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RESEARCH ARTICLE

Determinants of oilseed rape-service plant intercropping performance variability across a farmers' fields network in Western Switzerland

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Abstract

The intercropping of winter oilseed rape with frost-sensitive service plants can provide a diversity of services including weed control and N supply for oilseed rape. This practice started to be adopted by farmers and has therefore become one of the most popular intercropping in Western Europe. However, in Switzerland, such intercropping leads to contrasting yields. The growth of service plants and the benefits they provide have also been found to be variable. The factors explaining these variabilities remain unclear. Our study aimed to better understand this variability under a temperate climate thanks to the regional agronomic diagnosis framework. In this study, we first investigated the main factors explaining this variability and then aimed to rank them to identify ways to better manage such intercropping systems. A network of 28 farmers' fields planted with winter oilseed rape intercropped with service plant mixtures was studied. Farmers' practices were diverse in terms of specific composition of the service plant mixture, pest management, and fertilization. We observed that the growth of oilseed rape and service plants in fall was highly variable. We determined that in late fall, the main drivers of the service plant mixture dry weight were specific composition of the mixture and precipitation. The introduction of buckwheat in the service plant mixture enhanced its late fall biomass. The oilseed rape grain yields ranged from 0.4 to 5.0 t ha^{-1} and were lower than that of the local reference in 75% of the fields. This was mainly explained by insect pest damage in spring due to a very limited use of insecticide in our field network combined with a lack of alternative pest management strategies. This work provides further elements to investigate the causes leading to the high variability we observed, together with the local observations that will benefit the farmers.

Keywords Regional agronomic diagnosis · Intercropping · Oilseed rape · Service plant · Pest regulation

1 Introduction

Agroecological practices such as intercropping rely on interactions between plant species that are highly dependent on growing conditions. In their review, Malézieux et al. (2009) highlighted the need for mobilization of tools such as agronomic diagnosis (Doré et al. 2008) to enhance knowledge of multispecies systems by identifying intercropping performance drivers such as farming practices and environmental conditions. However, to the best of our knowledge, such an approach has rarely been implemented to study specifically intercropping. Only Clermont-Dauphin et al. (2003) and Jagoret et al. (2017) investigated the influence of fertilization on maize-bean intercropping in Haiti and the productivity variability in complex cacao agroforestry, respectively.

Intercropping winter oilseed rape (OSR; *Brassica napus* L.) with frost-sensitive service plants (SPs) has started to be adopted by Swiss farmers and is now one of the most common intercrops grown in the country. This practice is known to reduce, or even avoid, the use of herbicides (Cadoux et al. 2015; Gardarin et al. 2022; Dayoub et al. 2022; Lorin et al. 2015; Verret et al. 2017). Legume service plants are also known to favor the nitrogen nutrition of OSR in spring with a positive effect on grain yield in N limiting conditions (Lorin et al. 2016; Verret et al. 2017). In some cases, service plants also contribute to control insect pest damage

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in fall (Breitenmoser et al. 2020; Emery et al. 2021; Cadoux et al. 2015). In such intercrop, only the OSR is harvested whereas the frost-sensitive SPs are usually killed off by sub-zero temperatures during winter.

In Switzerland, this practice was adapted by mixing several different SP species together in mixtures of four to ten species. These mixtures include both legumes and non-legume SP species in most cases (Fig. 1a, b; Baux and Schumacher 2019). The survey of Baux and Schumacher (2019) highlighted that the perception of benefits from SPs and their effect on OSR were highly variable among Swiss farmers. Thus, some of them pointed out an increase in yield variability or a yield loss in intercropping, compared to OSR grown alone, which explained why some farmers have already given up this practice. In fact, OSR-service plant mixture performances remain difficult to assess.

On the other hand, OSR sole crop yield is also highly variable across years and climate conditions (Brown et al. 2019; Rondanini et al. 2012). Indeed, Andert et al. (2021) showed that German farmers started reducing their OSR production mainly due to difficulty in maintaining yields with reduced amounts of herbicides, insecticides, and fertilizers.

