European Journal of Agronomy 160 (2024) 127284

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Reducing tillage and herbicide use intensity while limiting weed-related wheat yield loss

Sandie Masson[a,*], Victor Rueda-Ayala[a], Luca Bragazza[b], Stephane Cordeau[c], Nicolas Munier-Jolain[c], Judith Wirth[a]

[a] *Weed Science in Arable Crops, Agroscope, Route de Duillier 60, Nyon 1260, Switzerland*
[b] *Field-Crop Systems and Plant Nutrition, Agroscope, Route de Duillier 60, Nyon 1260, Switzerland*
[c] *Agroécologie, INRAE, Institut Agro, Université Bourgogne, Université Bourgogne Franche-Comté, Dijon F-21000, France*

ARTICLE INFO

Keywords:
Reduced tillage
Mechanical weeding
Crop rotation
Weed harmfulness
Integrated weed management
STIR
HTFI

ABSTRACT

Integrated weed management (IWM) promotes the combination of non-chemical techniques to achieve sustainable weed control while reducing the reliance on herbicides. However, IWM strategies reducing both herbicide and tillage intensity remain unsatisfactory, leading to weed-induced yield loss. In this study, five different IWM strategies were implemented for three years (2020–2022), aiming at reducing herbicide application across four tillage intensities while limiting weed-induced yield loss. These strategies were annual moldboard ploughing without herbicides (PL0H), annual moldboard ploughing with reduced herbicide use (PLHred), occasional moldboard ploughing with reduced herbicide use (PLredHred), shallow tillage without herbicides (ST0H) and no-tillage with reduced herbicide use (NTHred). Over the three years, averaged soil tillage intensity rating (STIR) and herbicide treatment frequency index (HFTI) ranged from 6 to 87 and from 0 to 1.6, respectively, and showed an inverse relationship. Reducing herbicides led to more mechanical weeding and reducing soil tillage led to more herbicide use. The effects of IWM strategies and years since implementation, on total weed and crop biomass, estimated weed and crop volume, weed density, weed species richness and grain yield were analysed in winter wheat. No differences in weed biomass, volume, or species richness were observed between IWM strategies over the years. Weed density increased only in PL0H between 2020 and 2022. Wheat grain yield varied by years but not among IWM strategies over time. Estimated weed-related yield loss was moderate in 2020. The feasibility and performances of such systems must be assessed over a long-term period to ensure their sustainability.

1. Introduction

Numerous studies quantified yield losses due to weeds (Colbach et al., 2020; Milberg and Hallgren, 2004; Oerke, 2006; Petit et al., 2016) and emphasized a large variability and unpredictability of yield loss caused by different weed abundances, different species and across a range of diversity of weed communities (Storkey and Neve, 2018; Adeux et al., 2019b). Weed-related yield loss is influenced by resource availability and relative timing of crop and weed emergence (Keller et al., 2014; Colbach et al., 2023). Herbicides aim to minimize weed-related yield losses, but their intensive use raises concerns about risks to human health and the environment (Kaur and Kaur, 2018; Riedo et al., 2023). Additionally, poorly diversified crop rotations require more herbicide applications (Guinet et al., 2023), promoting selection of herbicide-resistant weed biotypes and tangling farmers in technical dead-ends (Busi et al., 2013). Public policies and consumers in different European countries encourage the transition towards less pesticide use (Neumeister, 2007; Huber and Finger, 2019; Schaub et al., 2020). The European Directive 2009/128/EC on the sustainable use of pesticides promotes integrated pest management strategies, such as integrated weed management (IWM).

IWM requires a diversification of weed management techniques combined at cropping system level to control weeds without relying on a single technique (Norsworthy et al., 2012). Recent reviews highlight the need of a holistic approach of IWM to maximize its effectiveness (Petit et al., 2018; MacLaren et al., 2020; Riemens et al., 2022). IWM remains poorly implemented worldwide despite its demonstrated capability to jointly contain weeds and reduce herbicide use (Gerowitt, 2003;

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* Corresponding author.
E-mail address: sandie.masson@agroscope.admin.ch (S. Masson).

https://doi.org/10.1016/j.eja.2024.127284
Received 30 April 2024; Received in revised form 3 July 2024; Accepted 16 July 2024

Nazarko et al., 2005; Liebman et al., 2016; Strehlow et al., 2020). Cropping system experiments facilitate monitoring the cumulative and long-term IWM strategies effects' (Cordeau et al., 2022) through decision rules and complex combinations of farming practices in a production situation (Deytieux et al., 2016; Lechenet et al., 2017b). Nevertheless, quantitative assessment of IWM effects on weeds, yield and weed-related yield loss remains critical and scarce (Adeux et al., 2019a). The extended quantification of weed population and crop-weed interaction over many years, across a range of innovative IWM strategies has been little studied (Jernigan et al., 2017; Koocheki et al., 2009).

IWM strategies designed to reduce the reliance on herbicides are frequently based on mechanical weeding and soil tillage, including ploughing (Rueda-Ayala et al., 2010; Adeux et al., 2019a). Intensification of soil disturbance raises concerns about soil health, *e.g.*, reduced soil fauna diversity and organic matter content (Congreves et al., 2015; Nunes et al., 2020), and soil erosion (Carretta et al., 2021). Reduced-tillage and no-till strategies were developed to face this issue, but favour high weed densities (Cordeau et al., 2022) or rely more on herbicides to control weeds and crop volunteers than tillage-based strategies (Tørresen et al., 2003; Jalli et al., 2021; Adeux et al., 2022). As weed-crop interaction is driven by the availability of soil resources and the relative emergence timing of weed and crop, reducing tillage and herbicide use may also impact weed-related yield loss through changes in soil fertility and weed phenology. A recent simulation-based study showed that reducing herbicide use and tillage intensity simultaneously is feasible but can increase weed-related yield loss if not assisted by other techniques (Colbach and Cordeau, 2022). Herbicide-free systems with reduced tillage and mineral nitrogen fertilization have rarely been tested (Zimmermann et al., 2021). Therefore, cropping system experiments are needed to assess the influence of herbicide-free/reduced tillage or no-till/reduced herbicide strategies on crop-weed competition and crop yield.

