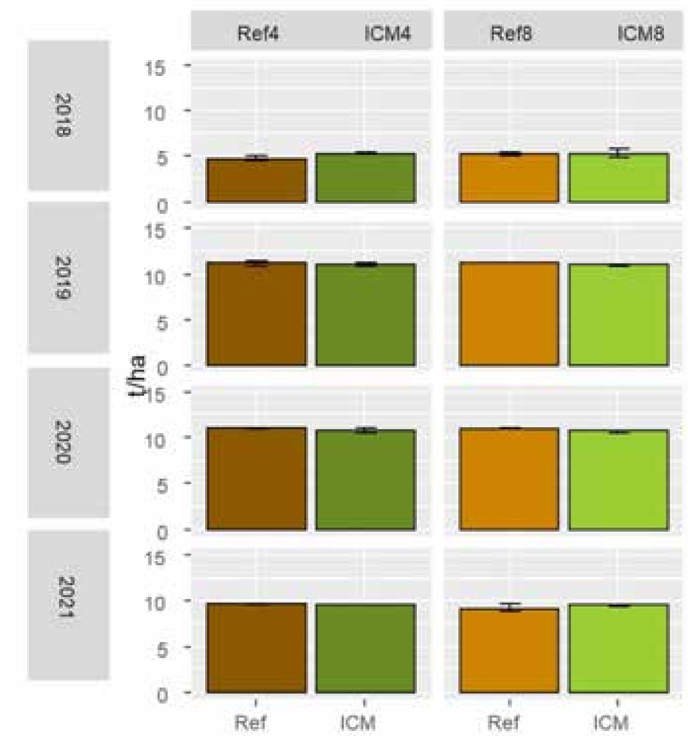


Figure 4 - Cereal yields in the four-year reference rotation and the eight-year IWM rotation. Spring barley in 2018, winter wheat in 2019-2021.

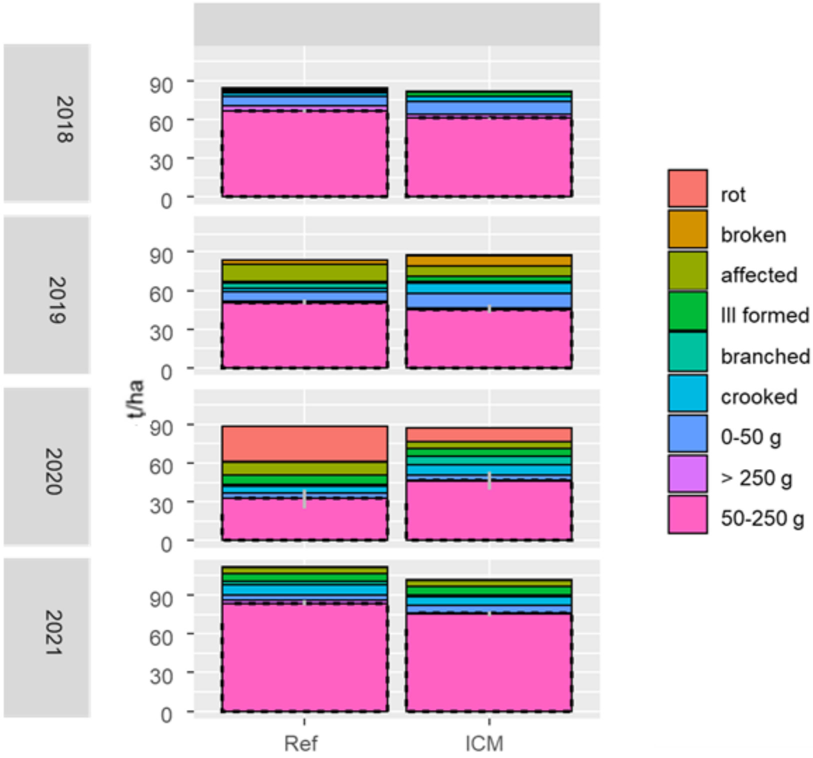


Figure 5 - Carrot yields in the IWM (ICM) and reference strategy (Ref).

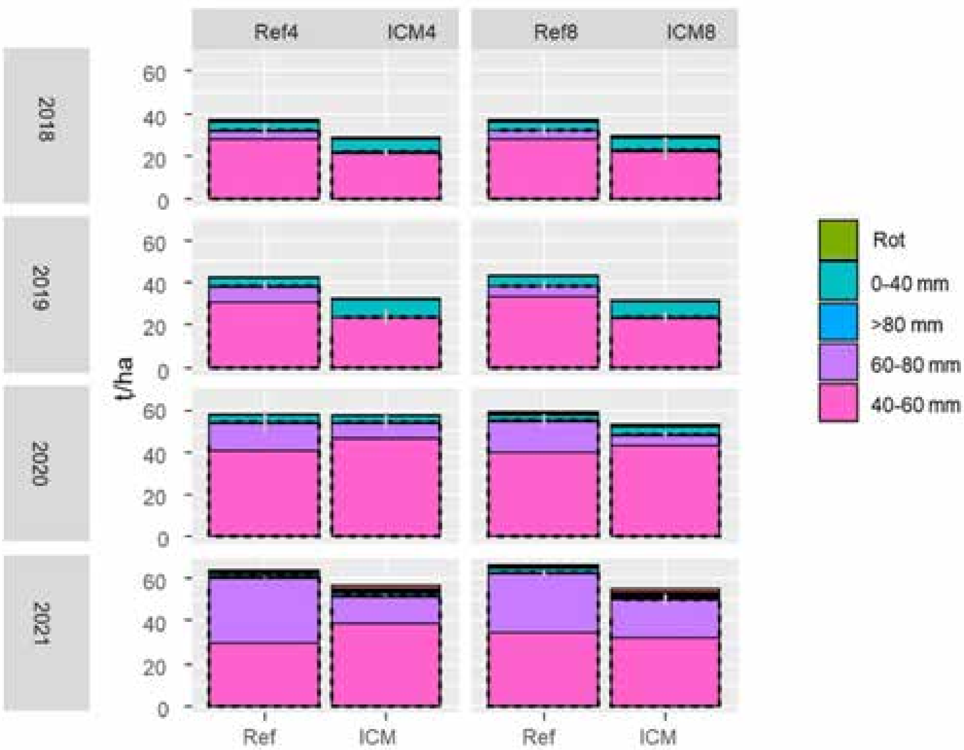


Figure 6 - Onion yields in the four-year reference rotation (Ref4) and the eight-year IWM rotation (ICM8), and intermediate strategies (Ref8 and ICM4).

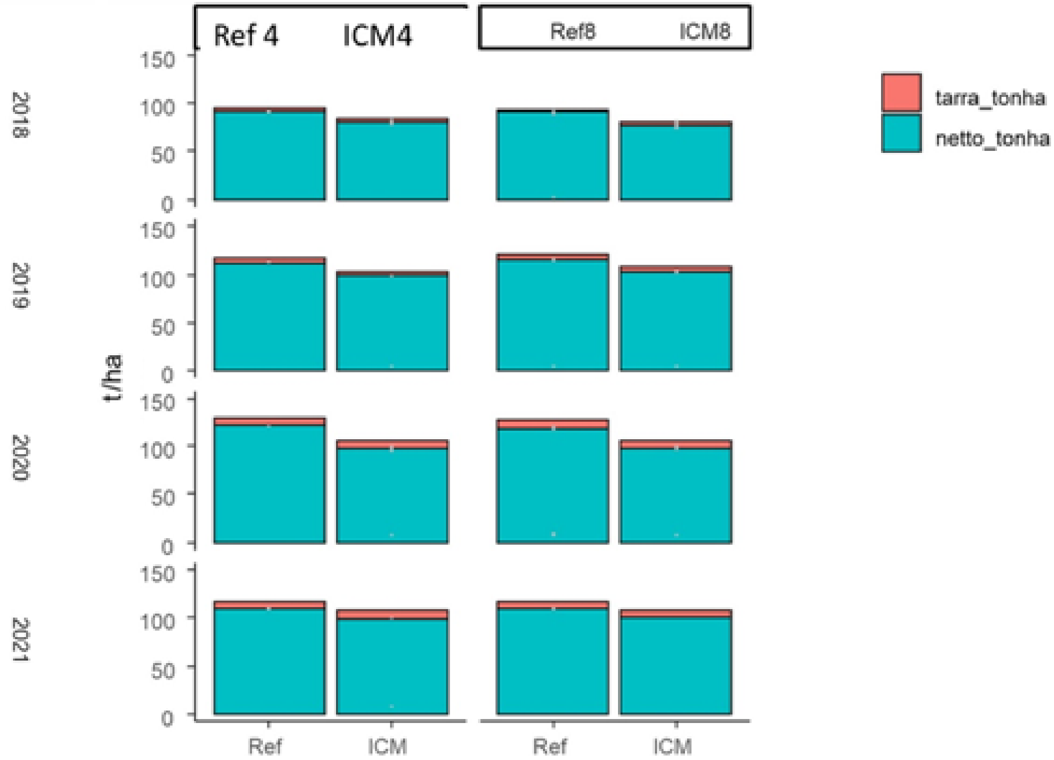


Figure 7 - Sugar beet yields in the four-year reference rotation (Ref4) and the eight-year IWM rotation (ICM8), and intermediate strategies (Ref8 and ICM4).

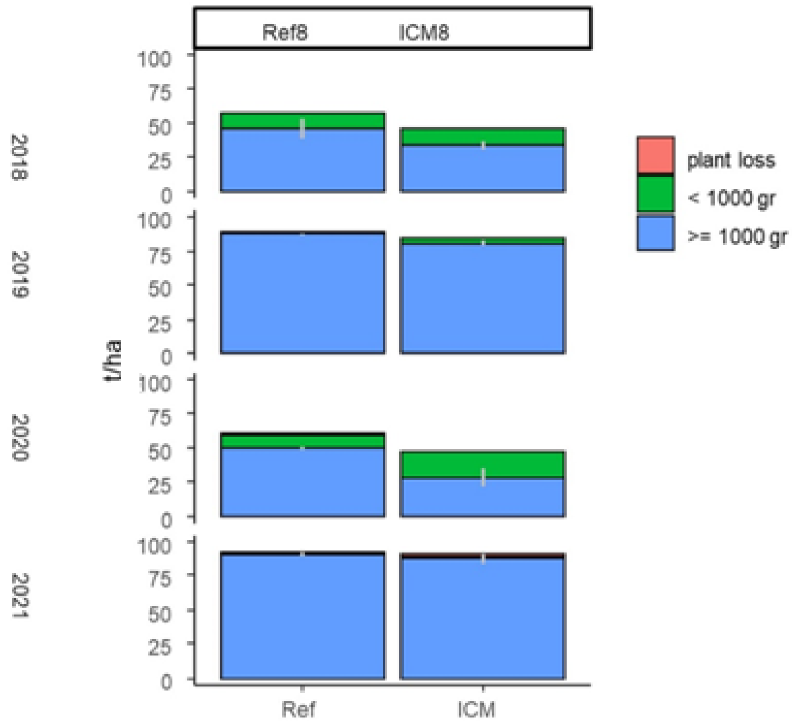


Figure 8 - Cabbage yields in the IWM (ICM8) and reference strategy (Ref8).

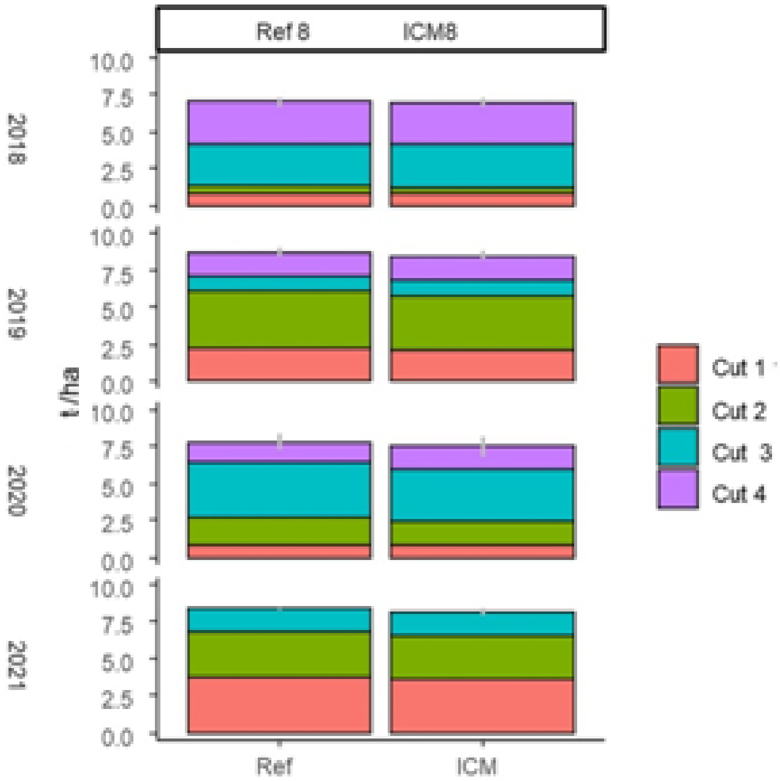


Figure 9 - Grass clover yields in the IWM (ICM8) and reference strategy (Ref8).

EXPERIMENT ON ANNUAL ROW CROPS – MAIZE

In this experiment, established in 2009, we investigate the effect of four tillage systems on the weed population in a maize monoculture. In this long-term experiment, we have tested two different varieties of maize: normal and short-season variety. The short-season variety was no longer part of the experiment from 2020 onwards. The experiment has three replicates. Two different weed management strategies are used: a herbicide-based system and one based on mechanical control. All fields were treated with glyphosate prior to soil tillage.
Chemical control consisted of a single spraying with a mix of herbicides in 2018 and two sprayings with a reduced dose of a mixture of herbicides in 2019, 2020 and 2021. In 2018, mechanical weed control was 3-4 times harrowing and 1-2 times hoeing for early cultivar and 2 times hoeing for the short season cultivar. Mechanical control in 2019 was 2 times harrowing and 4 times hoeing with finger-weeding in the early cultivar and 1 time harrowing and 3 times hoeing with finger-weeding in the late cultivar. Compared to other years, there were fewer possibilities for harrowing in the young maize because of dry weather and clods in the soil. To compensate for this, hoeing with finger-weeding was more frequent. In 2020, the mechanical weeding consisted of 6-8 operations depending on the tillage system. For the ploughing (A) and the deep-tine with rotary cultivation (C) systems, weed control was 4 and 6 times harrowing and 2 times hoeing with finger-weeders. In the other systems (D and E), mechanical weed control was 3-4 times harrowing and 4 times hoeing. Due to dry conditions, in the latter two systems the extra hoeing was needed to provide sufficient loose soil.
In 2021, the mechanical weeding strategy was only partly executed as a result of wet conditions, eventually resulting in adapting towards a chemical strategy in the mechanical plots of objects A, C and D. For deep-tine cultivation and direct sowing (E), the mechanical weed control strategy was even completely abandoned. Chemical weed control was applied in a higher dose to all plots of E once, followed by a second application at low dose. For the strip sown plots (D), a higher dose was used in the first application for the chemical weed control objects, followed by a low dose application for all objects D.