OSR yield is very sensitive to N deficiency, weeds, and insect pests (Rathke et al. 2005; Valantin-Morison and Meynard 2008; Zheng et al. 2020). Weather conditions also have a strong influence on OSR grain yield (Brown et al. 2019; Peltonen-Sainio et al. 2010; Sharif et al. 2017). Water availability could have a significant effect on yield, especially in the early stage (Zhang et al. 2017). OSR yield is also sensitive to drought, high average temperatures, and low radiation during flowering and high average temperatures after flowering (Kirkegaard et al. 2018; Weymann et al. 2015). OSR oil content could also be affected by high temperatures and low radiation after anthesis (Kirkegaard et al. 2018; Rathke et al. 2006; Walton et al. 1999). Temperature also interacts with other limiting factors, for example, late frost and snow after stem perforation by stem weevil could increase the proportion of cracked stems of OSR (Agridea 2021).

Climate conditions also interact with farming practices (Doré et al. 1997), which can have different consequences on biotic processes on a site-specific basis (Duru et al. 2015b). Soil type, nitrogen availability, fertilization practices, sowing date, and sowing density were also pointed out to be important for both OSR growth in fall and its grain yield (Dejoux et al. 2003; Khan et al. 2018; Sieling et al. 2017). In the case of OSR-SP intercropping the choice of the SP species has a strong impact on SP biomass before winter, OSR growth, and grain yield (Verret et al. 2017).

Intercropping OSR with service plant mixtures is a promising solution to reduce OSR reliance on chemical inputs. A better understanding of the factors involved in the variability of intercropped OSR yields is therefore needed to

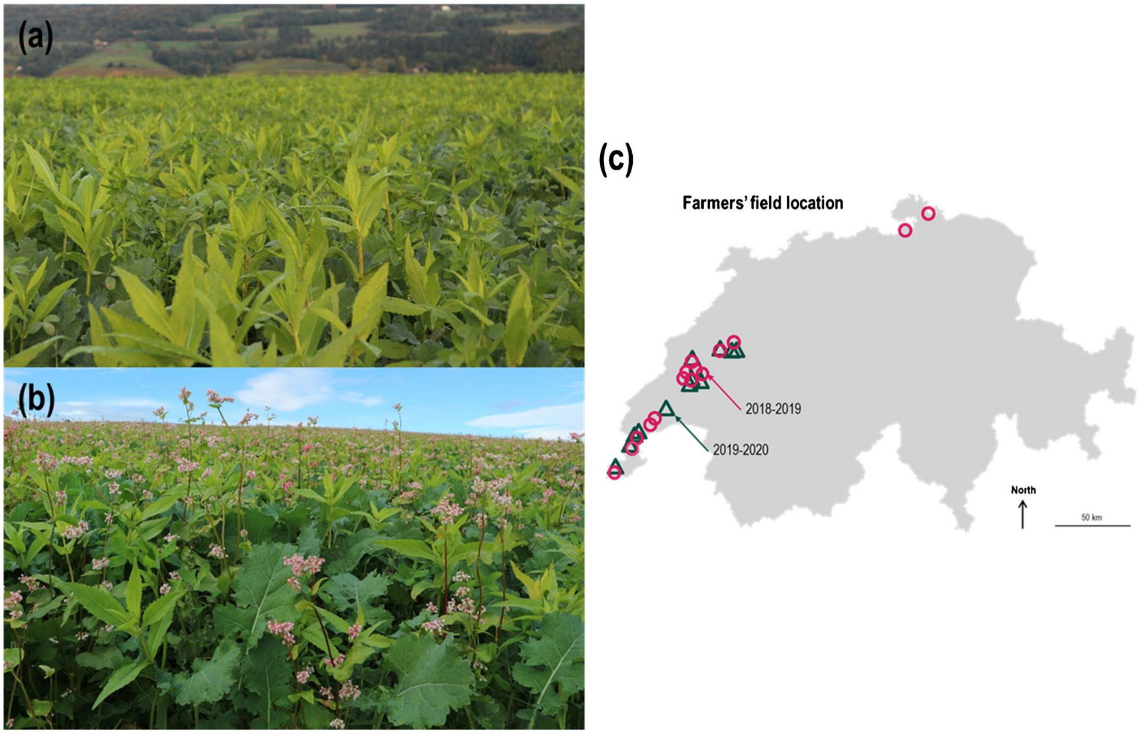

Fig. 1 Oilseed rape intercropped with service plant mixtures in fall (**a, b**) and location of the field network in Switzerland (**c**). The service plant mixtures intercropped with oilseed rape were made of niger, lentil, berseem clover, and fenugreek (**a**) or buckwheat, niger, vetch, berseem clover, lentil, and grass pea (**b**). Photo credit, Xavier Bousselin.

better adapt such practices to local contexts and help farmers to continue growing OSR. However, we lack studies about the hierarchy of these factors, especially in the case of OSR intercropped with complex SP mixtures in variable growing conditions. Filling this gap of knowledge between generic and local knowledge of agroecological practices is essential for agroecological transition (Duru et al. 2015a). It will also help to determine which practices and processes lead to the observed variability of yields and ecosystem services supply (Doré et al. 2008).