This study is based on the first three years of an IWM-cropping system experiment in Switzerland (hereafter called Herbiscope). Five IWM strategies using four tillage intensities and aiming at reducing herbicide use were implemented and assessed in winter wheat (*Triticum aestivum* L.), cropped in 2020 (1st. year), 2021 (2nd. year) and 2022 (3rd. year). The objectives of this study were to estimate weed-induced wheat yield changes due to variations in weed biomass measured after weeding treatments, and to evaluate complementary weed assessment methods, namely weed and crop biomass, visually estimated weed and crop volume, weed density, and weed species richness. Visual estimation of plant volume is proposed as a new non-destructive method to replace biomass sampling. The hypotheses were (i) all tested IWM strategies kept weed infestation low, thus preventing weed-induced yield loss, and (ii) the weed infestation and estimated yield loss remained stable and low over the three years and across all five strategies.

2. Materials and methods

2.1. Site description

This study was implemented at the Agroscope Agricultural Research Station Changins (46˚ 24' 15.2'' N, 06˚ 14' 19.3'' E and 430 m.a.s.l.) near Nyon, Switzerland. The soil type is silty, composed of 22 % clay, 46 % silt and 32 % sand; organic matter content is 2.7 %. The climate is oceanic, with an average annual precipitation of 1004 mm and a temperature of 12.1 ˚ C (15-years average, 2009–2022). Average daily temperature is 2.9 ˚ C in winter, and 21.7 ˚ C in summer (15-year average, 2009–2022) (Agrometeo, 2023). The weather in autumn 2019 and spring 2020 was within the norm (Figure S1.1) (Bader et al., 2021). October 2020 and summer 2021 were very wet (Figure S1.2) (Bader et al., 2022) while 2022 was particularly hot and dry compared with seasonal norms (Figure S1.3) (MeteoSwiss, 2023).

Over the past decade before implementing the experiment, the field was homogeneously cropped with the following rotation: winter wheat – sunflower (*Helianthus annuus* L.) – winter barley (*Hordeum vulgare* L.) – soybean (*Glycine max* (L.) Merr.) – winter wheat – maize (*Zea mays* L.) – winter wheat – spring-sown pea (*Pisum sativum* L.), with annual ploughing and regular applications of herbicides. The crop preceding the setup of Herbiscope was spring sown pea, harvested in July 2019 and followed by a cover crop mixture during the summer fallow period, with the species *Phacelia tanacetifolia* Benth., *Avena strigosa* Schreber, *Raphanus sativus* var. *longipinnatus*, *Guizotia abyssinica* (L.f.) Cass., and *Trifolium alexandrinum* L. The cover crops were shredded two months after sowing and the residues were left on the soil surface before sowing the first crops of the experiment.

2.2. Experimental design

The Herbiscope experiment is based on a 6-year crop rotation as follows: winter wheat – sugar beet (*Beta vulgaris* subsp. *vulgaris* L.) – autumn- or spring-sown pea – winter rapeseed – winter barley – soybean. All spring crops are preceded by multi-species cover crops during the fallow period. The crops included in the experiment are commonly grown in the Lake Geneva region on farms without livestock. However, the tested rotation has fewer winter cereals (wheat and barley) than local ones. The experiment tested five IWM strategies arranged in a split-plot design with three repetitions. The main plots were assigned to plots cultivated with the same crop in one year, and subplots were assigned to the five IWM strategies (Fig. 1). Randomisation was done only at the level of plot. For technical reasons subplots were not randomised. Field operations at subplot level required the same sequence to avoid mistakes while implementing the strategies. In 2020, plots were grown either with wheat, soybean or barley. In 2021, wheat was grown after soybean 2020, then in 2022 after soybean 2021, which followed barley 2020.

2.3. Integrated weed management strategies

The five strategies follow IWM principles but differ in the tillage intensity, tillage frequency and herbicide use. Emphasis is placed on preventive and cultural measures throughout the whole rotation. When the trial started, special attention was given to the alternation of crop botanical families and sowing dates over the cropping sequence (Weisberger et al., 2019). The wheat variety *Montalbano* is disease-tolerant and has a strong covering capacity throughout the cycle. Sowing took place in mid-October, about ten days later than recommended, and at 10 % increased rate (*i.e.*, 420 seeds m^2), in anticipation of plant losses due to mechanical weeding (GFT, 2024). Wheat received 110 kg nitrogen ha^{-1}, being 20 % lower than the Swiss fertilisation standards (Richner et al., 2010). Herbiscope follows the extensive cultivation federal Swiss program 'Extenso' rules (Böcker et al., 2019), except for sugar beet and rapeseed. Wheat and preceding crops were grown strictly without growth regulators, fungicides or insecticides.

Depending on IWM strategies, moldboard ploughing is either systematic and implemented annually (PL), non-systematic (PLred) or never implemented (ST, NT); herbicide use is either reduced (Hred) or banned (0H). PL0H is based on annual moldboard ploughing without herbicides, PLHred on annual moldboard ploughing with reduced herbicide use, PLredHred on occasional moldboard ploughing with reduced herbicide use, ST0H on no-tillage or shallow tillage up to 10 cm if necessary (ST) with no herbicides, and NTHred on no-tillage (NT) with reduced herbicide use. Machines and use frequency are chosen after visual field inspection and agreement between the researchers leading the experiment and the experimental farm manager (Table S2.1). For shallow tillage in wheat the machines used were the duck-foot cultivator Kerner, followed by the rotary harrow Alpego or by the rotary cultivator Kvenerland. After ploughing, the rotary harrow was used for seedbed preparation. For mechanical weeding the machines used were the flexible-tine harrow Treffler and the spike rotative weeder Einbock (the latter only in NTHred 2022).