Results

Crop yields

Dry matter yields of the standard maize cultivar are more or less similar between different tillage types and weed control strategies, except for the yields in 2021 (Figure 11). Harvests were completed on 18 September in 2018 and 2019, 24 September in 2020, and 14 October in 2021. For the short-season cultivar grown in season 2018 and 2019, dry matter yields were generally lower when compared to the standard cultivar.
In 2019, the short-season cultivar dry matter yield was lower after deep-tine cultivation of the soil without seed bed preparation (E) when compared to the other three tillage types. A possible explanation could be unfavourable sowing conditions after this type of tillage, resulting in poor germination and eventually a lower plant number. After deep-tine cultivation with a rotary cultivation (C) in combination with chemical weed control, the dry matter yields were lower in both 2018 and 2019 when compared to their mechanical weeding counterparts.
Weather conditions in 2021 lead to a delayed sowing by one month of the standard maize cultivar in early June for all tillage types. For the deep-tine cultivation without seed bed preparation (E), sowing was performed one week later than for the other objects in 2021. The shifted growing season resulted in lower dry matter yields. In addition, the effects of the higher herbicide applications might be reflected in the lower yields of objects D and E.

Weeds

In general, the strategy with ploughing as soil tillage and chemical weed control resulted in the lowest soil cover with weeds in both maize cultivars after the growing season (Figure 12). The short-season cultivar resulted in higher soil cover with weeds when compared to the standard cultivar for most combinations of tillage and weed control strategies. Exceptions were the objects with mechanical weed control strategies when combined with deep-tine cultivation with a rotary cultivation (C) in 2018 and strip rotary cultivation (D) and deep-tine cultivation without seed bed preparation (E) in 2019.
When the short-season cultivar was grown after tillage with the deep-tine cultivator and rotary cultivar (C), a higher soil cover with weeds was observed in both 2018 and 2019 for the chemical weed control strategies when compared to the mechanical weed control strategies (Figure 11). The same was observed for the rotary cultivated strips

(D) in 2019, but not in 2018 when the mechanical strategy resulted in higher soil cover by weeds. For the other two tillage types with the short-season cultivar and for all tillage types with the normal season, cultivar mechanical weed control resulted in higher soil cover by weeds in 2018 and 2019.
In 2021, soil cover with weeds after harvest was low for all tillage types. This observation was independent of the weed control strategy because both weed control strategies eventually relied on chemical weed control. An important factor to consider is the delayed sowing of the maize. As a result, in the systems with rotary cultivations (A and C) weeds that have a strong emergence peak in April/May would not have had the chance to establish in large numbers during the growing season. In the other tillage systems, weed pressures were higher during the growing season, but this was compensated for by using higher dosage of chemical weed control. The soil cover by weeds therefore does not reflect these observations, whereas the even lower yields for system D and E in 2021 (Figure 12) may be explained by stronger crop-weed competition during the early crop growth stages.

Code	Description			
	Main cultivation	***Sowing bed preparation***	***Sowing method***	***Remarks***
A	Plough Spring 25 cm	Rotary harrow	conventional sowing	-
C	Deep-tine cultivation	Rotary cultivator	conventional sowing	-
D	Strip rotary cultivation	Strip rotary cultivation	strip sowing	-
E	Deep-tine cultivation	None (direct sowing)	direct sowing	-
	Cultivar type	***Cultivar***	***Sowing time***	***Harvest time***
M1	Normal season length	P8057 (Pioneer)	Normal	Normal
M2	Short-season maize	Joy (DSV)	(1st week May)	(end Sep. early Oct)
			Late	Normal
			(4th week May)	(end Sep. early Oct)
			Weed control	
I			Conventional	No cover crop
II			Mechanical	No cover crop

Table 2 - Description of the three factors in the long-term maize field trial. Factors include soil tillage (A-E), maize cultivar (M1-M2), and weed control strategy (chemical or mechanical).

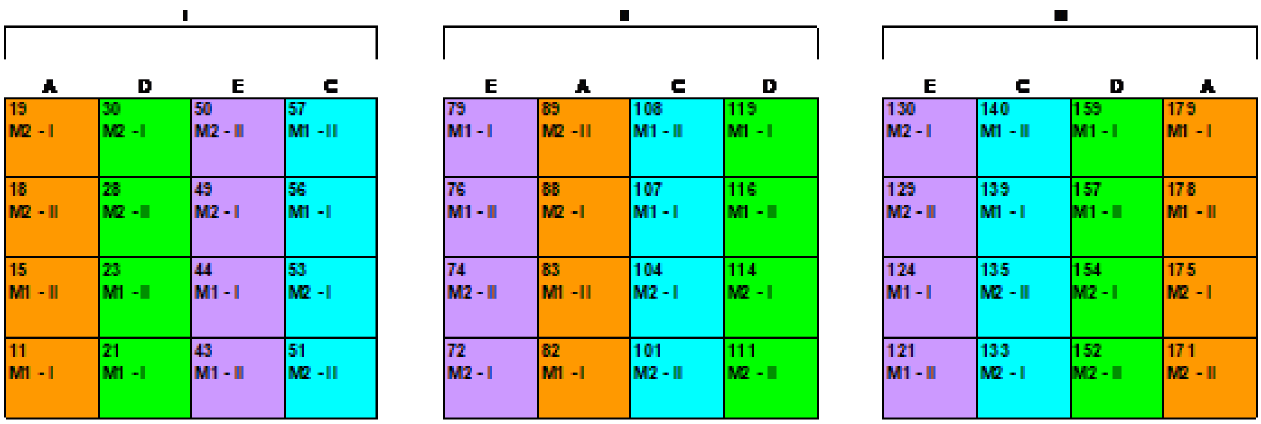


Figure 10 - Layout of the maize field experiment at the experimental farm of WUR Field Crops Lelystad.

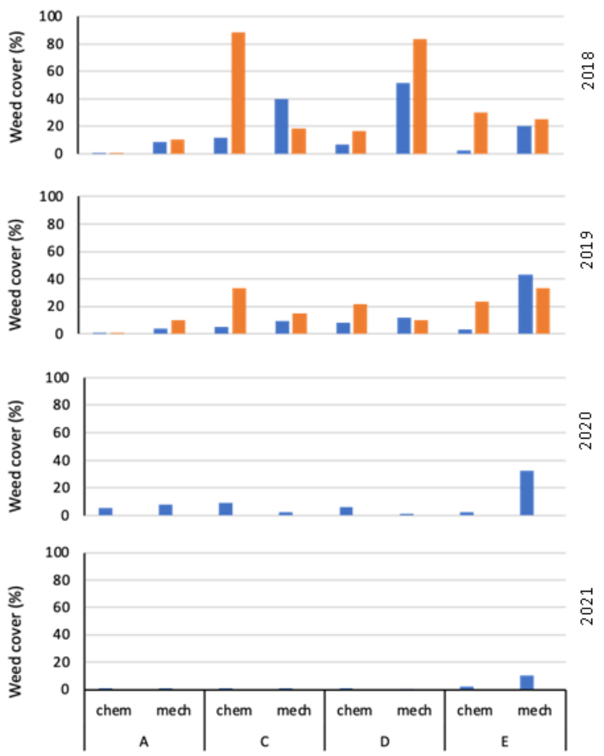


Figure 11 - Average soil cover with weeds (both dicotyledon and monocotyledon) one day after maize harvest.

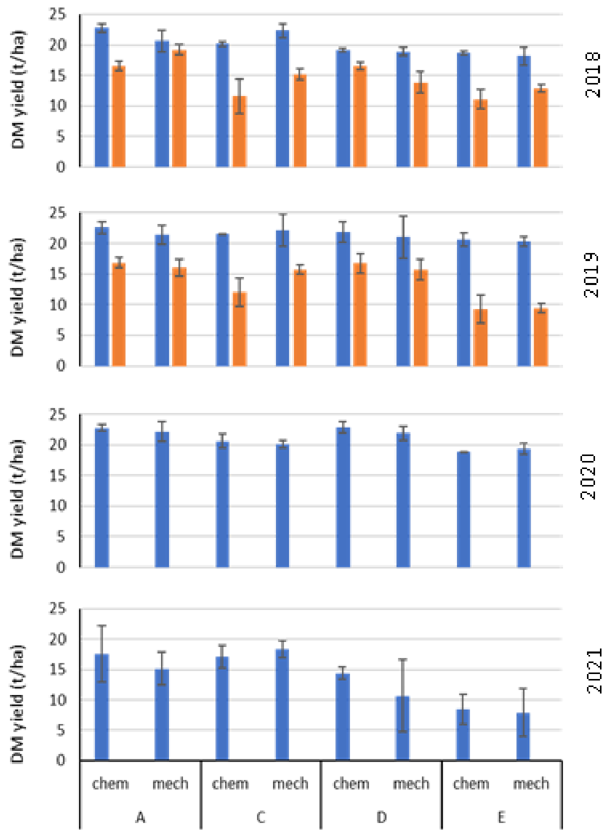
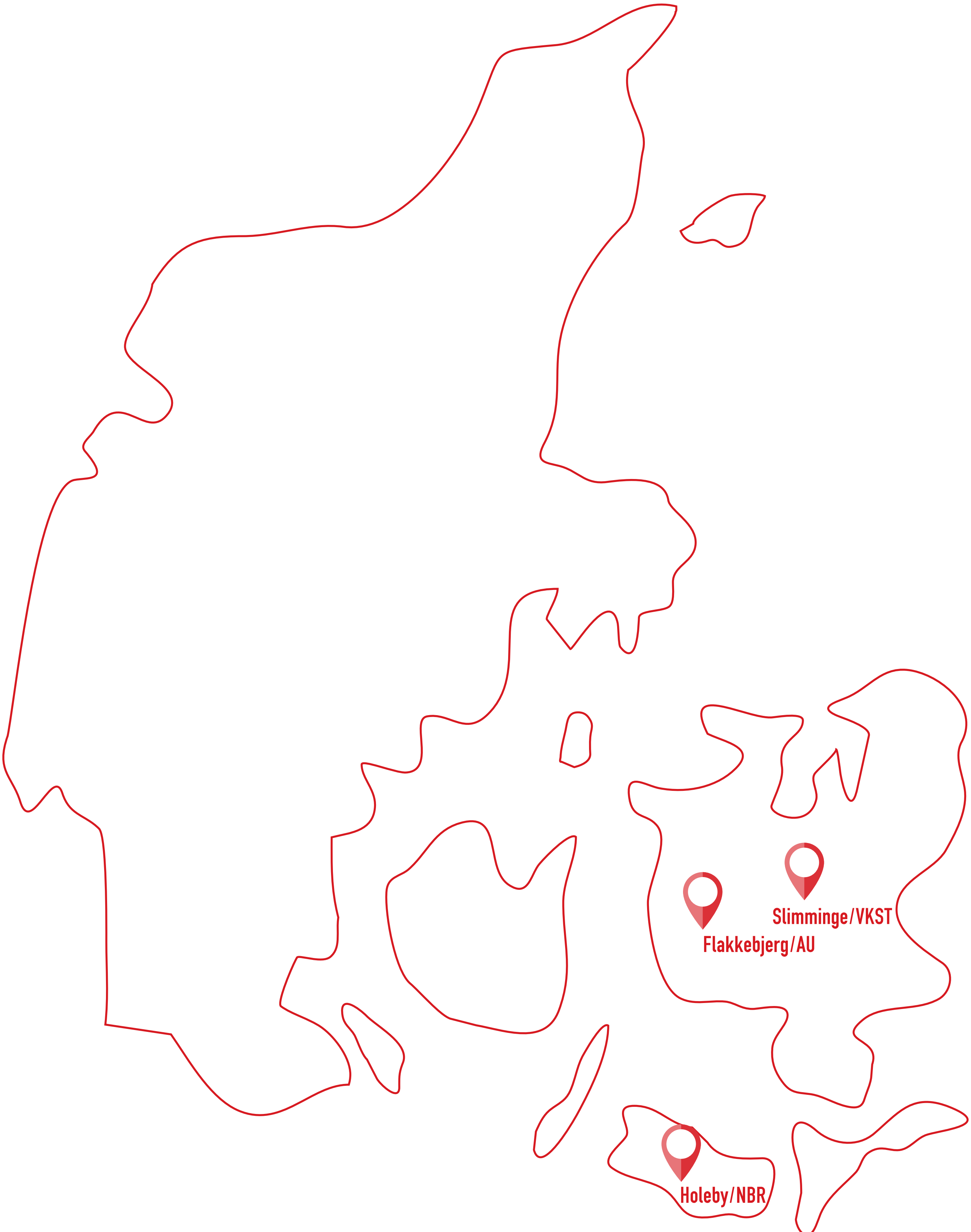


Figure 12 - Average dry matter yield of silage maize in t/ha per tillage system and weed control strategy for the period 2018-2021. For 2018 and 2019 the yield for both maize cultivars (blue = standard, orange = short season) is given. Error bars indicate SD (Standard Deviation).

DENMARK



EXPERIMENTAL TRIALS MANAGED BY AARHUS UNIVERSITY

AARHUS UNIVERSITY

Aarhus University's Department of Agroecology is located south of Slagelse on the island of Sjælland. It carries out research into agroecology, which is the interaction between plants, animals, humans and the environment within agroecosystems for the production of food, feed, energy and bio-based products. It contributes to sustainable production and growth via research, advice and teaching. Its experimental area covers approx. 200 ha and is managed primarily by conventional farming with some fields devoted to organic trials. The soil is a sandy loam with limited organic matter. The weed populations are mainly broadleaved weeds with some grassweeds, such as perennial ryegrass, blackgrass, silky bent grass and annual meadow grass.

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WP3 – EXPERIMENTAL TRIALS ON WINTER WHEAT

Objectives

The objective is to combine management practices into strategies for winter wheat cropping, which is designed to limit the germination of weeds and inhibit emergence and growth, thus contributing to a reduced dependence on herbicides. To demonstrate the effect of soil tillage, the trial comprises both no-till and ploughed strategies. Combinations of sowing time and direct management practices are in focus.