The purpose of our study was (i) to identify and explain the main factors of OSR intercropping grain yield variability and (ii) to understand which factors influenced most the growth of OSR and SP in early stages of this intercropping.

2 Materials and methods

2.1 Description of the field network

Twenty-eight farmer's fields planted with OSR-SPs intercropping located on 20 farms were investigated during the 2018–2019 and 2019–2020 cropping seasons (respectively, 16 fields in 2018–2019 and 12 fields in 2019–2020). These fields were mostly located in Western Switzerland in the cantons of Vaud and Geneva (Fig. 1c).

In each field, three zones of 10 m by 10 m representative of the field were defined. All the measurements and samplings were then performed within these three zones.

The altitude of these fields ranged from 371 to 806 m above sea level and the average temperature between sowing and harvesting ranged from 11.3 to 9.3 °C. The total precipitation between sowing and harvesting ranged from 588 to 790 mm in 2018–2019 and 823 to 1050 mm in 2019–2020 (Table 1). The fall of 2018 was particularly dry with total precipitation ranging from 24 to 88 mm (from 5 days before sowing to the late fall sampling, supplementary material Table S1). The soil texture was mostly loam or sandy loam (Table 1). The soil organic matter (SOM) ranged from 1.7 to 4.2% and the pH_{H2O} from 8.1 to 5.6. All the soils had less than 5% of active $CaCO_3$ (Table 1).

Among the 28 fields, two were damaged by hailstorm after the last sampling and prior to harvest, and one was too heterogeneous to link the field yield with the observations made on the three delimited zones. One field was destroyed by the farmer in early spring. Thus, the yield data were available for 24 fields.

2.2 Soil conditions and farming practices

All the farming practices performed from the harvest of the precrop to the harvest of the OSR of each field were recorded in interviews with each farmer.

Farming practices were highly variable within the field network (Table 1). Prior to sowing, five fields were plowed, twenty were unplowed, with tillage depth ranging from 4 to 30 cm, and three fields were not tilled. The sowing density of OSR ranged from 30 to 85 pl m^{-2} (Table 1). The SP mixture compositions were diverse, including two commercial mixtures. The first one comprised buckwheat (*Fagopyrum esculentum* Moench), niger (*Guizotia abyssinica* (L. f.) Cass.), clover (*Trifolium alexandrinum* L.), grass pea (*Lathyrus sativus* L.), lentil (*Vicia lens* (L.) Coss. & Germ, syn. *Lens culinaris* Medik.) and common vetch (*V. sativa* L.) and was implemented in eleven fields. The second one including niger, clover, fenugreek (*Trigonella foenum-graecum* L.) and blackening lentil (*V. lentoides* (Ten.) Coss. & Germ, syn. *L. nigricans* (M.Bieb.) Godr.) was sown in ten locations. In addition to these fields, farmers sowed their own mixtures in seven locations including two fields with only legumes; one mixture with niger and legumes; and four mixtures with buckwheat, niger, and legume SPs (supplementary material Table S2). Farmers also adapted the sowing density of SPs; the sum of SP sowing density varied from 60 to 178% of the recommended sowing density of these SPs in pure stand, with a mean of 101% (Table 1, supplementary material Table S2). OSR and SPs were either sown together (with a row spacing of 12.5 to 23 cm) in fifteen fields, or OSR was sown separately with a row spacing of 50 cm. Preceding crops were mostly cereals (wheat, spelt, or barley) except for one field that was preceded by silage maize. The straw was exported from twenty-three fields (Table 1). Eleven fields received organic or organic and mineral fertilization in late summer or fall.