According to IWM principles, there is no standard herbicide

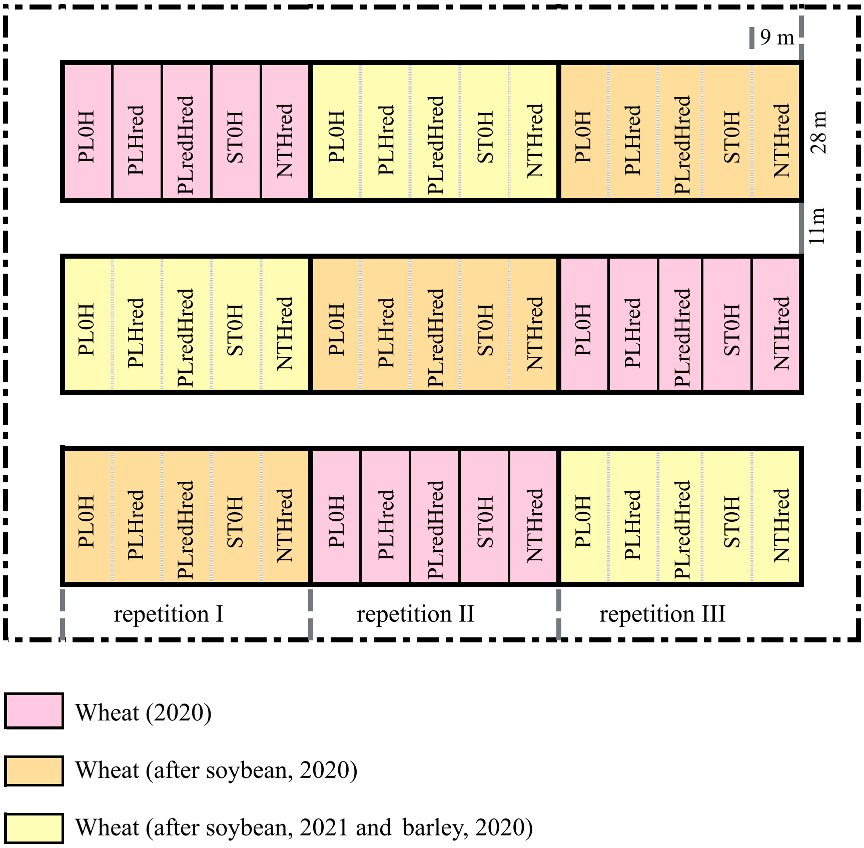

Fig. 1. Experimental design of the Herbiscope cropping system experiment. PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides; NTHred: no-tillage, reduced herbicide use. Three different crops are present per year and the same crop is grown in three repetitions per year corresponding to one colour.

treatment. Hred indicates a reduction in herbicide applications over the cultural cycle and rotation. Non-selective herbicides are the last resort, after applying preventive or non-chemical curative measures or when unfavourable weather conditions restrain their implementation; no pre-emergence herbicides were used in wheat. Soil structure and humidity, weeds and their growth stages and weather forecasts are the main decision-making criteria for machinery and herbicides. Furthermore, companion plants species were undersown together with the last weeding operation in wheat, on the strategies without tillage and without herbicides (NTHred, PL0H and ST0H). Crop management tactics in wheat and preceding crops (soybean and winter barley) are synthetised in Table 1, and detailed per IWM strategy (Table S2.1 and S2.2).

Herbicide use was quantified with the herbicide treatment frequency index (HTFI) for wheat and preceeding crops (Lechenet et al., 2016; Guinet et al., 2023), according to equation (1):

$$HTFI = \sum_{n=1}^{q} H \frac{(applied\ dose)_H}{(reference\ dose)_H} \times \frac{(treated\ surface)_H}{(subplot\ surface)} \tag{1}$$

Table 1

Overview of crop management (moldboard ploughing, shallow tillage, mechanical weeding and herbicide application) for the five IWM strategies, over years and crops. Numbers are the applications per year, with bold values corresponding to the wheat crop. PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides; NTHred: no-tillage, reduced herbicide use.

Year			Operation	PL0H			PLHred			PLredHred			ST0H			NTHred		
2020	2021	2022																
wheat			moldboard ploughing	**1**			**1**			**1**			**0**			**0**		
soybean	wheat			1	**1**		1	**1**		1	**0**		0	**0**		0	**0**	
barley	soybean	wheat		1	1	**1**	1	1	**1**	1	1	**0**	0	0	**0**	0	0	**0**
wheat			shallow tillage	**1**			**1**			**1**			**0**			**0**		
soybean	wheat			1	**1**		1	**1**		1	**2**		1	**2**		1	**0**	
barley	soybean	wheat		1	1	**1**	1	1	**1**	1	1	**2**	0	1	**2**	0	0	**0**
wheat			mechanical weeding	**2**			**2**			**0**			**2**			**0**		
soybean	wheat			4	**3**		4	**2**		0	**2**		4	**3**		3	**0**	
barley	soybean	wheat		2	2	**5**	0	0	**1**	0	0	**3**	2	2	**5**	0	0	**1**
wheat			herbicide	**0**			**0**			**1**			**0**			**1**		
soybean	wheat			0	**0**		0	**1**		1	**1**		0	**0**		1	**1**	
barley	soybean	wheat		0	1[a]	**0**	1	2	**1**	1	2	**0**	0	1[a]	**0**	1	3	**2**

[a] Application made by mistake.

where n is the number of herbicides (H) used (minimum 1), q is the maximum n used; *reference dose* refers to the Swiss maximum authorized dose per herbicide × crop × weed (*i.e.*, annual or perennial weeds) (OSAV, 2023). HTFI increases with the number of herbicides used and/or with the *applied dose*. The *treated surface* divided by the *subplot surface* determines the precise area treated with herbicides.

The intensity of soil disturbance due to ploughing, shallow tillage, and mechanical weeding was quantified with the soil tillage intensity rating (STIR). STIR is calculated from the speed, soil disturbance type (*e.g.*, inversion with some mixing, lifting and fracturing, mixing only), average depth and surface soil disturbance, with the RUSLE2 framework method (USDA, 2008; FiBL, 2022). The higher the STIR, the more disturbed the soil. For illustration, the STIR value for a plough pass in Herbiscope is 43, while for a harrowing pass is 6. The STIR values of all individual operations used in Herbiscope are shown in Table S2.3.

2.4. Data collection

Weed density per species, total biomass and volume were determined at subplot scale (*i.e.*, 252 m^2), at least 2 weeks after the last weeding operation in May, before wheat flowering at BBCH 65 (hereafter called pre-flowering), and in late June, two weeks before harvest (hereafter called pre-harvest). Weed density per species was also monitored in November (season 2021) at least two weeks after autumn weeding (hereafter called autumn) and in January (seasons 2021 and 2022) before spring weeding (hereafter called winter). By walking through the subplots in a W-shaped pattern (Figure S3.1), weed species were identified and the density of each species was estimated visually, using the scale of 11 abundance classes developed by Barralis (1976) (Table S3.1). Species densities (plants m^{-2}) were computed using medians of weed abundance classes and then added up to obtain the total weed density. Weed species richness was computed as the total number of weed species per subplot. Species with a density above 1 plant m^{-2} were classified as the most abundant; these were averaged by strategy, period and year. Total weed and crop biomasses were sampled within three randomly distributed 0.25 m^2 frames along the W-shaped path. Samples were oven-dried for 48 h at 80 ˚C and weighed. Weed and crop volumes were estimated within eight randomly placed 0.25 m^2 frames, including the three frames where biomass was collected (Figure S3.2). An imaginary rectangular parallelepiped was formed based on the frame surface and the measured crop height (*hmax _crop*, equation (2)). Within this parallelepiped the relative space occupied by crop (*crop.%*, equation (2)) and weeds (*weed.%*, equation (3)) was visually estimated (Figure S3.2). When weeds were taller than the crop, a second imaginary rectangular parallelepiped was considered above the first one, based on the frame surface and the difference between maximum above crop weeds height (*hmax _weed*, equation (4)) and crop height. Within this second parallelepiped the relative space occupied by above crop weeds (*weed.%.above*, equation (4)) was estimated. The volume (assessed in $m^3 \cdot m^{-2}$) occupied by crop and weeds was estimated with equations (2), (3), (4), and (5).