Season 2017/2018

The trial was established at Aarhus University in Flakkebjerg for demonstration purposes. It included strategies with no-till and others with conventional ploughing, as well as various levels of herbicide application combined with mechanical weeding. The aim was to lower the herbicide application to a minimum by optimizing establishment and crop growing conditions.
Five alternative strategies were established and arranged in wide stripes with a standard strategy in the middle for comparison; two strategies with no-till and three were ploughed conventionally.
The management practices, which varied in each strategy, include soil preparation, sowing time, row width depending on weeding strategy, herbicide application and mechanical weeding. In order to facilitate mechanical weeding in Strategy 4 and Strategy 6, the crop was sowed in wider rows. The no-till strategies were sown in wider rows as well due to the sowing equipment used. Fertilizer application and variety selection was the same across all strategies. Fertilizer was broadcast and the winter wheat variety Sheriff was chosen as it is disease-tolerant with good competitive characteristics and potential high yield. In no-till strategies, glyphosate was applied prior to sowing and no other autumn application of herbicides was carried out. Herbicide

	Strategy 1 5 m	Strategy 2 5 m	Strategy 3 6 m	Strategy 4 5 m	Strategy 5 6 m	Strategy 6 5 m
	Reference/standard	Ploughing similar to standard	No-till direct sowing Moderate risk	Ploughing Higher risk	No-till direct sowing Higher risk	Ploughing No herbicides
Soil tillage	Ploughed	Ploughed same timing as Strategy 1	Straw harrow Direct drilling	Ploughed same timing as Strategy 1	Straw harrow Direct drilling	Ploughed same timing as Strategy 1
Sowing time	Normal sowing time (planned 15-20 sept.)Real 28. sept.	Late sowing normal + 20 days	Late sowing normal + 20 days	Late sowing normal + 20 days	Late sowing normal + 20 days	Late sowing normal + 20 days
Seeding density	Reference/standard	Higher than standard due to later sowing	Higher than standard due to later sowing	Higher than standard due to later sowing	Higher than standard due to later sowing	Higher than standard due to late sowing
Row width	Standard row 12 cm	Standard row 12 cm	Wide rows 18 cm Horsch	Wide rows 20 cm Kongskilde sowing machine	Wide rows 18 cm Horsch	Wide rows 20 cm Kongskilde sowing machine
Herbicides	Standard herbicide application autumn Need-based spring	Standard herbicid application autumn No herbicides spring	Glyphosate before sowing, same timing in str. 3+5 Need-based her-bicide application spring	Reduced herbicide application autumn No herbicides spring	Glyphosate before sowing, same timing in str. 3+5 No herbicide application spring	
Mechanical weeding	-	-	-	Row cultivation in spring	-	Row cultivation in spring Tine harrow

- Straw chopped and left in field before trial was established
- Ploughing in the same direction as the strategy strips to avoid driving in the no-till strips
- Seeding density and row width is the same in all strategies
- Standard fungicides application and insecticides as needed
- Standard fertilizer in all strategies

Table 1 - WP3 trial plan for season 2017/2018.

application for ploughed strategies included autumn application (prosulfocarb, diflufenican and pendimethalin in autumn 2017) combined with need-based spring application or no spring application. In Strategy 4 and Strategy 6, mechanical weeding is planned for spring treatment.
The trial was established in autumn 2017 under difficult conditions due to repeatedly intense rain. Three sowing dates were initially planned, with a delay of 10 and 20 days respectively. The weather conditions resulted in the standard sowing date being postponed for 10-15 days, and the first sowing was conducted on 28 September. Delayed sowing was then conducted approximately 20 days later, as stated in the table. This resulted in smaller differences among the strategies than planned. Sowing was fairly successful, however the no-till strategies suffered from sub-optimal soil conditions and the establishment of the crop appeared somewhat scattered in late autumn. In spring 2018, weather conditions were cold with some bare frost on the area.
After the problematic weather conditions at sowing with very wet conditions, winter refused to let go of Denmark until just before April, after which came a sudden shift to very high temperatures and no rain. From April to September 2018 the trial location received 198 mm of rain, which was 184 mm less than the year before and very low for the region. At the same time, the temperature of these five months was on average 2°C higher than in 2017 with maximum temperatures in summer 2018 reaching 32°C in July compared to 25°C in 2017. No irrigation was possible in the field, as the need for water was not expected.
This might be one of the explanations for differences in the best performing strategy in early season compared with final yield. Even with the poor conditions for establishment, the directly sown strategies had a higher crop plant number per row meter than the standard row width strategies. In June, however, there was a lower crop biomass than in other strategies. The strategies sown in wide row distances had the highest crop biomass at this time of the season. At harvest, however, the directly sown strategies yielded much better than all other strategies, and the strategies with wide rows gave the lowest yield (Figure 3). The standard strategies had intermediate values for biomass of crop in June and yield.
Weed biomass in June was sampled at the same time as crop biomass, but the amounts of weeds in all of the strategies were very low (Figure 4). The dry summer inhibited any new weed flushes after control measures in spring. It is difficult to conclude

Figure 1 - Plots of WP3 trials.

Figure 2 - Direct sowing in stubbles with Horsch sowing machine 18 cm rows.

on the results regarding strategy performance, but there was an indication of better conditions in the directly sowed strategies during the drought. The ploughed strategies with wide rows showed promising establishment and early summer biomass production, but were least resilient during the drought. The difference in yield between strategy 4 and 6 is hard to explain as both had very low weed biomass and the only management practice to differ in spring was a tine harrowing in strategy 6.

Season 2018/2019

The demonstration trial was located on the eastern part of Zealand and hosted by VKST, an independent advisory company owned by farmers in the region. VKST is an independent advisory company owned by farmers in the region and was established in 2017 as a fusion of DLS and GEFION (two agricultural advisory services providers). VKST offers a broad range of advisory services for farmers within crop production, which includes accounting and economical advice along with practical management advice. The advisory work for private farmers is the corner stone of VKST, but VKST has activities such as field testing and trials for companies and SEGES,

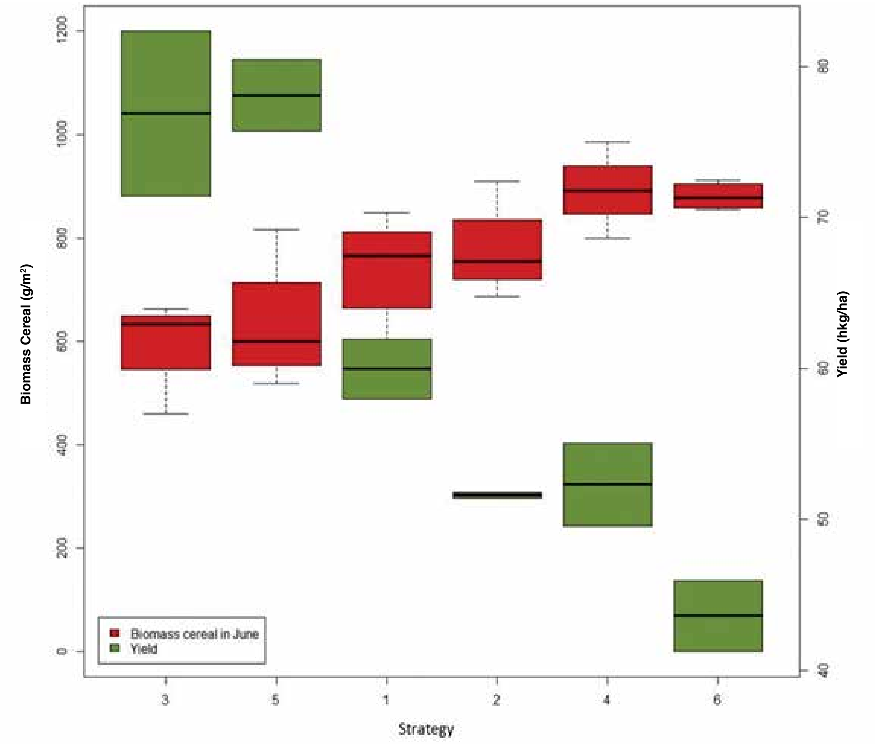

Figure 3 - Crop biomass and yield. There was a shift among the strategies during the very dry summer and, in the end, the directly sown strategies yielded higher than other strategies despite a poor emergence rate and lower biomass in early summer. For strategy explanation, see Table 1 or legend in Figure 4.

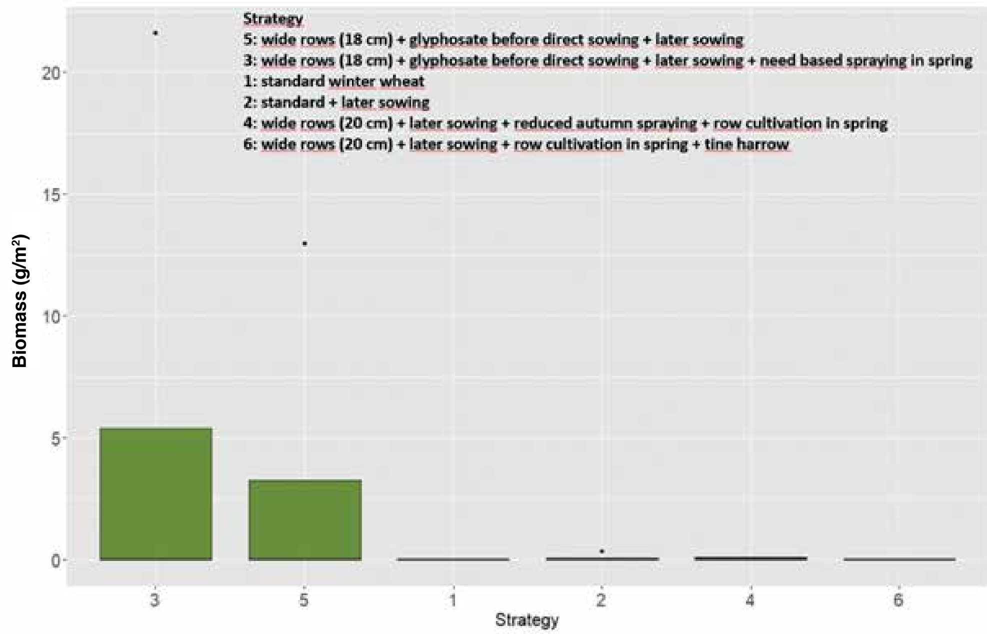

Figure 4 - Weed biomass in June 2018.

the national advisory service, as well. VKST conducts field trials on new varieties, fertilisers and plant protection products. VKST has a large area of field dedicated to demonstration purposes and contact to a large network of farmers within different farming practices: conventional, conservation agriculture and organic farming. The experimental unit within VKST has machinery and expertise to conduct most advanced weed management strategies in winter wheat.

Figure 5 - Aerial photo of the experimental area including the demonstration trial on winter wheat.

The trial largely followed the same layout as in season 2017/18 and was located in an experimental field area with other winter wheat trials at VKST increasing the demonstration value.
The focus of the 2018/19 trials was on sowing time and seeding density combined with different levels of herbicide application and mechanical weeding. A directly sown strategy was established, but the emergence of the crop was very poor and the strategy was abandoned in spring.

	Strategy 1 5 m	Strategy 2 5 m	Strategy 3 5 m	Strategy 4 5 m	Strategy 5 5 m
	Reference/standard	High seeding density	Ploughing Early sowing	Direct sowing	Ploughing No herbicides
Soil tillage	Ploughed same timing as strategy 3	Ploughed same timing as strategy 3	Ploughed	No ploughing	Ploughed same timing as Strategy 1
Sowing time	Normal sowing time	Normal sowing time		Normal sowing time	Late sowing normal + 14 days
Seeding density	Standard	Standard + 50%	Standard	Standard	Standard
Row width	Standard row 12 cm	Standard row 12 cm	Standard row 12 cm	Standard row 12 cm	Wide rows 18 - 20 cm
Herbicides	Standard herbicide application autumn same growth stage of crop as strategy 3 Need based spring	Standard herbicide application autumn same growth stage of crop as strategy 3 Need based spring	Standard herbicide application autumn Need based spring	Glyphosate before sowing No herbicide application autumn No herbicides spring	No herbicides
Mechanical weeding	-	-	-	-	Row cultivation in spring

- Straw chopped and left in field before trial establishment
- Ploughing in the direction of the strategies strips to avoid driving in the no-till strips
- Same variety in all strategies
- Standard application of fungicides and insecticides as needed
- Standard fertilizer standard in all strategies

Table 2 - WP3 trial plan for season 2018/2019.

Figure 6 - Border between a strategy sown at normal sowing time and the late-sown strategy just before herbicide application in the normal sowing time strategy.

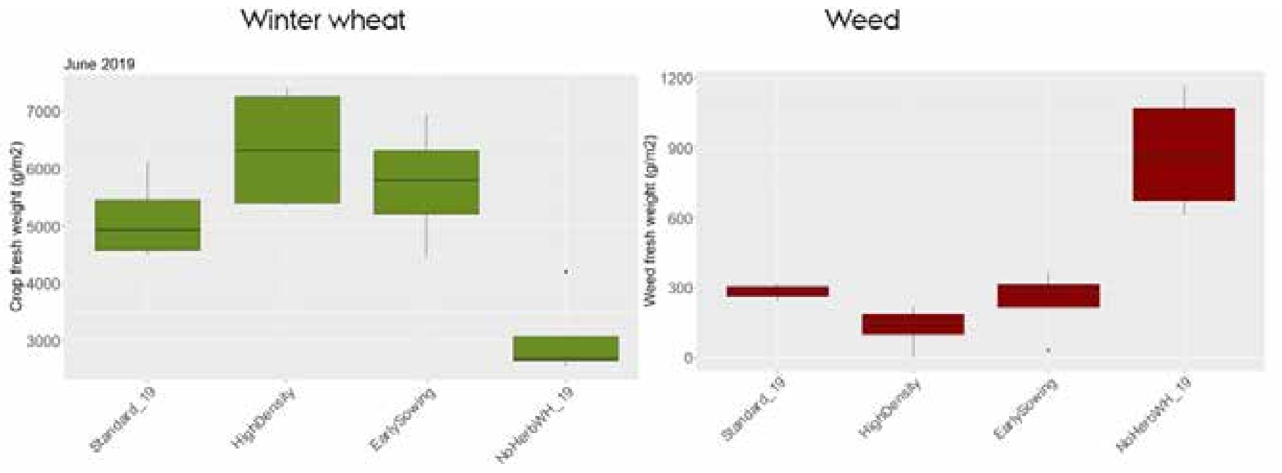

Figure 7 - Comparison of crop and weed biomass sampling (fresh weight) in June 2019.

Legend:
- **Standard_19** following local standard management with seedbed preparation and sowing in mid-September after ploughing two weeks before. Herbicide application with standard program in autumn around crop emergence.
- **HighDensity** 50% increase in seed amount otherwise the same as Standard_19.
- **EarlySowing** ploughed and sowed immediately after at the beginning of September. Autumn herbicide application as Standard_19, plus spring application after inspection.
- **NoHerbWH_19** sowed late in mid-October with high row distance (25 cm), no herbicide use, and inter-row weed hoeing in spring.

The weed population of the new location primarily consisted of broadleaved weeds and volunteer oilseed rape was abundant. Additionally, *Aethusa cynapium, Matricaria* sp., *Papaver rhoea, Poa annua, Geranium pursillum, Viola avensis, Galium aparine* and *Veronica* sp. was frequently observed. Some other grass weeds appeared, such as *Lolium, Vulpia* and *Alopecurus*. *Vulpia* was only observed in the early sown strategy, but the appearance was scattered and could have been random.
In June 2019, biomass of cereal and weed was measured and there was a fairly high weed pressure all over the area (150 -300 g/m^2 of fresh weight) (Figure 7). As the layout did not facilitate true replicates, the samples were taken in four positions along the strategy strip in 0.25 m^2 plots. High seeding density (235 pl/m^2 emerged in November 2018) tended to suppress the weed better than standard density (163 pl/m^2 emerged in November 2018), whereas early sowing (119 pl/m^2 emerged in November 2018) and standard strategy had the same weed pressure. The strategy with only mechanical hoeing was unsuccessful in managing the weeds that year. This was due to bad timing of the weed hoeing, partly because of weather conditions in spring. The fairly high weed amount left after spraying in spring

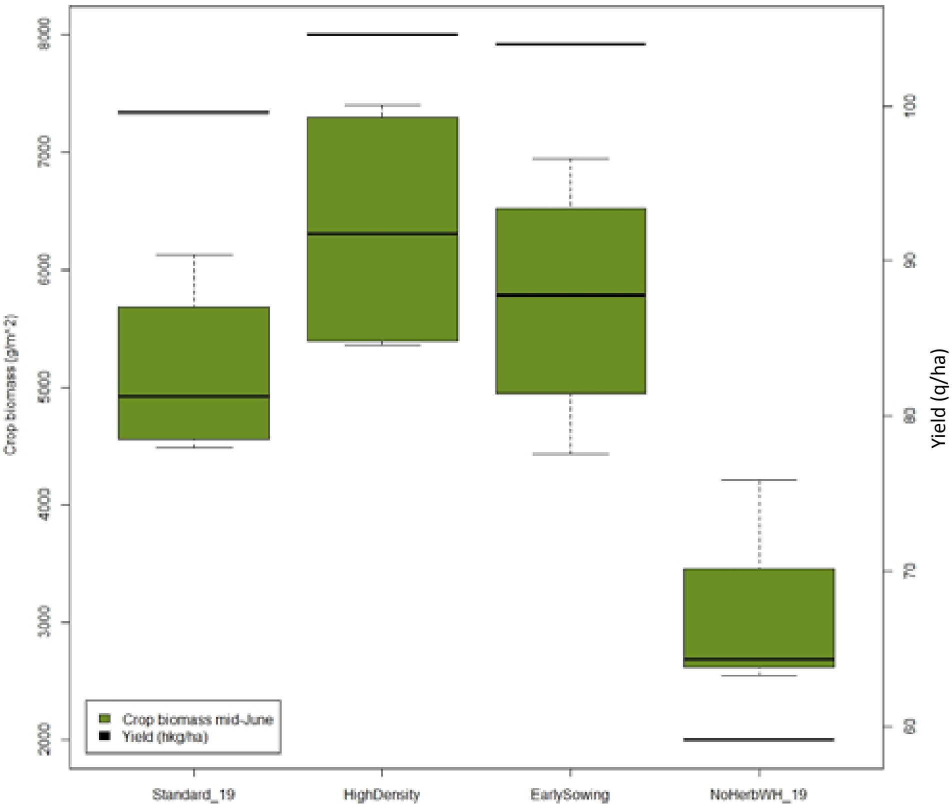

Figure 8 - Crop biomass in June 2019 (green boxes, left y-axis) and yield (vertical black lines, right y-axis). Yield was registered as a single measure, hence no variation was measured. The yield correlated with the biomass samplings in June with even more distinct differences.

was caused by uneven weed emergence and late-coming flushes of weeds, which were not sprayed. In both the standard strategy and high-density strategy, it was decided that no spring application was necessary. Herbicide application in the early sown strategy was based on a single weed species (*Galium aparine*) in spring and several other weed species emerged after spraying. A different herbicide choice might have had a better effect on a larger number of species. This led to the conclusion that a decision support system should be consulted for spring herbicide application.
At harvest, yield was highest in the high-density strategy and early sowing strategies, closely followed by the standard strategy (Figure 8). The difference in crop biomass in the strategy with mechanical hoeing only was even more distinct at harvest, where the high weed pressure had suppressed yield substantially. Experiments with this weed control strategy in previous years had a higher success, and were included in the following season 2019/2020.