After sowing, farmer practices were also variable. Six fields received at least one herbicide application and nine fields received at least one insecticide. Insecticide application occurred in fall for five fields and in spring for eight fields. Only two fields were sprayed with fungicide in fall and none in spring. These extensive practices can be partially explained by the fact that farmers receive subsidies when they avoid using herbicide or when they avoid using both fungicide and insecticides throughout the crop season. Finally, the spring N fertilization ranged from 77 to 181 kg ha^{-1}, with an average of 139 kg ha^{-1} (Table 1).

2.3 Climate factors

Due to elevation and precipitation variability according to location, weather conditions differed within the field network (Table 1). We used an extraction of MeteoSwiss grid-data for each farmer field. These data have a 0.02-degree and a daily resolution. It includes cumulated precipitation in mm as well as mean, minimum and maximum temperature in °C and relative sunshine duration in percentage (Frei et al. 2015; Isotta et al. 2014; MeteoSwiss 2021). The relative

Table 1 Pedoclimatic conditions and practices description of the field network. In the header the abbreviations are SOM, soil organic matter; temp., temperature; exp., export; Nb, number of; till, Tillage; OSR, oilseed rape; SP, service plant; herb., herbicides; ins., insecticides; Fall N fert, N fertilization applied before winter; Spring N fert., N fertilization applied after winter. The texture abbreviations are sl, sandy loam; l, loam; cl, clay loam; scl, sandy clay loam; according to the USDA texture classes of (Schoeneberger et al. 2012). For tillage type, ST, simplified tillage; DS, direct sowing. For service plants mixture, BNiLeg, SP mixture with buckwheat, niger, and other SP species; NiLeg, mixture without buckwheat with niger and other SP species; Leg, mixture or pure stand of legume SPs. [a]Estimation of the sowing density of oilseed rape in seeds m^{-2} based on sowing density in kg ha^{-1}. [b]Mixture different than the two most popular SP mixtures described in the main text

Year	Altitude (m)	Texture	SOM (%)	pH_{H2O}	Precipitation (mm)	Mean temp (°C)	Precrop	Straw exp.	Till. type	Nb till	Till. depth (cm)	Sowing date	OSR density (seed m^{-2})	SP mixture	SP density (%)	Nb herb.	Nb ins.	Fall N fert.	Spring N fert ($kg\ ha^{-1}$)
18–19	415	sl	2.6	7.6	667	9.3	wheat	yes	ST	3	15	29.08	32	BNiLeg	127	0	4	yes	140
18–19	411	sl	2.6	6.6	790	9.6	maize	yes	ST	3	30	30.08	85	NiLeg	80	0	0	yes	118
18–19	425	l	3.0	7.4	653	11.1	wheat	yes	ST	3	17	23.08	60[a]	BNiLeg	127	0	0	no	149
18–19	412	l	2.1	7.3	643	10.8	wheat	yes	ST	3	15	28.08	62	NiLeg	92	0	1	yes	154
18–19	410	l	2.3	6.9	643	10.8	wheat	yes	ST	3	15	28.08	62	BNiLeg	147	0	1	yes	154
18–19	435	sl	2.9	5.8	625	10.9	wheat	no	DS	0	0	18.08	75	BNiLeg[b]	83	1	0	no	140
18–19	403	l	1.9	8.0	609	10.7	wheat	yes	ST	3	10	23.08	60[a]	BNiLeg	16	0	0	no	181
18–19	637	cl	4.0	6.5	735	11.2	wheat	yes	DS	0	0	15.08	40	Leg[b]	100	1	0	no	104
18–19	434	l	3.7	8.0	694	10.2	wheat	yes	ST	2	15	22.08	50	NiLeg	70	1	1	no	145
18–19	693	l	2.4	6.5	711	9.4	wheat	no	Plowed	3	20	18.08	71	NiLeg	80	0	0	no	135
18–19	662	l	2.7	5.6	709	10.0	wheat	yes	ST	2	10	26.08	60[a]	BNiLeg	127	0	0	no	150
18–19	435	l	2.5	8.1	683	9.9	wheat	yes	Plowed	2	20	27.08	63	NiLeg	80	0	2	no	151
18–19	579	l	2.3	7.9	730	9.8	wheat	yes	ST	3	17	28.08	63	NiLeg	60	1	1	yes	161
18–19	496	l	2.2	7.0	588	9.6	wheat	yes	ST	3	20	19.08	30	NiLeg	80	0	0	no	110
18–19	457	l	1.7	5.8	640	9.8	spelt	no	ST	1	4	24.08	70	BNiLeg[b]	98	1	0	yes	151
18–19	534	sl	2.3	7.4	659	10.2	wheat	yes	ST	3	10	21.08	47	BNiLeg	110	0	0	yes	110
19–20	371	sl	4.2	7.4	836	11.3	wheat	yes	DS	0	0	14.08	70	BNiLeg[b]	86	3	3	no	175
19–20	454	l	3.5	6.5	960	10.7	wheat	yes	Plowed	3	20	24.08	59	NiLeg	92	0	2	no	151
19–20	450	l	3.2	7.9	1050	10.7	wheat	yes	ST	2	17	28.08	65	BNiLeg	127	0	0	no	149
19–20	449	l	2.6	7.9	1003	11.1	barley	yes	ST	3	15	26.08	55	BNiLeg	127	0	0	no	120
19–20	806	sl	2.6	6.5	964	9.4	wheat	yes	ST	3	10	28.08	78[a]	NiLeg	92	0	0	no	77
19–20	455	l	3.3	8.1	861	10.1	wheat	yes	ST	3	12	24.08	63	NiLeg	72	0	3	no	150
19–20	511	l	3.7	5.8	892	10.5	wheat	no	Plowed	2	25	05.09	65	Leg[b]	72	0	0	yes	124
19–20	653	l	2.3	7.4	882	10.1	wheat	yes	ST	3	12	26.08	67[a]	BNiLeg	127	0	0	no	150
19–20	453	l	3.7	6.2	-	-	spelt	no	ST	3	5	26.08	50[a]	BNiLeg[b]	127	0	0	no	-
19–20	666	l	2.8	6.8	905	9.7	wheat	yes	ST	2	5	26.08	60	NiLeg[b]	178	0	0	yes	130
19–20	509	scl	4.2	8.1	823	10.2	spelt	yes	Plowed	4	23	23.08	45	BNiLeg	127	0	0	yes	133
19–20	436	sl	2.3	7.6	918	10.6	wheat	yes	ST	3	12	17.08	45	BNiLeg	127	0	0	yes	133