$$Crop\ volume = hmax\_crop * crop.\% \tag{2}$$

$$Weed\ volume\ A_{under\ the\ crop} = hmax\_crop * weed.\% \tag{3}$$

$$Weed\ volume\ B_{above\ the\ crop} = (hmax\_weed - hmax\_crop) * weed.\%.above \tag{4}$$

$$Total\ weed\ volume = Weed\ volume\ A + Weed\ volume\ B \tag{5}$$

The proportion of weed relative to the total plant (crop + weeds) biomass (WBR) or volume (WVR), respectively, were calculated with equations (6) and (7).

$$WBR\ (\%) = Total\ weed\ biomass / (Crop\ biomass + Total\ weed\ biomass) \tag{6}$$

$$WVR\ (\%) = Total\ weed\ volume / (Crop\ volume + Total\ weed\ volume) \tag{7}$$

At crop maturity, plots were harvested with a 2.20 m wide combine harvester on a total area of 61.6 m^2 in the plot center, avoiding areas where biomass was previously sampled. The net grain yield was standarised at 14.5 % humidity and expressed in t ha^{-1}. The average Swiss wheat yields in 2020, 2021 and 2022 come from Swiss cereal interprofession (Swissgranum, 2023).

2.5. Data analysis

A linear mixed-effects model fitted by the restricted maximum likelihood approach (REML) was applied using the statistical software R, version 4.3.3 “Angel Food Cake” (R Core Team, 2024) and the package `nlme` (Pinheiro and Bates, 2000; Pinheiro et al., 2023). *Year* as a continuous variable (1, 2, or 3 years of continuous implementation of IWM strategies), *IWM* and the interaction between these two variables were considered as fixed effects. The regression intercept was estimated by each *IWM*, while slope coefficients were estimated in the interaction *Year:IWM*. Calendar year (2020, 2021 and 2022) and three repetitions, both assigned as factors, were treated as random. Calendar year was nested in repetition and distributed in the random intercept directed to *Year*. The proportion of weed relative to the total plant biomass (%), the proportion of weed relative to the total plant volume (%), weed density (plants m^{-2}) and weed species richness (species count per subplot) were response variables to evaluate effects on weed competition management. Additionally, these weed competition variables were tested as covariates of *IWM* to evaluate effects on grain yield. Model reduction was applied when factors where non-significant. Grain yield was assessed to evaluate benefits of using IWM strategies over years. To ensure heterogeneity of variance and normality of residuals, all weed variables were log-transformed. Model reduction at $\alpha = 0.05$ was performed and model evaluation was done using the lowest akaike information criteria (AIC). Marginal means adjusted with the Tukey HSD ($\alpha = 0.05$) method were used to explore differences in model predictions of *Year*, *IWM* or their interaction. Marginal means were calculated using the package `emmeans` package (Lenth, 2023). This package allows a weighted analysis based on standard errors for estimation of marginal means. The asymptotic yield loss function (8) developed by Cousens (1985) was used to assess yield loss imputable to crop:weed competition as a function of weed biomass:

$$y = y_{wf} * (1 - (i * x)/(1 + i/A * x)) \tag{8}$$

where, y is the estimated yield under increasing weed biomass, y_{wf} is the estimated weed-free yield, i is the yield loss per unit of weed biomass when biomass approaches zero, x is the weed biomass range, and A is the maximum yield loss caused due to weed competition. Although this model was initially developed with weed density (plants m^{-2}), it fitted well the weed dry biomass in g m^{-2}. Finally, the yield loss in all plots under the five IWM strategies was calculated with equation (9):

$$yl = (y_{wf} - y_{obs})/y_{wf} \tag{9}$$

where yl is the calculated yield loss and y_{obs} is the measured grain yield. Yield loss was analysed using the same previously described REML but using a random intercept without random slope.

3. Results

3.1. Variation in tillage intensity and herbicide use

Three-year average STIR and HTFI for winter wheat (Average_WW) and all crops (Average_All) showed an inverse relationship of NTHred and PL0H (Fig. 2a). PL0H had the highest STIR and the lowest HTFI values (both for WW and on average over all crops) unlike NTHred; the other three strategies were intermediate. Yearly STIR and HTFI winter wheat values showed contrasting development (Fig. 2b). With an HTFI of 0, STIR increased over the years up to 87 for ST0H and up to 80 for PL0H. HTFI for NTHred increased continuously from 1 to 1.4, while STIR was stable (near 0). For PLHred, HTFI increased from 0 to 1.6, and STIR decreased from 62 to 56. For PLredHred, HTFI decreased from 1 to 0, and STIR increased from 50 to 75.

3.2. Weed composition variation across IWM strategies

Ninety one weed species were identified in wheat across the five IWM strategies and the three years. In autumn and winter 2020–2022, weed densities were low in all strategies ($\leq$8 plants m^{-2}) and the predominant species was VERPE (*Veronica persica*) (Table S5.1). At pre-flowering, weed density and species composition were similar in 2020 and 2021 for all strategies, except NTHred (Fig. 3). In 2022, weeds were almost absent in PLHred and PLredHred; similar densities were observed between PL0H and ST0H, with the dominant species VERPE, MATCH (*Matricaria chamomilla*), and CAPBP (*Capsella bursa-pastoris*). NTHred showed a high abundance of ECHCG (*Echinochloa crus-galli*) and CONAR (*Convolvulus arvensis*). Species composition and densities at pre-harvest varied by year and strategies. In 2020, grass weeds were mainly present in ST0H and NTHred, whereas the other strategies were dominated by broad-leaved weeds in comparable densities. In 2021, weeds appeared only in ST0H dominated by ECHCG. In 2022, weeds were absent in PLHred and PLredHred, whereas the other strategies were dominated by CHEAL (*Chenopodium album*) and PLAMA (*Plantago major*).