Season 2019/2020

The demonstration trial was established close to the previous trial in the fields of VKST located on the eastern part of Zealand. The trial plan was agreed upon by project partners at a national cluster meeting in September 2019.
Based on the observations of the 2017/18 and 2018/19 seasons, the 2019/2020 trial plan focused on strategies with wide rows, band-spraying and weed hoeing. The standard strategy was maintained. Observations in 2018/2019 showed that the purely mechanical weed hoeing strategy was dependent on good conditions and careful timing for hoeing. The weather conditions were a limitation, even for experienced staff. Therefore, strategies with band-spraying were included to study the possibilities of supporting mechanical weed hoeing (Strategy 2 and Strategy 3) with herbicide application in the crop row (Strategy 4 and Strategy 5). Both sets of strategies were sown at two sowing dates (standard in mid-September and late in mid-October), with sowing density being increased to optimise crop competitiveness in the rows. In 2018, the directly sown strategies were observed to provide high yields

	Strategy 1 10 m	Strategy 2 10 m	Strategy 3 10 m	Strategy 4 10 m	Strategy 5 10 m	Strategy 6 10 m	Strategy 7 10 m
	Reference/ standard Winter wheat	Ploughing No herbicides Winter wheat	Ploughing No herbicides Winter wheat	Ploughing bandspraying and wide rows Winter wheat	Ploughing bandspraying and wide rows Winter wheat	No-till Winter wheat Cover crop	No-till, spring wheat very late sowing Spring wheat Cover crop
Soil tillage	Ploughed	Ploughed same timing as Strategy 1	Ploughed same timing as Strategy 1	Ploughed same timing as Strategy 1	Ploughed same timing as Strategy 1	Direct sowing	Direct sowing
Sowing time	Normal sowing time	Normal sowing time	Late sowing normal + 14 days	Normal sowing time	Late sowing normal + 14 days	Late sowing normal + 14 days	Very late sowing November
Seeding density	Standard	Higher density in row	Higher density in row	Higher density in row	Higher density in row	Increased	Increased
Row width	Standard row 12 cm	Wide rows 25 cm	Wide rows 25 cm	Wide rows 25 cm	Wide rows 25 cm	Standard row 12 cm	Standard row 12 cm
Herbicides	Standard herbicide application autumn Need based spring based on DSS (CPO)	No herbicides	No herbicides	Bandspraying with normal spraying boom in low height Standard her-bicide choice in autumn	Bandspraying with normal spraying boom in low height Standard her-bicide choice in autumn	Cover crop removal with glyphosate Consider need based spring application based on DSS (CPO)	Cover crop removal with glyphosate Consider need based spring application based on DSS (CPO)
Mechanical weeding	-	Row cultivation	Row cultivation	Row cultivation	Row cultivation	-	-

Table 3 - WP3 trial plan for season 2019/2020 in a winter wheat field in Denmark. The strategies were established in 10 m wide plots running approximately 100 m long. This means that sampling was performed in four sampling areas distributed at different places in the plots.

under very dry conditions. In 2019, establishment was poor and the directly sown strategy had to be cancelled. The new plan included two no-till strategies with cover crops established in autumn 2019 and late direct sowing at two timings with an SLY Boss drill machine (https://www.slyfrance.com/en/boss/). Late sowing of winter wheat was performed in mid-October, and very late sowing of spring wheat in mid-November. Late sowing of spring wheat in autumn is a practice some farmers have started as the winters are getting warmer and there is less risk of frost damage. Spring wheat has a better yield potential with very late sowing than winter wheat. The cover crops were destroyed with glyphosate application in the autumn before sowing.

The standard strategy proved highly efficient, as no weeds were observed in the sampling areas (Figure 9). The alternative strategies combining weed hoeing and band-spraying (Strategy 4 and Strategy 5) were the second most-efficient strategies in terms of weed biomass (Figure 10). The very late directly sown spring wheat (Strategy 7) had a low visual weed cover, as well, and resembled Strategy 5 in terms of comparable weed biomass in June. The crop biomass in June and the yield did not reflect the weed biomass results for the alternative strategies, as at the time of sampling in June the standard strategy had the highest crop biomass followed by the directly sown winter wheat strategy (Strategy 6). There was a tendency for this strategy to achieve a higher biomass in June and a higher yield than the other strategies, yet it was still lower than the standard strategy (Figure 11). The strategies combining weed hoeing with band-spraying (Strategy 4 and Strategy 5) increased their yield more than the strategies with sole weed hoeing (Strategy 2 and Strategy 3), which was in line with the results for weed biomass. The yield of Strategy 7 cannot be compared directly with the other strategies, as spring wheat generally has a lower yield than winter wheat.

In Strategy 4 and Strategy 5, the Treatment Frequency Index (TFI) was 53% lower than the TFI

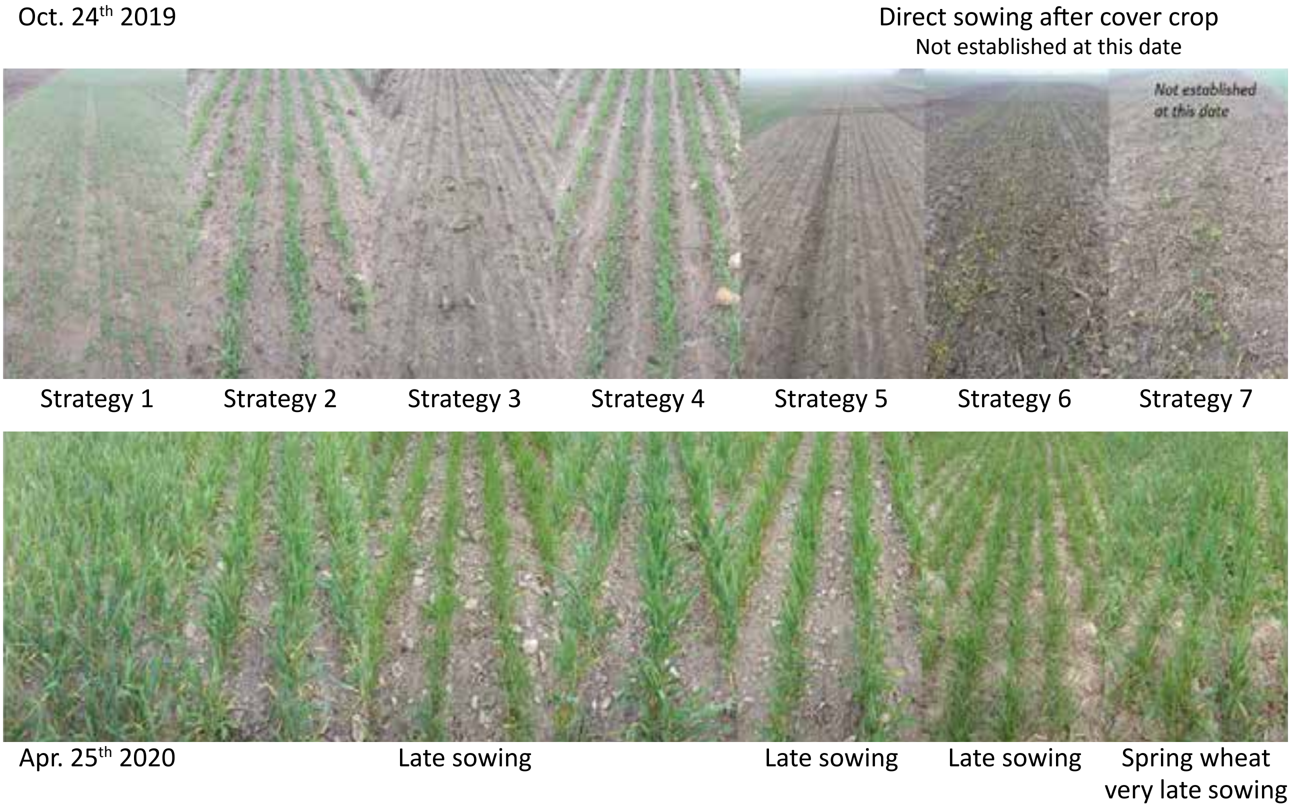

Figure 9 - Photos from autumn 2019 (top row) and spring 2020 (bottom row) of the seven strategies. Note that Strategy 7 had not yet been established in autumn 2019. In Strategy 6 and Strategy 7, the desiccated cover crops can still be seen as dead plant material after the glyphosate spraying.

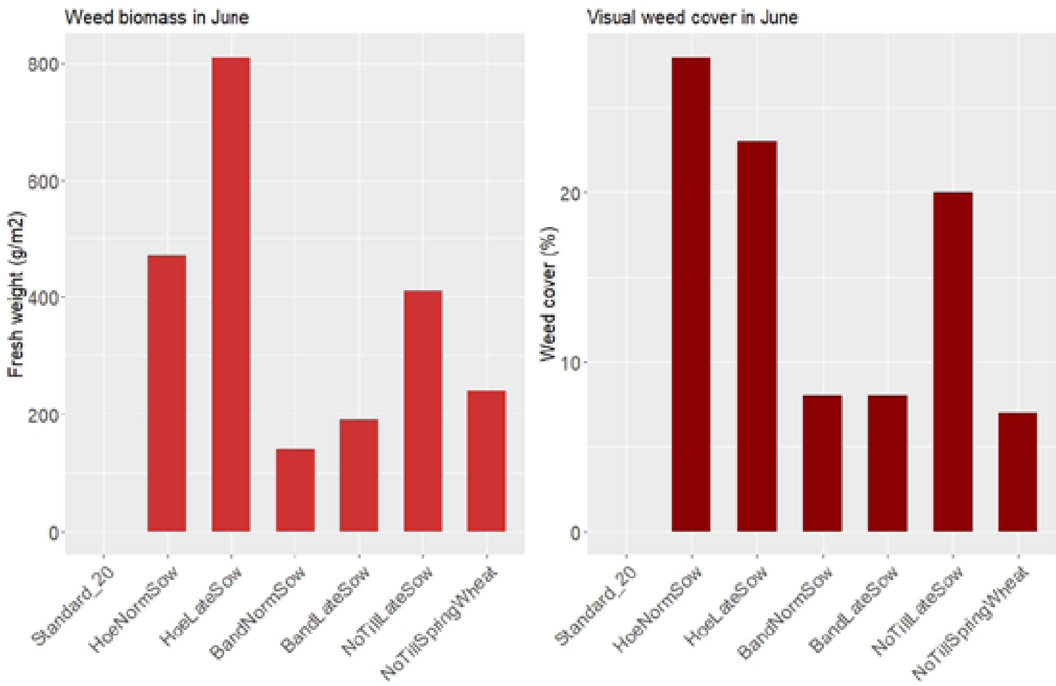

Figure 10 - Fresh weight and visual cover of weeds in June 2020. 'Strategies' corresponds to the strategies in Table 3 from left to right. Note that Strategy 7, NoTillSpringWheat, is the only strategy not established with winter wheat. No weeds were found in the standard strategy.

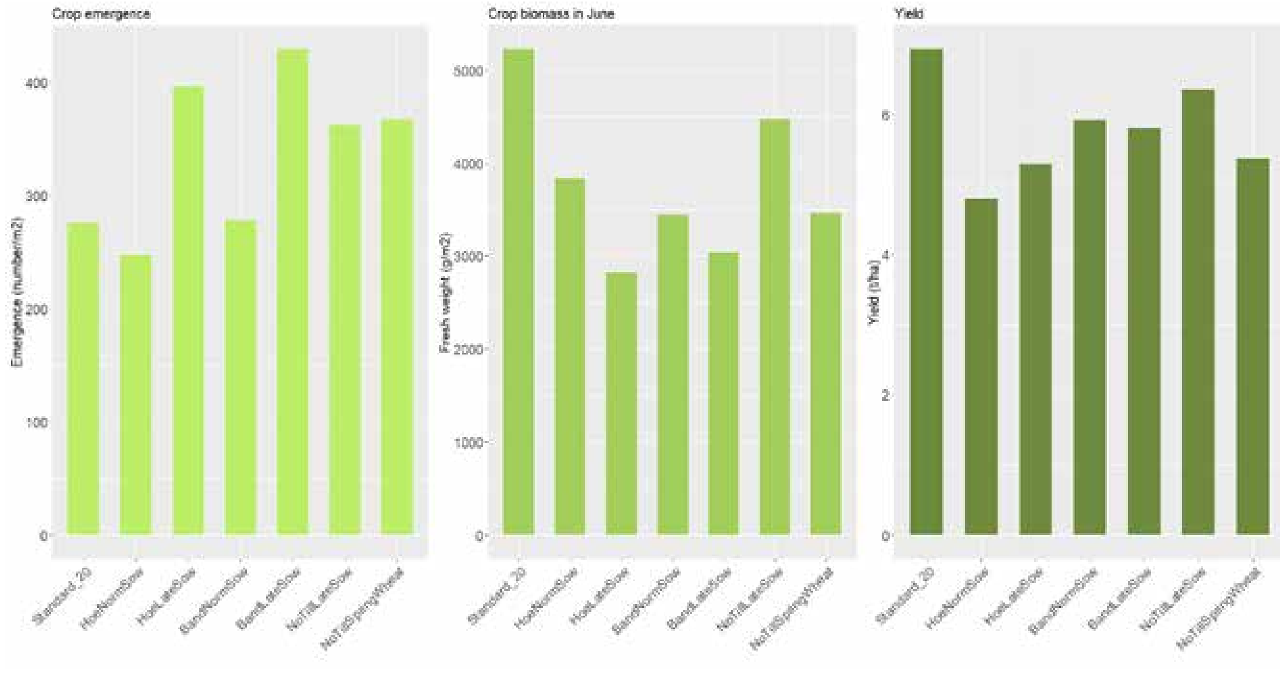

Figure 11 - Crop emergence in late November, crop weight in terms of fresh weight in June, and yield at harvest for the established strategies. 'Strategies' corresponds to the strategies in Table 3 from left to right. Note that Strategy 7, NoTillSpringWheat, is the only strategy not established with winter wheat.

of the standard strategy (TFI=1.69). Strategies 2 and 3 were not treated with any herbicides, while the glyphosate application to terminate the cover crops resulted in a TFI that was 49% lower than the standard strategy.