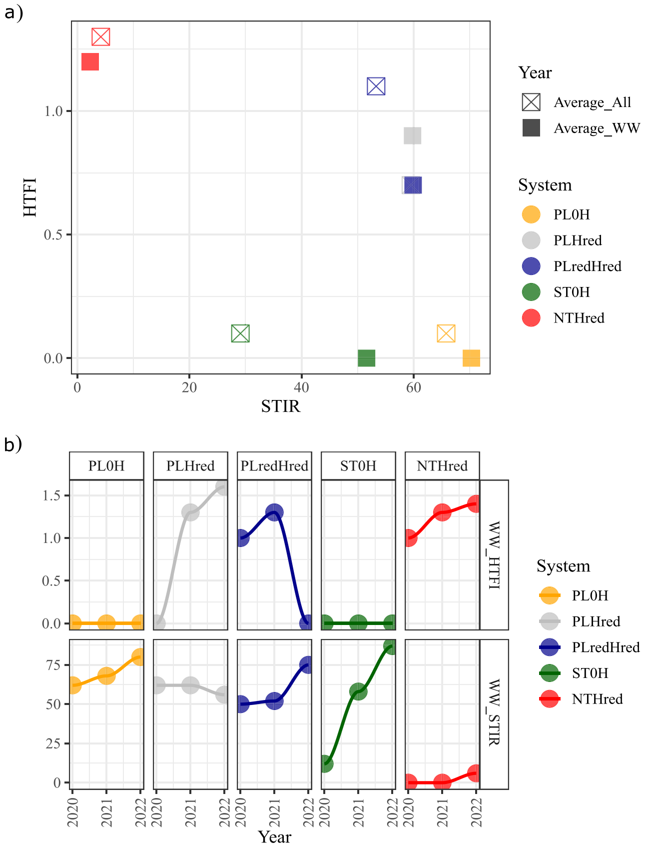

Fig. 2. Relationship between soil tillage intensity (STIR) and herbicide use (HTFI) for the five IWM strategies. a) Averages over three years of experiment for wheat (Average_WW) and for all crops (wheat and precedent crops, Average_All). Average_All TFI for PL0H and ST0H were not equal to 0 due to a mistakenly herbicide application in 2021 before soybean sowing preceding wheat 2022. b) Evolution of the two indices over three years (WW_STIR and WW_HTFI). STIR was calculated from ploughing, shallow tillage and mechanical weeding operations, and HTFI from all herbicides applied. PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides; NTHred: no-tillage, reduced herbicide use.

3.3. Weed dynamics over years and across IWM strategies at pre-flowering

The proportion of weed relative to the total plant biomass (%) and the proportion of weed relative to the total plant volume (%) did not vary across strategies and years (Fig. 4a, b). Medians by strategy (three repetitions) per year of both variables were below 8 % and 4 %, respectively. Visual estimates of weed volume at pre-flowering did not correlate well with weed biomass assessments, $R^2 = 0.31$, all years and strategies included, ranging from 0.18 to 0.38 over the three years (Figure S4.1). Weed density (plants m^{-2}) varied significantly over years and across IWM strategies (Fig. 4c, *Year:IWM*). Weed density in PL0H increased by 5.08 plants m^{-2} (CI: 1.98–13) every year whereas it increased only by 1 plant m^{-2} (CI: 0.34–2.22) per year in PLredHred. For PLHred, ST0H and NTHred the yearly increases were 1.85, 1.30 and 2.28 plants m^{-2}, respectively (CI: 0.27–12.50). Weed density medians by strategy per year were all below 40 plants m^{-2}. Weed species richness (species count) did not show statistical differences among strategies and over the years (Fig. 4d); medians by strategy per year were all below 20 weed species.

3.4. Grain yield and weed competition

Differences in grain yield trend for the applied IWM strategies over the years were insignificant (Fig. 5, *Year:IWM*), but important for years ($P = 0.04$, *Year*). Grain yield in 2022 was significantly lower than in 2020 and 2021. In 2020 and 2021, wheat yield was comparable to the average wheat yield in Switzerland (Swissgranum, 2023). In 2022, average Swiss wheat yield was low in Switzerland, and particularly low in Herbiscope across all IWM strategies. According to the REML analysis applied on grain yield as a response variable over the three years and across the five strategies, including the weed variables as covariates, it was not affected by weeds at pre-flowering ($P > 0.05$).

The weed-related yield loss was estimated by year with the Cousens' model, because of the high variability of yield over the years (Fig. 6). Wheat yield decreased when weed biomass increased only in 2020. The estimated weed-free yield was 7.5 t ha^{-1} (CI: 6.4 – 8.7), the yield loss per g m^{-2} of weed biomass [i in equation (8)] when biomass approaches zero was 0.3 % (CI: −0.7 – 1.3), and the asymptotic maximum yield loss [A in equation (8)] was 38 % [CI: −34 – 110]. Average estimated yield loss in 2020 varied across IWM strategies, ranging from − 4 % in PLredHred, to 19 % in NTHred (4 % for PLHred, 9 % for PL0H, 16 % for ST0H), without statistical differences ($P = 0.12$).

4. Discussion

4.1. All IWM strategies resulted in effective weed control

All five strategies implemented over the three years resulted in similar weed infestation and grain yield. Annual wheat yields were comparable to average Swiss yields (Swissgranum, 2023), while produced under limiting tillage and/or reducing herbicide use. Estimated weed-induced yield loss was observed only in 2020 (first year of experiment) in PL0H, PLHred, ST0H and NTHred. In contrast, no yield loss was spotted in the subsequent years, despite the high variability. In 2021, low yields were achieved in weed-free conditions, whereas high

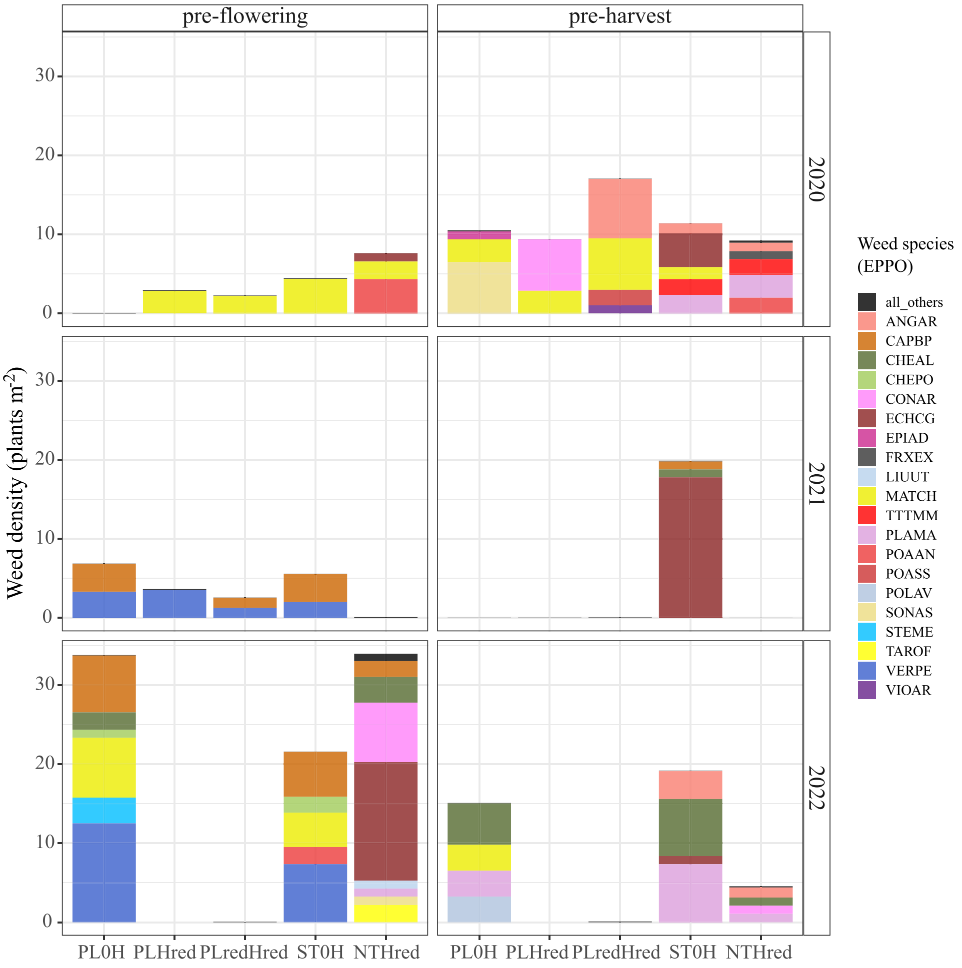

Fig. 3. Weed density of the 20 most abundant species in wheat at pre-flowering and pre-harvest, according to five IWM strategies (plants m^{-2} averaged across 3 repetitions per year, N = 9), colored by species, in the Herbiscope experiment 2020–2022. PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides; NTHred: no-tillage, reduced herbicide use. PLHred 2022 data were omitted as herbicide was applied after weed assessments. Weed species were named according to the EPPO Codes https://gd.eppo.int/. ANGAR (*Lysimachia arvensis*), CAPBP (*Capsella bursa-pastoris*), CHEAL (*Chenopodium album*), CHEPO (*Lipandra polysperma*), CONAR (*Convolvulus arvensis*), ECHCG (*Echinochloa crus-galli*), EPIAD (*Epilobium tetragonum*), FRXEX (*Fraxinus excelsior*), LIUUT (*Linum usitatissimum*), MATCH (*Matricaria chamomilla*), TTTMM (monocotyledoneous ssp.), PLAMA (*Plantago major*), POAAN (*Poa annua*), POASS (*Poa sp.*), POLAV (*Polygonum aviculare*), SONAS (*Sonchus asper*), STEME (*Stellaria media*), TAROF (*Taraxacum officinale*), VERPE (*Veronica persica*), VIOAR (*Viola arvensis*).

yields were obtained with weed biomass up to 80 g m^{-2}. Apparently, other factors than weed competition were responsible for yield variation, because weed biomass explained only about 30 % of yield loss variation (Milberg and Hallgren, 2004).

A high weed species richness at pre-flowering resulted in a low weed biomass, despite the high weed density in PL0H, ST0H and NTHred. Adeux et al. (2019b) found that high weed species richness at similar weed biomass ranges for winter wheat (*i.e.*, 63 g m^{-2} at heading stage and 114 g m^{-2} at filling stage) mitigate yield loss. Weed density, particularly of many small weeds after weed control increased significantly over years in PL0H but not in PLredHred. However, these differences did not increment the proportion of weed in the total biomass. The dominant weed species at pre-flowering were *Veronica persica*, *Capsella bursa-pastoris* and *Matricaria chamomilla*, three poorly competitive broad-leaved species in winter wheat (Masson et al., 2021). Weed assembly was not dominated by strongly competitive perennials or problematic (*i.e.*, herbicide-resistant) weed species, such as thistle (*Cirsium arvense*) or ryegrass (*Lolium sp.*), blackgrass (*Alopecurus myosuroides*) or cleavers (*Galium aparine*). Such communities have been reported as prone to cause greater yield loss than balanced ones (Storkey and Neve, 2018; Adeux et al., 2019b). The observed weed composition in Herbiscope is representative of arable farming areas in Switzerland. *Chenopodium album*, *Poa sp.*, *Polygonum aviculare*, *Veronica persica*, *Viola arvensis* and *Taraxacum officinale* were within the twenty most abundant species over the five strategies and three years of the experiment. Those species were within the ten most common reported in 232 cultivated fields in the Swiss Plateau region (Richner et al., 2017). Weed species richness in Herbiscope averaged 14.2 species per plot (all strategies, years and repetitions), being twice more diversified than that reported by Richner et al. (2017). The minor weed infestation and rich species diversity observed in Herbiscope might result from the great crop diversification employed over the past 30 years. Diverse crop rotation is known to favor low weed densities and high weed richness (Jalli et al., 2021).

The most challenging IWM strategies (*i.e.*, without herbicides, nor ploughing or without tillage and with reduced herbicide use) did not lead to yield reduction, increased weed infestation or changes in dominant weed species. Weed infestation remained stable over the years, validating our second hypothesis across three different climatic conditions (*i.e.*, within seasonal norm in 2020, wetter in 2021 and drier in 2022). Grain yield was more severely affected by dry and hot conditions in spring and summer 2022 than by weed infestation. These results authenticate that reducing herbicide and tillage in wheat with low weed pressure and in the absence of competitive species does not impact