Pesticide Load Index (PLI) is a Danish index that considers both the environmental and human-related toxicity of the pesticides. It is calculated as the amount of the product applied multiplied by the toxicity to non-target organisms. The PLI of Strategy 4 and Strategy 5 was only 34% compared to the standard strategy (PLI=1.07), as the spring herbicide application was omitted and a smaller area was sprayed in the autumn. Strategy 4 and Strategy 5 had higher PLI than the standard strategy, as glyphosate is considered to have a higher toxicity for non-target organisms.

None of the alternative strategies achieved as high a yield as the standard strategy, but a lower herbicide amount was used. The most promising alternative was the combination of weed hoeing and band-spraying. The directly late sown strategy with winter wheat achieved a higher yield, but saw a lower level of weed control.

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WP4 – EXPERIMENTAL TRIALS ON SUGAR BEET

Objectives

The objective is to combine management practices into strategies for sugar beet cropping, which is designed to limit the germination of weeds and inhibit emergence and growth. Different combinations of mechanical weeding and herbicide application is demonstrated, including band-spraying and weed harrowing. Furthermore, an ALS-tolerant sugar beet variety is included in a strategy the first year.

Season 2018

A trial was established in spring 2018 at the research station of Aarhus University in Flakkebjerg for demonstration purposes. In sugar beets, several herbicide applications with herbicide mixtures are the standard weed management. In order to lower the herbicide application to a minimum further inclusion of mechanical weeding was necessary. Several options for herbicide reduction were available in combination with band-spraying. Three alternative strategies were established and arranged in wide stripes with a standard strategy for comparison. Three strategies with herbicide band application were combined with weed harrowing, with one using ALS-tolerant sugar beets. The management practices, which varied in the strategies, included band-spraying, weed harrowing between rows and false seedbed before sowing.
A follow-up treatment with flaming was planned for the strategy with false seedbed (Strategy 3), but the conditions were highly favourable for germination and the beets germinated quickly. Therefore, there was no opportunity or need for flaming. The soil preparation before sowing controlled the weed population until after germination.
From April to September 2018, the trial location received 198 mm of rain, which was 184 mm less than the year before and very low for the region. At the same time, the temperature of these five months was on average 2°C higher than in 2017, with maximum temperatures in summer 2018 reaching 32°C in July compared to 25°C in 2017. No irrigation was possible in the field, as the need was not expected.
The very dry conditions made the standard herbicide application programme difficult. The weeds developed a thick wax layer and were less susceptible than under normal conditions. Volunteer oilseed rape and *Chenopodium album* were especially difficult to control with the normal herbicide programme, which consisted of metamitron, ethofumesate and phenmidipham. The band-spraying in Strategy 2 and Strategy 3 used the same active principles as the standard strategy. The ALS-tolerant variety was treated with foramsulfuron and thiencarbazone, which are less inhibited by the wax layer. Due to the poor efficacy of the herbicides, a weed harrowing was added to all strategies. This

Figure 12 - Plots of WP4 trails.

	Strategy 1 6 m	Strategy 2 6 m	Strategy 3 6 m	Strategy 4 6 m
	Reference/standard	Band spraying High + weed harrow	Band spraying Low + weed harrow	Conviso SMART
Soil tillage	Ploughed	Ploughed	Ploughed, False seed bed + flaming,	Ploughed
Sowing time	Normal sowing time	Normal sowing time	Sowing delayed	Normal sowing time
Variety	Fairway, Maribo Seed	Fairway, Maribo Seed	Fairway, Maribo Seed	CONVISO® SMART ALS-tolerant
Herbicides	Standard herbicide application 3-4 applications	Band spraying with conventional sugar beet herbicides 3-4 applications	Band spraying with conventional sugar beet herbicides 1-2 applications	CONVISO One band spraying adjusted to 1 l/ha in row corresponding to approx. 0.2 l/ha on field average
Mechanical weeding	-	Between row harrowing	Between row harrowing and in-row finger wheel	-

Table 4 - WP4 trial plan for 2018.

means that weed harrowing was conducted twice in Strategy 2 and Strategy 4 and once in Strategy 1 and Strategy 3. Strategy 3 was sown two weeks later than other strategies, and the first weed harrowing (Strategy 2 and Strategy 3) was obsolete.
In the end, the yield was poor due to drought, but some differences were observed among strategies (Figures 13 and 14).

Season 2019

In 2019 the sugar beet trial was located in the fields of Nordic Beet Research (NBR) on Lolland close to Holeby. NBR is the industry's research and development company founded by the sugar beet growers and the sugar industry in Denmark and Sweden. They contribute to a better beet production through experimental work, innovation, dissemination and demonstration. NBR bridges between research and other stakeholders. In February 2019, a national cluster meeting among the Danish partners of WP 4 decided to focus the trial on band-spraying combined with weed hoeing. As the 2018 season was unusual, with very high temperatures and very little emerging weeds, the ALS-tolerant sugar beets were maintained as a strategy to compare two seasons' results (Table 5).
In spring 2019, three strategies combining band-spraying at different herbicide application levels with weed hoeing were established. At the low herbicide application level, band-spraying was supported by either weed hoeing alone, or combined with a finger weeder.
Only two replicates were established and, as their weed biomass varied substantially, both are shown in Figure 16. Strategy 2 used a variable weed control level in the two replicates. The main weed species in the standard strategy (Strategy 1) and the ALS-tolerant variety (Strategy 5) was *Veronica* sp. This weed species was present in all strategies but band-spraying, and *Polygonum convolvulus* was the dominant weed species in Strategy 2 (band-spraying with three herbicide applications). It was responsible for the large difference between the two replicates, as it was only dominant in Replicate 1. In Strategy 3, *Veronica* sp., *Polygonum aviculare* and *Stellaria media* were equally frequent. In Strategy 4, *Raphanus sativus* var. oleiformis was most frequent (primarily in Replicate 1), followed by *Veronica* sp.
Weeds were best-controlled in the standard strategy and the ALS-tolerant variety (Strategy 5). The band in Strategy 5 was 37.5 cm wide, which is much wider than the band of the other band applications (15 cm). The herbicide application rate in the row of the ALS-tolerant sugarbeets is the label rate and bandwidth, which will be realistic for a Danish authorisation (not currently authorised as band application). Overall, the alternative strategies did not provide the same level of control as the standard strategy, but the biomass of the sugar beets was on average similar in all strategies.
Biomass sampling in June 2019 showed that fresh weight of sugar beets in treatments with a low dose rate used in band-spraying tended to be higher than the other strategies, whereas the crop weight of standard, band-spraying with standard dose rate and

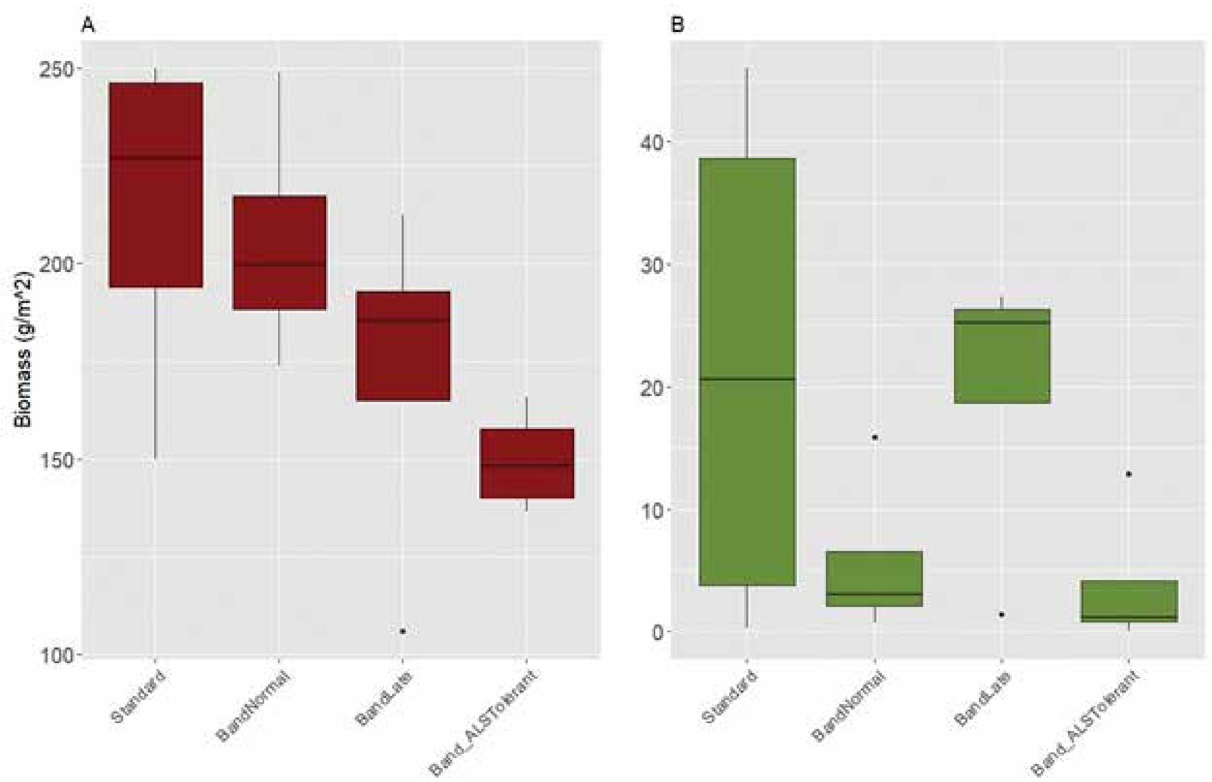


Figure 13 - Fresh biomass of crop (A) and weed (B) in June 2018 in the four strategies: Standard (Strategy 1), BandNormal (Strategy 2), BandLate (Strategy 3) and Band_ALStolerant (Strategy 4). These strategies are described in Table 4.

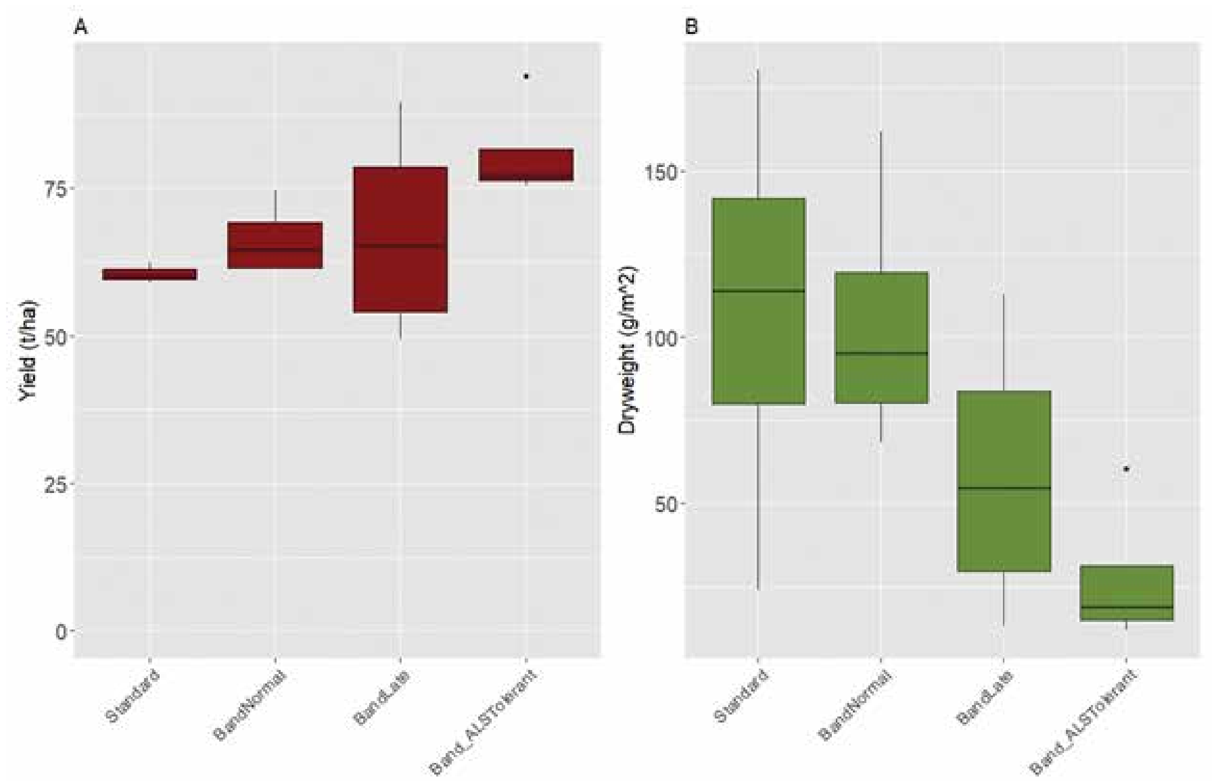
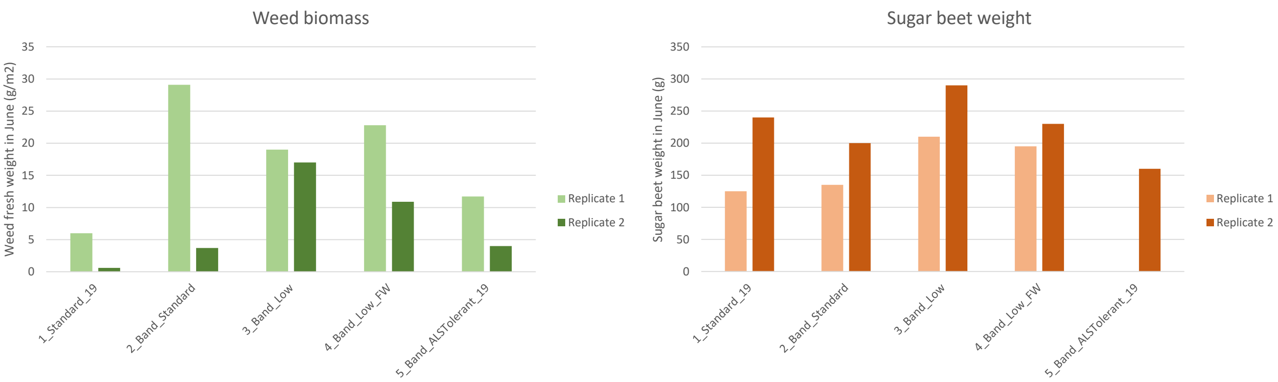


Figure 14 - Yield (A) and weed biomass (B) at harvest in the four strategies: Standard (Strategy 1), BandNormal (Strategy 2), BandLate (Strategy 3) and Band_ALStolerant (Strategy 4). The strategies are described in Table 4.