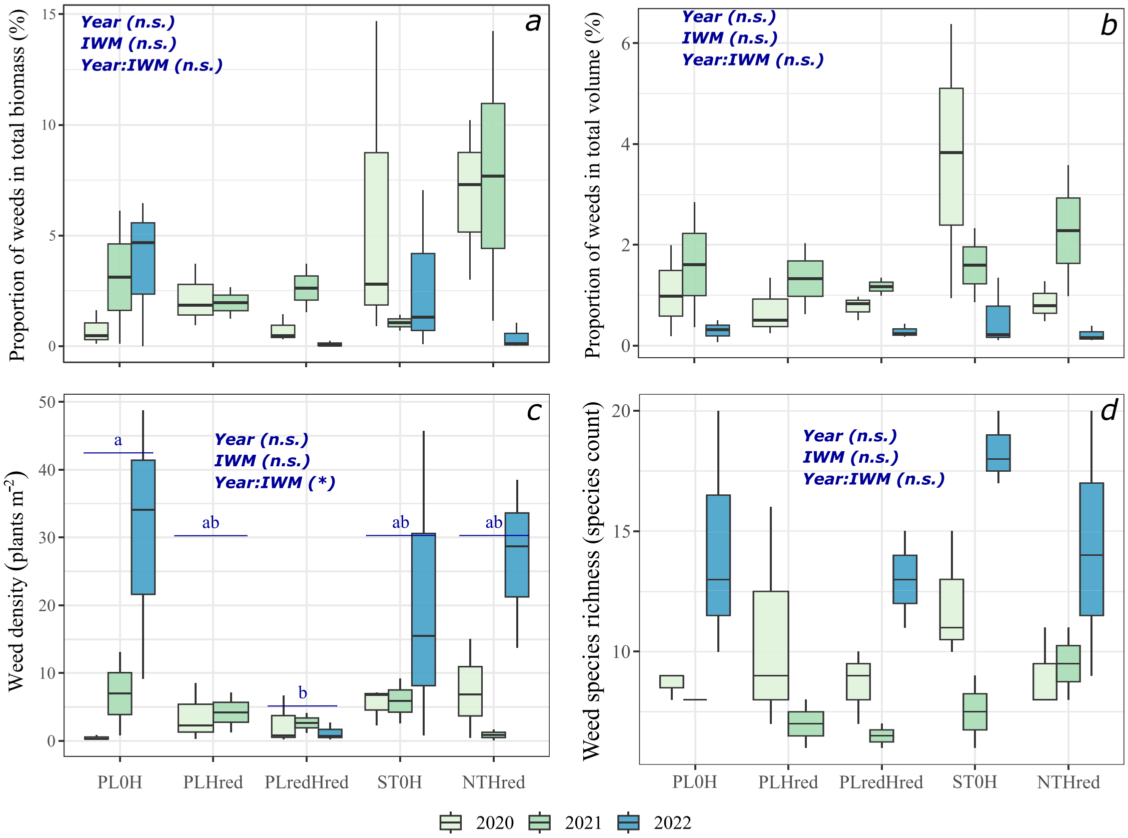

Fig. 4. Weed variables assessed in the five IWM strategies (*IWM*) at pre-flowering, during three years (2020–2022). a) Proportion of weed relative to total plant biomass (%). b) Proportion of weed relative to total plant volume (%). c) Weed density (plants m^{-2}). d) Weed species richness (species count). Statistical significance ($\alpha = 0.05$), n.s.: not significant; *: significant. PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides; NTHred: no-tillage, reduced herbicide use. PLHred 2022 data were omitted from the analysis as herbicide was applied after weed assessments.

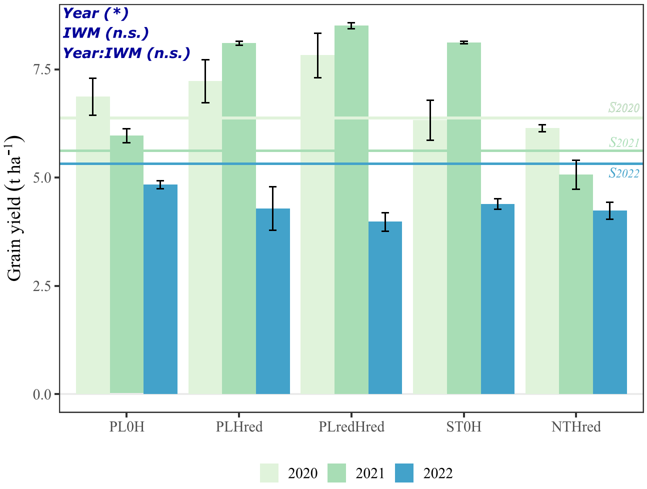

Fig. 5. Wheat grain yield trend variation (14.5 % humidity) during three years of applying five IWM strategies, 2020–2022. PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides; NTHred: no-tillage, reduced herbicide use. S2020, S2021 and S2022 are the average of farmers' wheat yield in Switzerland in 2020, 2021 and 2022, respectively (Swissgranum, 2023).

yield. A general increase of winter annual and perennial weed species under shallow tillage affected yield only after seven years (Tørresen et al., 2003). Weed infestation during the first five years of a long-term field experiment was low among tested IWM-based cropping systems (Chikowo et al., 2009). However, in the same experiment after seventeen years, weeds became more abundant in IWM systems than in the conventional one and reaching their maximum in the herbicide-free system. Only one IWM system, combining all techniques in a diversified crop rotation –comparable to PLredHred– kept weed dynamics stable over the years, contributing to a high crop productivity (Adeux et al., 2019a).

4.2. Optimizing weed control strategies

Efficient weed control across all IWM strategies was a consequence of the intense and frequent weed management activities, especially in strategies without herbicide (0H) or without ploughing (NT). No-tillage (NT, average STIR = 2) was offset by increased herbicide use as compared to other strategies, although the average wheat HTFI of 1.2 was lower than the Swiss, German and French average HTFI, being 1.5, 1.7 and 1.8, respectively, according to representative surveys (Agreste, 2017; Helbig, 2024). The ban of herbicides in ST0H and PL0H was compensated by more frequent mechanical weeding. When ploughing was reduced (ST0H and PLredHred), shallow tillage intensity increased. Consequently, STIR values of PL0H, PLredHred and ST0H increased over years, but stayed lower than those computed in conventional (STIR = 94) and organic (STIR = 139) systems in other winter wheat studies (Büchi et al., 2019). Over the three years, herbicide use increased when STIR was low and STIR increased when HTFI was close to 0. This