	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
	Reference/standard	Band spraying standard dose + weed hoe	Band spraying red. dose + weed hoe	Band spraying red. dose + weed hoe/ finger weeder	ALS-tolerente beets + band spraying and weed hoe
Soil tillage	Plough	Plough	Plough	Plough	Plough
Sowing time	15th April	15th April	15th April	15th April	15th April
Variety	Daphne, KWS	Daphne, KWS	Daphne, KWS	Daphne, KWS	SMART Renja, KWS ALS-tolerant
Herbicides	Standard herbicide program 3 applications In total 7.5 g triflu-sulfuron + 1120 g phenme-dipham + 2100 g metamitron	3 applications in 15 cm band Total per ha corre-sponds to: 2.25 g triflusulfuron + 352 g phenme-dipham + 630 g metamitron Same dose in band as standard	2 applications in 15 cm band Total per ha corre-sponds to: 1.125 g triflusulfuron + 256 g phenme-dipham + 420 g metamitron	2 applications in 15 cm band Total per ha corre-sponds to: 1.125 g triflusulfuron + 256 g phenme-dipham + 420 g metamitron	2 band sprayings in 37.5 cm band Total per ha coo-responds to: 175 g ethofumesate + 22.5 g foramsul-furon and 37.5 g thiencarbazone Both products are apllied twice
Mechnical control		3 x weed hoeing	3 x weed hoeing	2 x weed hoeing 1 x finger weeder	3 x weed hoeing

Table 5 - WP4 trial plan for 2019.

Figure 15 - Photos of the strategies in June 2019. Strategies 1 to 4 with conventional sugar beet varieties, and Strategy 5 with an ALS-tolerant variety.



Figures 16A and 16B - Fresh biomass of Weed (A) and Crop (B) in June 2019 in the five strategies. The strategies are further described in Table 5.

Strategy 5 (ALS-tolerant variety), tended to be a little lower but still similar (Figures 16A and 16B). Crop biomass for Strategy 5 could not be measured for Replicate 1. No statistical tests have been applied. The differences observed in June 2019 were not evident at harvest, with all strategies producing similar yields with smaller deviations (Figure 17). The strategy with finger weeder (Strategy 4) and the ALS-tolerant variety (Strategy 5) had the lowest yields in Replicate 2 and Replicate 1 respectively. The finger weeder tool was not observed to damage the sugar beets. However, there were slightly more weeds left late-season, and this was deemed to be the cause of yield reduction as sugar beets are highly sensitive to weed competition. ALS-tolerant beets were generally found to produce lower yields. All of the strategies were deemed to be positive. No problems were caused when the herbicide amount in Strategies 1, 2 and 3 was lowered and weed hoeing introduced. Therefore, similar strategies were included in the season 2020 trials. The only exception was the strategy involving the ALS-tolerant variety of sugar beet combined with band-spraying. This proved to be a viable strategy and produced fairly positive results in the two previous years of trial, and it was not included in the 2020 trial.

Season 2020

Based on the experiences from seasons 2018 and 2019, a trial plan was agreed by Danish partners at the online national cluster meeting in March 2020. The season 2020 trial still focused mainly on band-spraying combined with weed hoeing, but automated weed management tactics were also applied. The trial was established in the trial fields of NBR (contact details below).

Strategy 2 and Strategy 3 of the 2020 plan were similar to 2019's Strategy 3 and Strategy 4. Both standard strategies (Strategy 1) were the same. In 2020, Strategies 2 and 3 were similar to Strategies 4 and 5, but the latter two used a method that enabled narrower bands (8 cm). Strategy 5 performed automated weed hoeing with a Robovator. Two organic strategies were also introduced (Strategy 6 and Strategy 7), being based on combinations of tine harrowing, weed hoeing and a finger weeder. Strategy 6, however, involved weed hoeing with a Robovator, and Strategy 7 included ridging. The intensity and frequency of Strategies 6 and 7 were based on weed emergence. The Robovator was camera-guided with a software for recognising sugar beets and enabling both inter- and intrarow management (Figure 18).

There was high weed pressure in the trial field and the two organic strategies especially could not provide sufficient weed control for Replicate 1 (Figurea 19A and 19B). The 2020 season was characterised by very dry conditions early season, with limited weed emergence followed by more rain, which induced later weed emergence. The combination of band-spraying with weed hoeing was the best alternative to the standard broad-sprayed strategy. The inclusion of a finger weeder (Strategy 3) did not improve the weed control level of Strategy 2. The narrower band of 8 cm tended to result in Strategy 4 and Strategy 5 producing more weeds than Strategy 2. The crop biomass in June 2020 was similar across all strategies, with Replicate 1 producing lower biomasses than Replicate 2.

At harvest, there were larger differences among the treatments (Figure 20). Replicate 1 continued to produce less biomass than Replicate 2, but

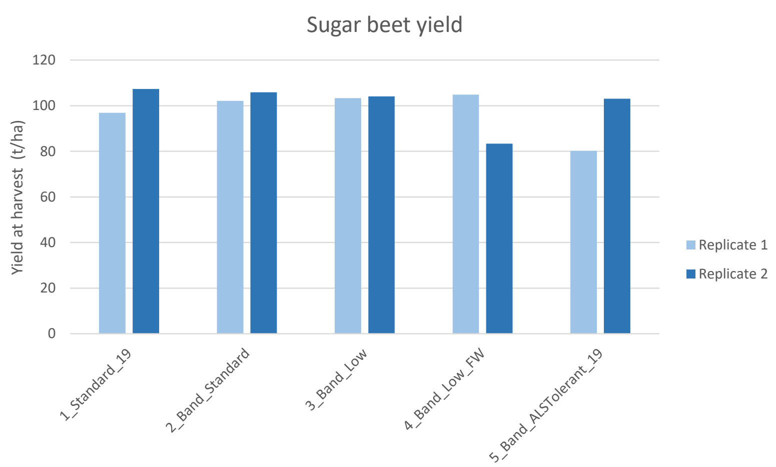


Figure 17 - Sugar beet yield 2019 for the five strategies. The strategies are further described in Table 5.

	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5	Strategy 6	Strategy 7
	Reference/standard	Band spraying red. dose + weed hoe	Band spraying red. dose + weed hoe/finger weeder	Band spraying narrow band, red. dose + weed hoe/finger weeder	Band spraying narrow band, red. dose + Robovator/finger weeder	Organic with Robovator / finger weeder	Organic with weed hoe/finger weeder
Soil tillage	Plough	Plough	Plough	Plough	Plough	Plough	Plough
Herbicides	Standard herbicide program 3 applications In total 7.5 g triflusulfuron + 150 g ethofumesat 560 g phenmedipham +2100 g metamitron	2 applications in 15 cm band Total per ha corresponds to: 3.75 g triflusulfuron + 200 g phenmedipham + 50 g ethofumesat 700 g metamitron	2 applications in 15 cm band Total per ha corresponds to: 3.75 g triflusulfuron + 200 g phenmedipham + 50 g ethofumesat 700 g metamitron	2 applications in 8 cm band Total per ha corresponds to: 2.0 g triflusulfuron + 107 g phenmedipham + 27 g ethofumesat 373 g metamitron	2 applications in 8 cm band Total per ha corresponds to: 2.0 g triflusulfuron + 107 g phenmedipham + 27 g ethofumesat 373 g metamitron	-	-
Mechanical control	-	3 x weed hoeing	3 x weed hoeing 2 x finger weeder	3 x weed hoeing 2 x finger weeder	Combination of weeding robot and weed hoeing including finger weeder	Combination of tine harrow, weeding robot and weed hoeing including finger weeder	Combination of tine harrow and weed hoeing including finger weeder and ridges

Table 6 - WP4 trial plan for 2020.

Figure 18 - Robovator developed for automated weed management, here in lettuce (Picture by Frank Poulsen, http://www.visionweeding.com/robovator/).

the differences increased between the summer and harvest. The highest yield was achieved with the 15 cm band-spraying combined with weed hoeing (Strategy 2). For the strategies with the narrow 8 cm band (Strategy 4 and Strategy 5) and the organic strategy with ridges (Strategy 7), the variation between the two replicates was high. The organic strategy including the Robovator (Strategy 6) provided more consistent results, yet they were lower than the standard strategy.

Overall conclusion

Over the three-year trial, the main conclusion was that a combination of banded herbicide application with weed hoeing was the most promising alternative to the standard broad-sprayed herbicide usually applied to sugar beets. It was also clear that the weather conditions were a major factor, as soil moisture has a strong influence on the ability to perform weed hoeing, with its efficacy also being dependent on post-treatment conditions. ALS-tolerant sugar beets also provided good results, but dependency on ALS-inhibitors is already high in rotational crops, as is the risk of resistance. Using sugar beets in crop rotation should thus be viewed as an opportunity to apply different modes of action and non-chemical weed control.

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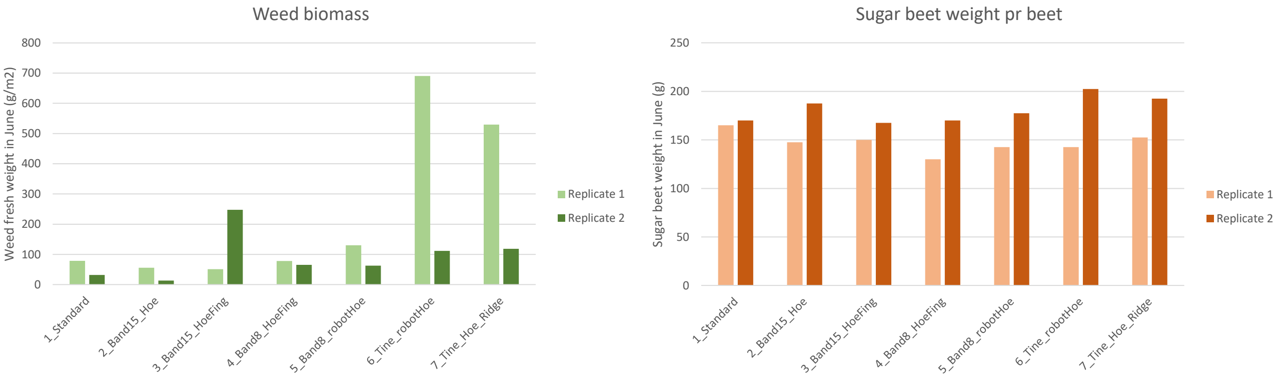

Figures 19A and 19B - Fresh biomass of Weed (A) and Crop (B) in June 2020 in the seven strategies. The strategies are further described in Table 6.

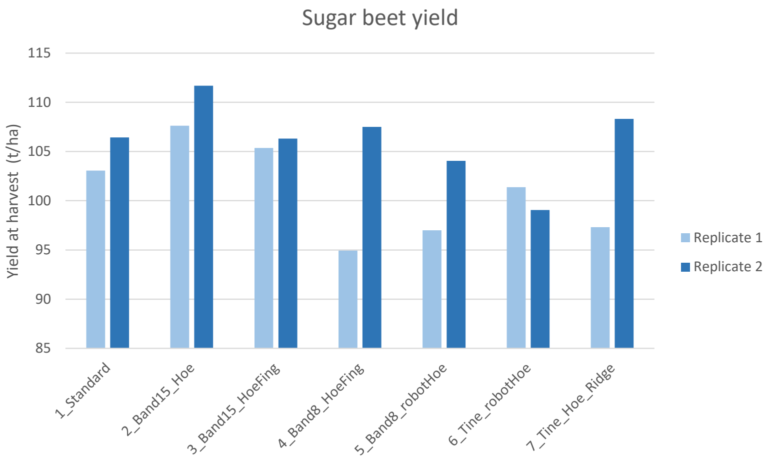

Figure 20 - Sugar beet yield 2019 for the seven strategies. The strategies are further described in Table 6.

Figure 21 - Experimental field of Nordic Beet Research in Lolland.

WP7 – WEED MANAGEMENT IN THE TRANSITION PHASE FROM CONVENTIONAL TO CONSERVATION AGRICULTURE IN DENMARK

Danish farmers want to reduce their costs for arable cropping and reducing tillage is one major option. Going from inversion tillage to non-inversion tillage has several implications, with reduced yield stability and an increased consumption of pesticides being of greatest concern. Previous research and experiences from practice have often shown that annual grass weeds, cleavers and perennials, such as couch grass and creeping thistle, can become troublesome weed problems in non-inversion tillage systems.
Most results and experiences with weed problems in non-inversion tillage systems in Denmark relate to non-inversion tillage systems, where tine tillage has been applied to various depths prior to crop sowing. There is currently little information about direct drilling and conservation agriculture, though these systems receive increasing attention.
Diversified crop rotations are a prerequisite for sound management of non-inversion tillage systems, and this message appears to be accepted by most growers practicing non-inversion tillage. Diversification means variations in:
1) season of crop establishment (autumn, early autumn, spring, late spring);
2) broadleaved crops versus monocotyledonous crops;
3) growth length (annual versus perennial crops); row crops (e.g. sugar beets, maize) versus narrow-rowed crops (cereals, pulses etc.).
However, more knowledge about measures and methods for weed control with less reliance on herbicides is still needed when transforming a conventional cropping system into conservation agriculture or other non-inversion tillage regimes.

Objective

Adopting a range of measures to minimize the reliance on herbicides in the transition phase from mould-board based tillage systems to non-inversion tillage systems where 1) some tine tillage prior to crop sowing, and 2) conservation agriculture are used. The experiment studies the situation when a diversified crop rotation is established, and focus is mainly on measures that help reduce the input of herbicides in each crop.

Materials and methods

The treatments are organized in a split-plot design with three replicates. The cropping system is used on the main plot and sub-plots are planted with the individual crops in the three-year crop rotation. All the rotation crops are grown each year to eliminate the confounding effects between weather and the actual crop grown. An outline of the experiment is shown in Table 7.

Cropping systems
TS = traditional non-inversion tillage system with normal herbicide inputs
RI = non-inversion tillage system with reduced herbicide input
CA = conservation agriculture aimed at reducing herbicide input

Crop rotation
TS = winter wheat → spring barley → faba beans →
RI = winter wheat → spring barley → faba beans →
CA = winter wheat → spring barley → faba beans →

Three-year crop rotation with all crops grown each year in each cropping system. With the three systems, three crops and three blocks, the plot number amounts to 27. The experiment was established in autumn 2017 and the first crops were harvested in 2018.

Tillage treatments
TS = tine tillage to 8-12 cm soil depth before crop sowing using a Horsch Terrano stubble cultivator.
RI = direct drilling of faba beans and spring barley. For winter wheat: tine tillage to 5-8 cm soil depth just after the harvest of faba beans using a Horch Terrano stubble cultivator, then light cultivation to create a false seedbed until wheat sowing. Wheat is sown about 10 days later than the sowing time for wheat in the TS and CA systems.
CA = all crops sown directly.

Cover crops
TS, RI and CA = cover crops are established in the period between winter wheat and spring barley and between barley and faba beans. Cover-crop mixtures known to suppress weeds are used.

Weed control
TS = glyphosate applied before tine tillage, applied in spring in case of spring-sown crops. Thereafter, selective herbicides according to need.
RI = no glyphosate before winter wheat. Glyphosate in spring before spring-sown crops. Selective herbicides in barley and wheat according to need. Inter-row hoeing is used for the cereals, where possible. For faba beans, the aim is to replace chemical control with inter-row cultivation and weed harrowing.