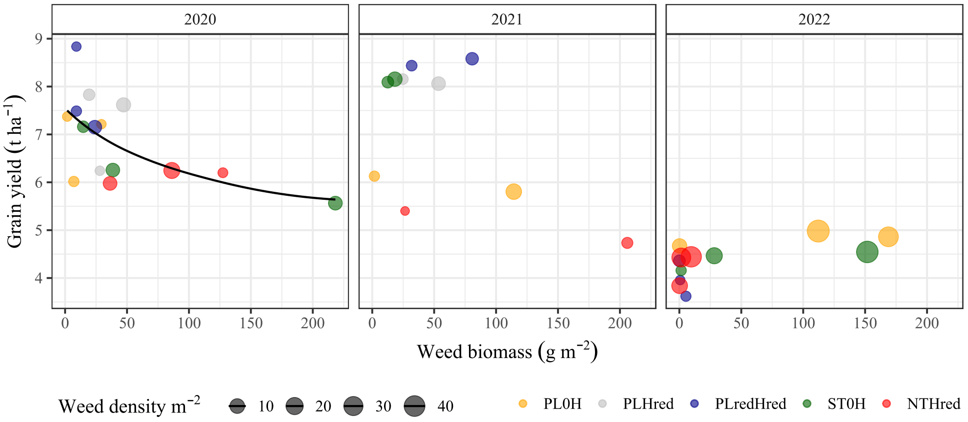

Fig. 6. Predicted wheat yield response to weed biomass (pre-flowering), after (Cousens, 1985, equation (8), over three years in five IWM strategies (colored dots). Bubble size increases with weed density (plants m − 2). PL0H: annual moldboard ploughing without herbicides; PLHred: annual moldboard ploughing, reduced herbicide use; PLredHred: occasional moldboard ploughing, reduced herbicide use; ST0H: shallow tillage (5–10 cm depth) without herbicides, mechanical weeding; NTHred: no-tillage, reduced herbicide use.

negative relationship between STIR and HTFI was also confirmed by Büchi et al. (2019) and is typical in many production situations (Colbach and Cordeau, 2022). This highlights the importance of combining different weed control solutions (Riemens et al., 2022) to implement long-term efficient IWM without high soil disturbance, whatever the motivation for reduced tillage.

The efficacy of weed control is highly influenced by the weather conditions. Frequent and heavy rainfalls during key crop growing stages might hinder mechanical weed control (Keller et al., 2014; Rueda-Ayala et al., 2010). In contrast, very dry years might affect the efficacy of some herbicide active ingredients, but do not prevent their use (Kudsk, 2017). Contrasted climatic conditions over the 2020–2022 period enabled to identify the effects of the weather on the efficacy of IWM strategies. Over the three years, similar yields and weed infestation levels were observed across strategies. However, considering only the wettest year 2021, the strategy PL0H with ploughing and no herbicides achieved lower wheat yields as compared to strategies with herbicides (PLHred, PLredHred) or with shallow tillage (ST0H). Frequent and heavy rainfalls in autumn 2020 resulted in a soil crust in ploughed plots that hampered wheat emergence and prevented any mechanical weed control during the critical period. Wheat emerged well in ST0H, providing rapid ground cover and competition with weeds. Despite these weather conditions in autumn 2020, herbicides were applied properly in PLHred and PLredHred. When weather conditions were optimal again for mechanical weeding, the control efficacy was reduced in PL0H because weeds were too big. The combination of mechanical and chemical weed control measures in a diversified rotation can therefore facilitate the adaptation to weather constraints (Colbach and Cordeau, 2018).

During the third year, herbicide-free strategies demanded more mechanical weeding than strategies combining all possible weed control methods, in order to achieve the same weed control and yield. Consequently, questions about the long-term sustainability of such systems arise, in terms of economics, workload and soil disturbance. For instance, Lechenet et al. (2017a) did not find any conflict between limited pesticide use and high profitability for the majority of the DEPHY network farms. Rather some obstacles for adoption of IWM strategies were determined by Wossink et al. (1997); Sattler and Nagel (2010); Petit et al. (2016), closely linked to the additional workload and the elevated complexity of work organization perceived/required. Assessment of the IWM-based strategies should be continued on a longer term, since weed seed bank may change over time and reveal enhanced weed density in the coming years (Cordeau et al., 2022; Jernigan et al., 2017).

4.3. *Critical analysis of field-based assessment of weed-crop volumes: a promising method*

The proportions of weed volume in the total plant volume and of weed biomass in the total plant biomass did not differ among strategies over the three years. In comparison with weed density, volume estimation considers weed growth habits and phenological stages at the time of weed survey (Mueller-Dombois and Ellenberg, 1974; Adeux et al., 2021; Hanzlik and Gerowitt, 2016). Volume estimation could become more reliable than plant density and faster than biomass sampling for assessing weed-induced effects on crop growth and yield. Nevertheless, the correlation between weed biomass and weed visual volume estimation was low in Herbiscope. This new method developed at Agroscope seems promising, provided a more thorough study is carried out for validating its utility, considering biological characteristics of weed species and crops. The use of depth cameras to estimate weed volume could increase the correlation with weed biomass. Andújar et al. (2016) reported a 83 % correlation between estimated weed volume and weed biomass in maize, based on 3D images with RGB (Red, Green, Blue) recognition. Rueda-Ayala et al. (2019) found a 66 % correlation with on-ground methods and 57 % with aerial ones to characterize lay grass fields.

5. Conclusion

The present study investigated effects of five different IWM strategies on weeds, wheat yield and weed-related yield loss over the first three years of the cropping system experiment Herbiscope. Over this period, weeds were maintained at low levels, preventing significant weed-induced yield loss over time. The diverse sets of weed control techniques along a gradient of tillage and herbicide use intensity were keys for an efficient weed management. The intensity of tillage operations in herbicide-free systems increased over time to contain weed pressure, questioning the long-term suitability of these strategies. Exploring performance of these strategies across a larger set of production situations would confirm that reducing pesticides and tillage is feasible and encourage the development of agri-environmental policies to sustain their implementation.

CRediT authorship contribution statement

Sandie Masson: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Victor Rueda-Ayala:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Luca Bragazza:**

Writing – review & editing, Validation. **Stéphane Cordeau:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Nicolas Munier-Jolain:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Judith Wirth:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This research is funded by Agroscope, part of the "Work Programme 2022–2025". Data analysis is part of the COMBHERPIC project (Combining alternative techniques to manage weeds in arable farming systems) funded by the Office Francais de la Biodiversité (OFB) under the Ecophyto 2021. Special thanks to Nicolas Widmer, Yves Grosjean, Cyril Dubuis, Matthieu Nussbaum and Cindy Bally for field assistance and technical operations implementation. Many thanks to all who helped regularly or occasionnally with weed surveys: Marie Fesselet, Frederick Tschuy, Pauline Canelle, Lucien Schneeberger, Mirjam Nyffenegger, Aurelie Gfeller, Max Fuchs, Aude Jarabo, Julie Buchmann, Anne-Valentine de Jong, Amelie Lagrange.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127284.

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