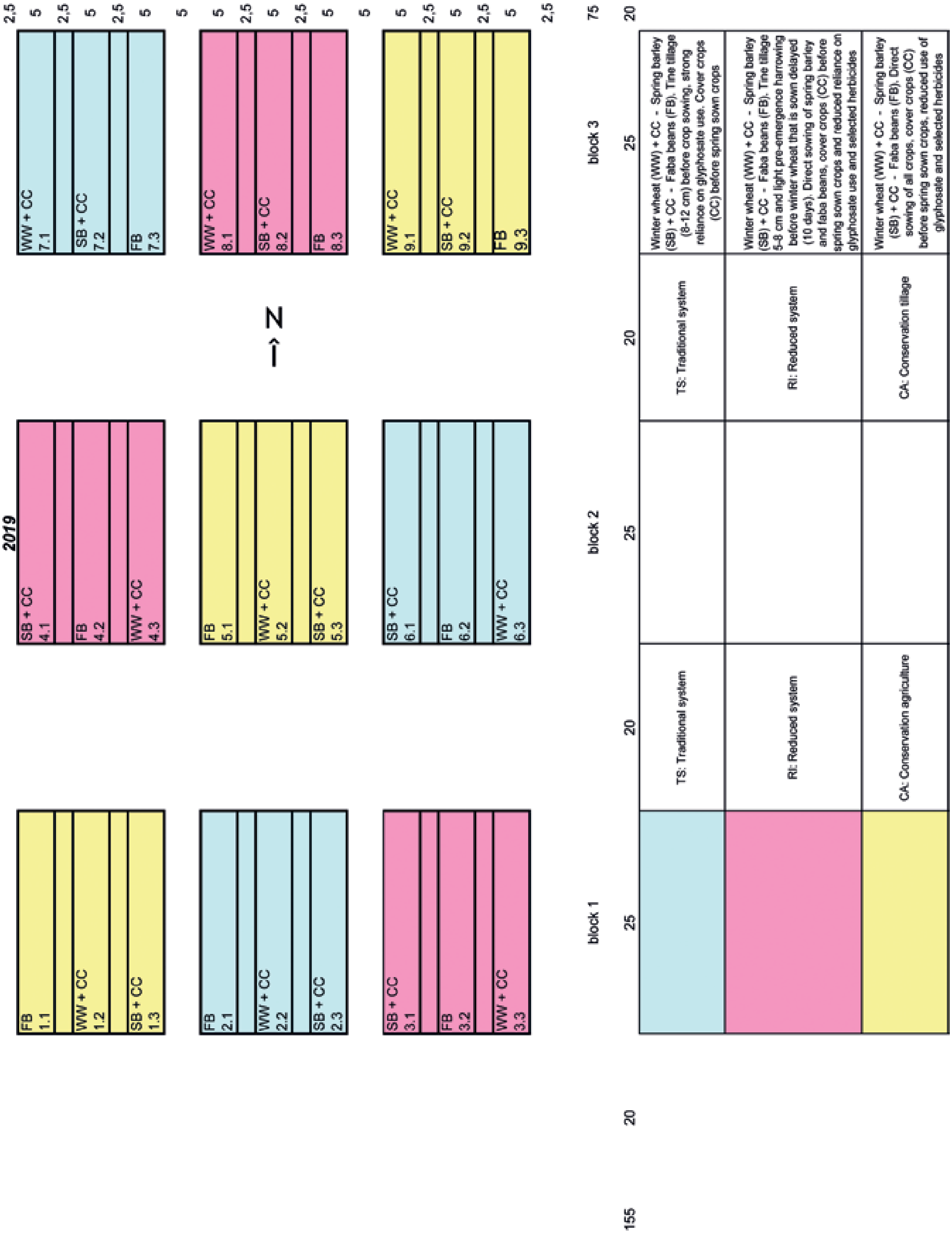

Table 7 - WP7 experimental layout.

CA = glyphosate before direct drilling, but applied in spring before spring-sown crops. Selective herbicides are then applied, but in low doses if possible.

Assessments

The content of weed seeds in the seed bank was recorded in all plots before the experiment was started. Weed emergence was counted in all crops and systems and weed biomass remaining after weed control treatments was assessed in late June in all years, crops and systems. Crop plant numbers are counted and yields were obtained by plot-wise combining in all years.

Results from 2018

2018 was the first experimental year. It was very difficult to differentiate the herbicide inputs for the cereals in all three cropping systems; the weed pressure required similar herbicide inputs. However, for faba beans, it was possible to reduce the herbicide input in the RI system, mainly by inter-row cultivation. The TS and CA cropping systems had three inputs of herbicides in faba beans, namely one treatment with glyphosate plus two with selective herbicides. The input of glyphosate and the first selective herbicide treatment were the same for the RI system but, in contrast to TS and CA, inter-row cultivation replaced the second selective herbicide treatment. Crop establishment was successful in all crops and systems (Figure 27) and yields were similar for all systems (Figure 28). Weed control was satisfactory in all systems and crops, resulting in very little weed biomass in proportion to crop biomass (Figure 29).

Results from 2019

The 2019 growing season was the second experimental year. The two spring-sown crops, faba bean (Figure 30) and spring barley, established well in all three systems: CA, RI and TS. The cover crops sown in autumn 2018 survived into the two spring crops in 2019. Fodder radish and volunteer spring barley were not killed by frost during the mild winter 2018/19, and the pre-sowing glyphosate dose of 540 g/ha did not completely kill the cover crop. However, these “survivors” did not become serious problems later in the growing seasons; weed biomasses were generally small and crop yields were similar among the three systems, as shown in Figures 31 and 32.
The treatment frequency index (TFI) for the input of selective herbicides in spring barley was 1.65 for the CA and TS systems, and 30% lower for the RI system (TFI 1.15). TFI was 1.56 in faba bean for the CA and TS systems, and 50% lower for the RI system (TFI 0.78). Inter-row hoeing had been scheduled in the RI system as the last treatment in the weed control program, but crop residues blocked the hoe, making it impossible.
Weed control in winter wheat was successful in the CA system (Figure 31) because 20 g metsulfuron-methyl/ha applied in spring removed the extensive weed growth that had survived the pre-sowing glyphosate treatment in the autumn. The use of selective herbicides applied in autumn in the TS system was almost as effective as the spring application in CA (Figure 31). However, TS yielded significantly less than CA (Figure 32). No selective herbicides were used in the RI system, which relied entirely on non-chemical weed control treatments: false seedbed and delayed sowing in autumn, followed by inter-row hoeing, plus weed harrowing in spring. This strategy clearly failed, as shown in Figures 31, 32 and 33.
In conclusion, reducing herbicide input in 2019 was only attempted in the RI system, with success

Figures 11 and 12 - Direct drilling.

Figures 24 - Directly sown Faba beans.

Figure 25 - Directly sown winter wheat.

Location
The experiment is located on a sandy loam at Flakkebjerg Research Centre (55o20'N, 11o23'E), Denmark.

Figure 26 – Plots of WP7 trials.

in the two spring-sown crops and failure in winter wheat. This shows how challenging it can be to reduce herbicide input in the transition phase from inversion-tillage to non-inversion tillage systems.

Results from 2020

Growing season 2020 was the third and final experimental year, after which the experiment was terminated. The two spring-sown crops, faba bean and spring barley, established reasonably well in all three systems: CA, RI and TS. However, the delayed sowing of winter wheat in the RI-system resulted in patchy establishment in some places.
It was possible to reduce the treatment frequency index (TFI) of selective herbicides in RI in all three crops, while TS and CA had similar herbicide inputs in the spring-sown crops (Table 8). TFI was greatest in the CA-system in winter wheat because weed pressure necessitated a spring application in addition to an application the previous autumn. No non-chemical strategies were used in 2020, except for the standard treatment with false seedbed and delayed sowing for winter wheat in RI. Weed biomasses following the weed management strategies showed no difference between cropping systems within each crop (Figure 34). Crop yields were also similar across the three systems (Figure 35). The delayed sowing of winter wheat in RI yielded similar to CA and TS, unlike 2018 and 2019; winter 2019/2020 was extremely mild.

Summary for 2018, 2019 and 2020

Table 8 shows the total TFIs for each crop within CA, RI and TS cropping systems for the three-year experimental period (2018, 2019 and 2020). Herbicide consumption was fairly similar in CA and TS for all three crops, while TFIs were 20-60% lower in RI depending on the crop and the specific comparisons with CA and TS. Herbicide reductions in RI did not result in significantly more weed biomass in faba beans and spring barley when analysing weed biomasses across the three years (Figure 36). Only in winter wheat did the TFI-reductions in RI result in significantly more weed biomass than in CA and TS. However, weed biomass in RI was still below 50 g DM m^{-2} on average, which is not a major concern in competitive winter wheat stands.
Grain yields of the two spring-sown crops did not differ between cropping systems when analysing crop yields across 2018-2020 (Figure 37). However,

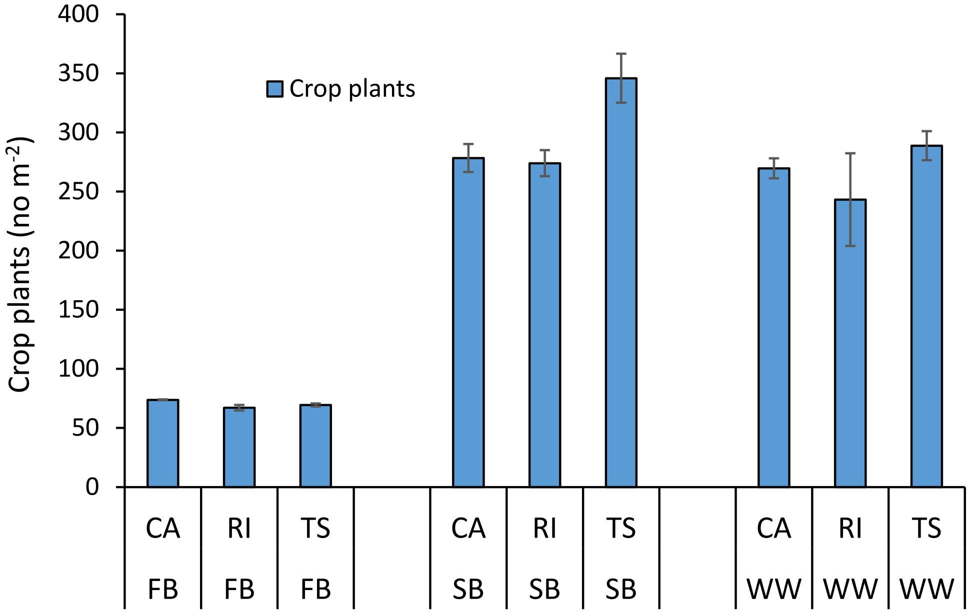

Figure 27 - Crop plants in 2018 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

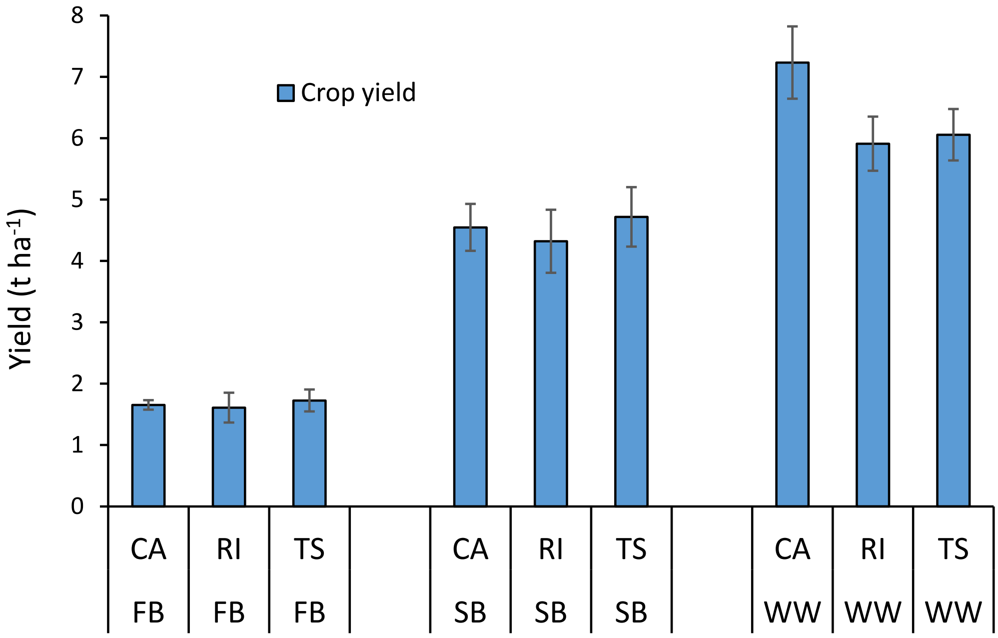

Figure 28 - Crop yield in 2018 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

winter wheat yield was significantly lower in RI than in CA and TS. Delayed sowing of winter wheat in RI is probably the main reason for the differences observed and, to a lesser extent, the slightly greater weed abundance in RI.

In general, herbicide reductions were possible in faba bean and spring barley without compromising crop yields or weed pressure. It turned out that reducing herbicide input by using non-chemical methods was difficult and that reducing herbicide dose and/or number of applications was more feasible. Mechanical methods for direct weed control in the crops struggled to work effectively with crop residues and solid soil surfaces. It was particularly difficult to manage CA with reduced reliance on herbicides, although herbicide consumption did not exceed the usage in TS.

Annual grass weeds did not proliferate during the

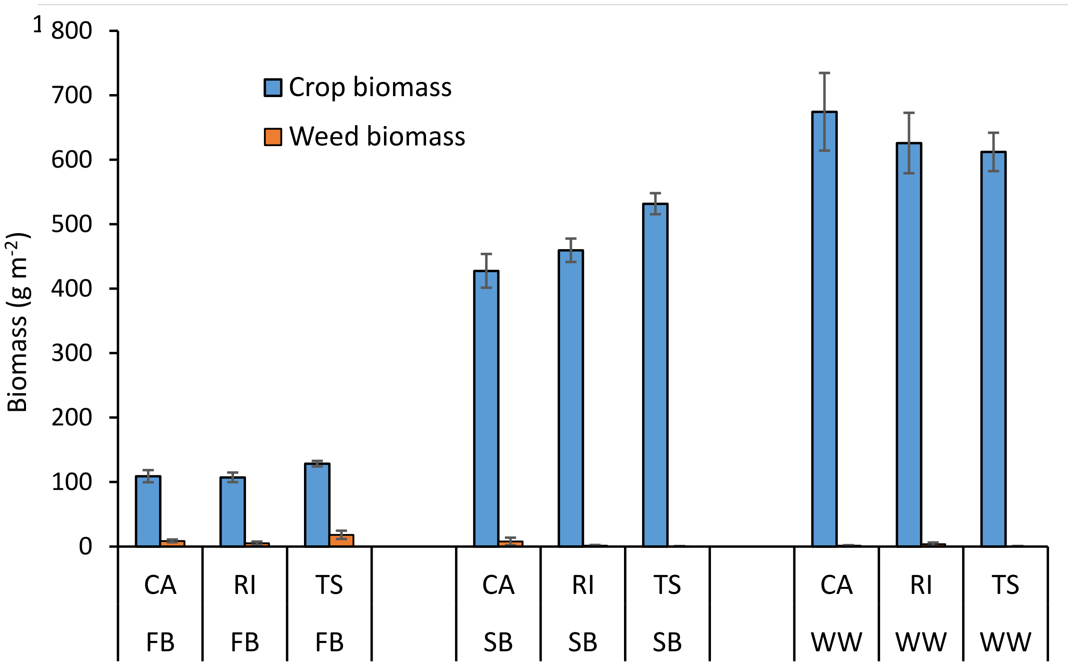

Figure 29 - Crop and weed biomasses assessed in June 2019 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

Figure 30 - Well-established faba bean in the CA system in 2019.

three-year experiment, despite the general belief that infestations would increase when mould-board ploughing was abandoned in favour of non-inversion tillage. The high proportion of spring-sown crops in the cropping systems seems to be responsible for stemming this increase. Moreover, the regular use of glyphosate prior to crop sowing may have prevented the proliferation of couch grass (*Elytrigia repens*). However, infestations of creeping thistle (*Cirsium arvense*) were not managed satisfactorily, despite the use of selective herbicides. Thistle shoot numbers were unacceptably high in July 2020, irrespective of the cropping system.

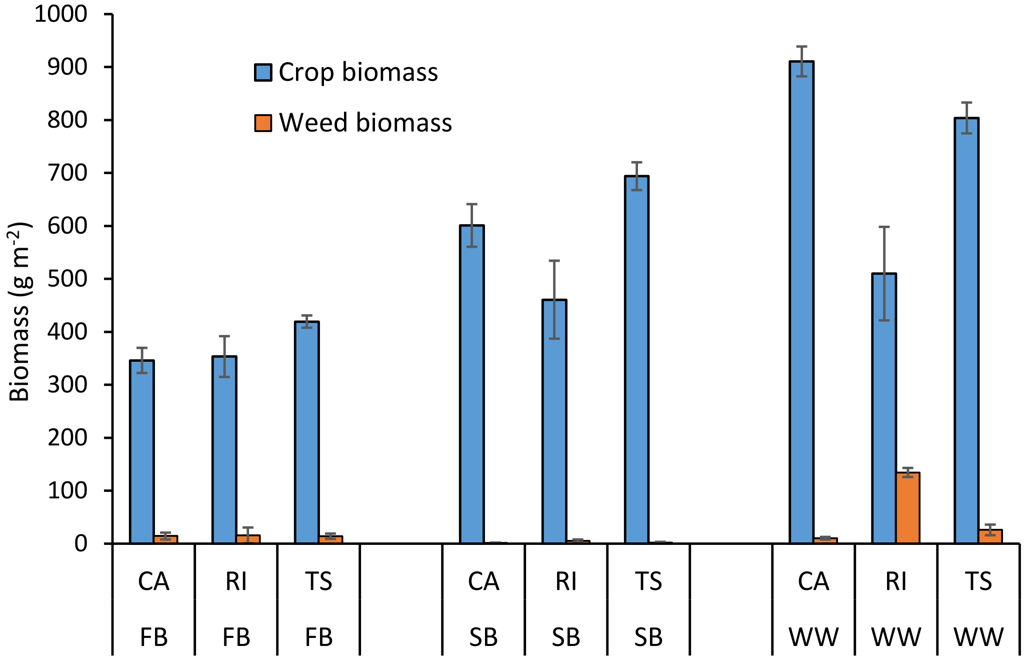

Figure 31 - Crop and weed biomasses (DM) assessed in late June 2019 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

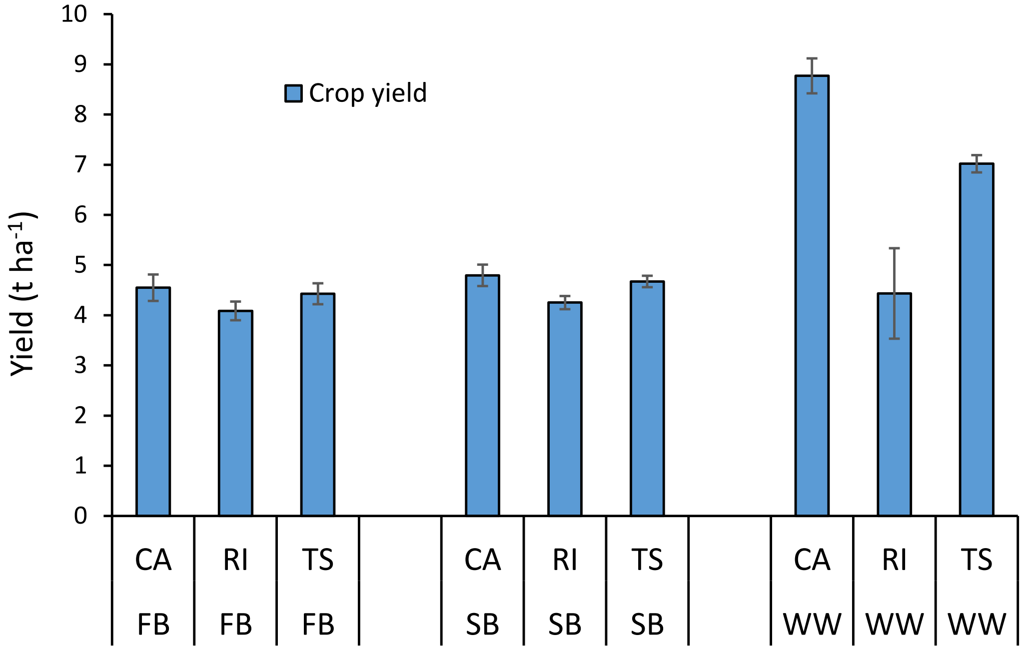

Figure 32 - Crop yields in 2019 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

Figure 33 - Poor weed control in winter wheat in the RI system in 2019.

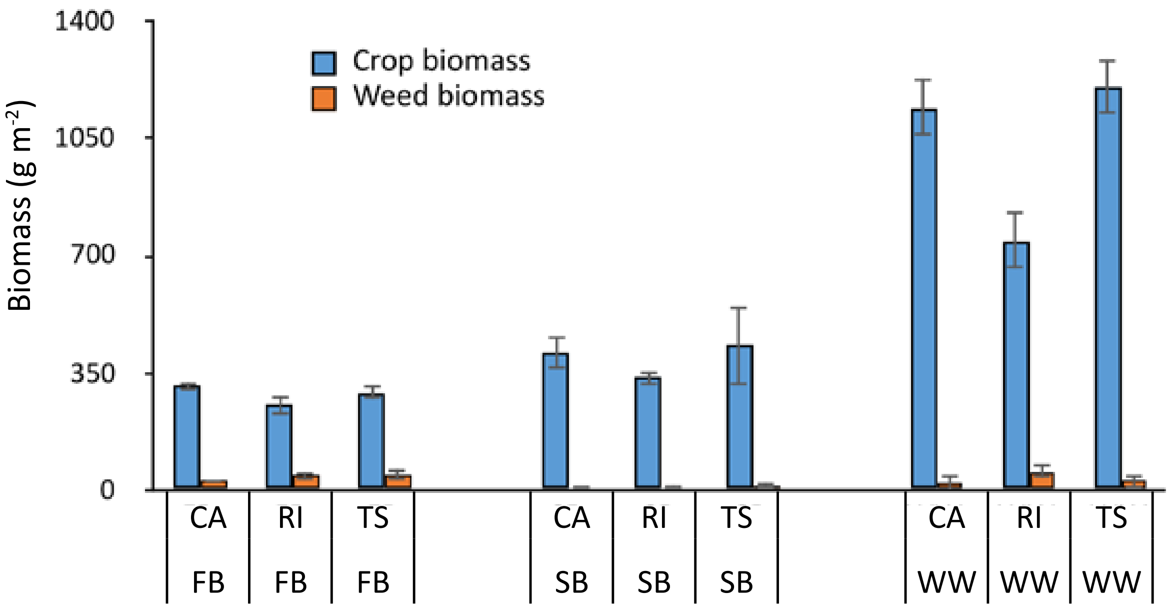

Figure 34 - Means for crop and weed biomasses (DM) assessed in late June 2020 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

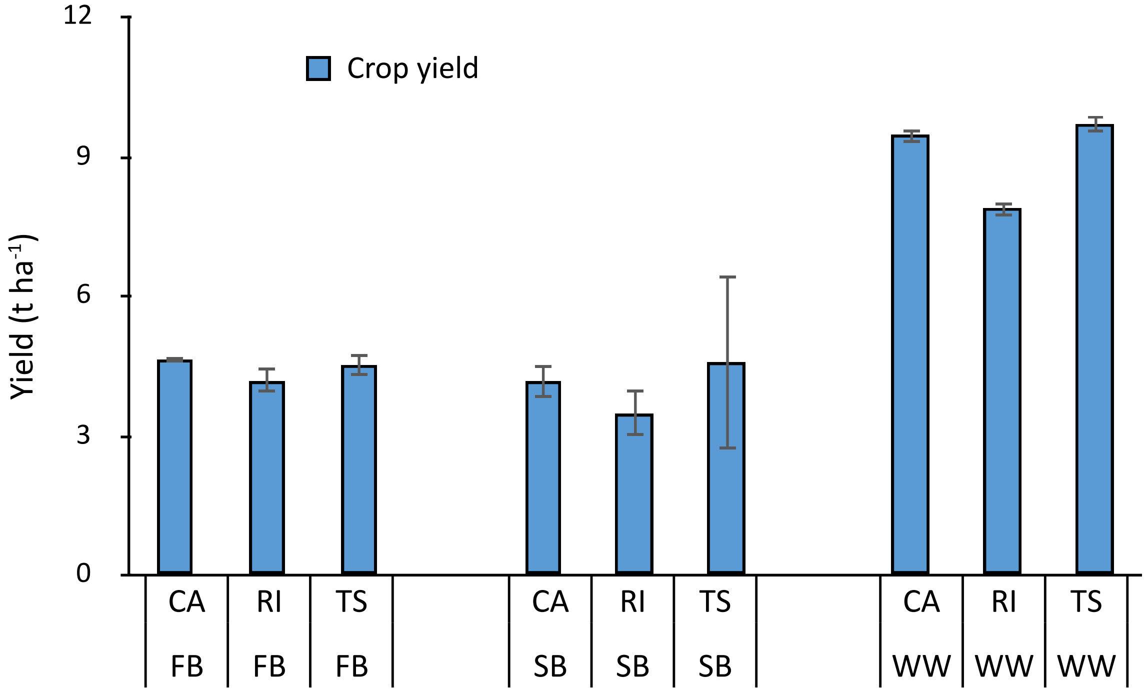

Figure 35 - Means for crop yields in 2020 in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS.

Crop	Cropping system CA	RI	TS
2020			
FB	1.56	0.78	1.56
SB	2.53	2.03	2.53
WW	2.26	0.72	1.54
2018-2020			
FB	5.78 (1.93)	3.22 (1.07)	5.78 (1.93)
SB	5.01 (1.67)	4.01 (1.34)	5.01 (1.67)
WW	3.65 (1.22)	1.55 (0.52)	3.80 (1.23)

Table 8 - Treatment frequency indexes (TFI) for the input of selective herbicides in faba bean (FB), spring barley (SB) and winter wheat (WW) in 2020 and in total for the three-year period 2018-2020 (with averages in parentheses).

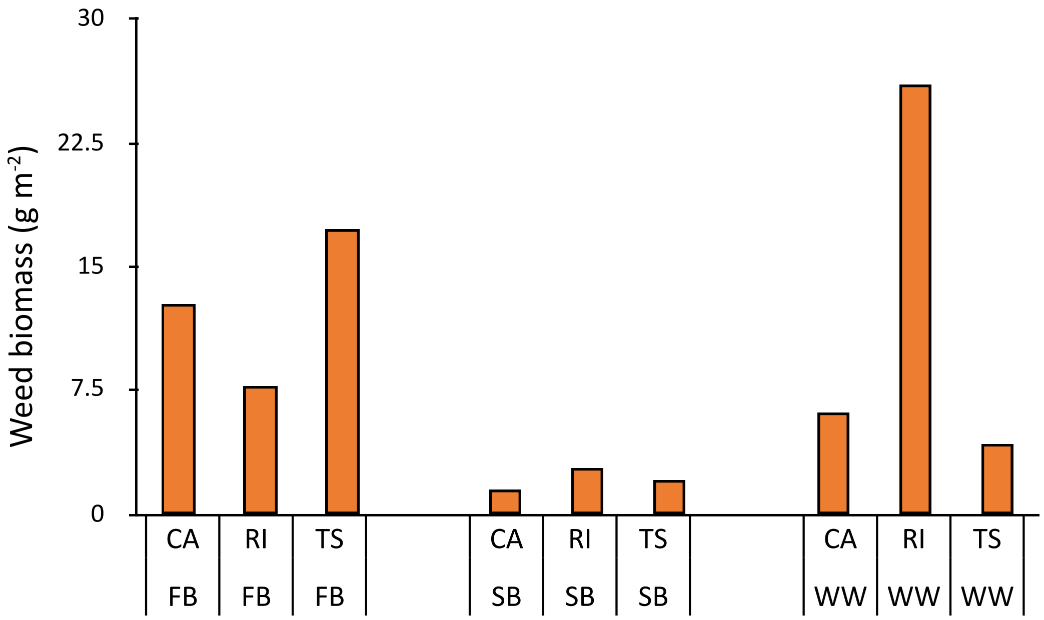

Figure 36 - Weed biomasses (DM) assessed in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS. Biomasses are shown as adjusted means averaging the years 2018, 2019 and 2020 and are outputs (back transformed means) from a statistical analysis.

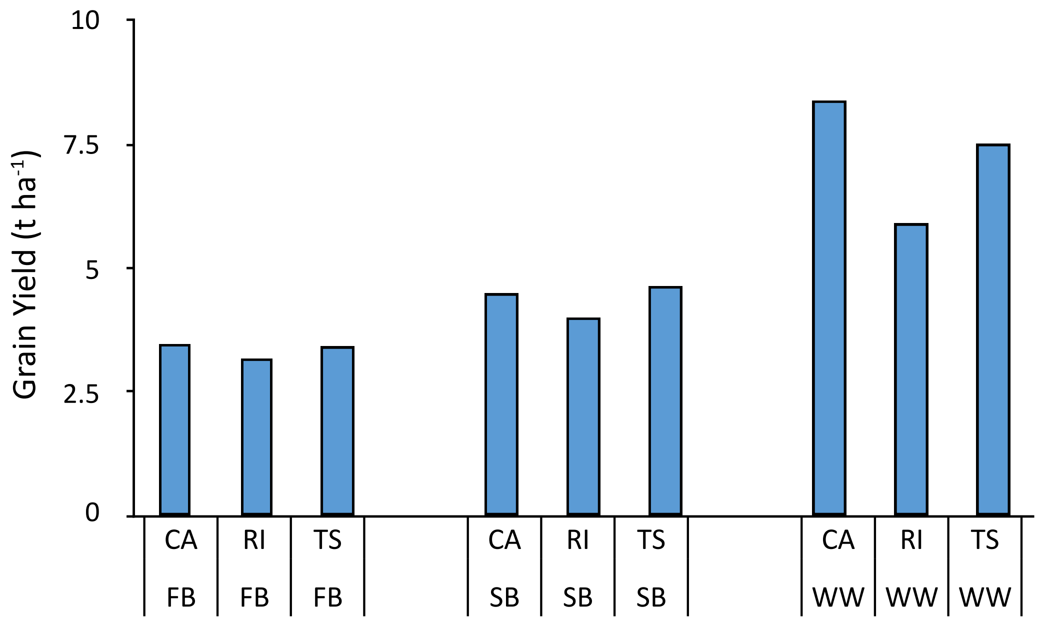

Figure 37 - Grain yields in faba bean (FB), spring barley (SB) and winter wheat (WW) in the three cropping systems: CA, RI and TS. Grain yields are shown as adjusted means averaging the years 2018, 2019 and 2020 and are outputs (back transformed means) from a statistical analysis.

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