sunshine duration was defined as the ratio between the duration of sunshine (when direct solar irradiance exceeds 200 W m^{-2}) and the maximum sunshine duration in clear weather conditions. These data together with sowing, sampling, and harvesting dates were used to calculate indicators (supplementary material Table S1).

In fall, two indicators were calculated: fall precipitation (mm) which is the cumulated precipitation from 5 days before sowing to the late fall sampling date, and the sum of temperatures between sowing and the late fall sampling date (°C d, base 0 °C). In spring, three indicators were calculated: the cumulated precipitation, the average relative sunshine duration, and the number of days with a minimum temperature below 0 °C in the last 45 days before the sampling at the end of flowering. As flowering is known to be a critical stage in terms of the impact to abiotic stresses on grain yield and content (Zhang et al. 2017; Kirkegaard et al. 2018; Weymann et al. 2015). Finally, the number of days with a minimum temperature below 0 °C between 1 March and sampling date at the end of flowering was also calculated as a potential factor explaining the intensity of stem weevil (*Ceutorhynchus napi* (Gyll.) and *C. pallidactylus* (Mrsh.)) damage.

2.4 Soil sampling and measurements

In each field, soil texture, soil organic matter content, pH_{H2O}, and soil mineral content were measured. The soil samples were taken at 0–20 cm and 20–50 cm depths. Three sampling points within each of the three zones were pooled together per depth prior to performing analysis. This measurement was performed in late summer after the sowing of the fields.

In late fall before the first frost and in late winter before vegetation starts, mineral nitrogen content ($N\text{-}NO_3^-$ and $N\text{-}NH_4^+$) of the soil was measured, using a discrete analyzer (THERMO FISHER SCIENTIFIC Gallery, Waltham, MA, USA) after KCl extraction. The soil was sampled at a 0–30 cm and 30–60 cm depth. Again, three sampling points in each of the three zones were pooled per depth. The soil samples were stored below −18 °C prior to analysis.

2.5 Plant sampling and analysis

Plant samples were collected at three stages: in late fall (LF), in late winter (LW), and at the end of flowering (EFlo). In each field, a representative 1-m^2 plot was sampled in the three zones previously defined for biomass measurements. The OSR, legume, and non-legume SPs as well as weed biomass were sorted, before drying at 60 °C for 72 h and weighing. At all sampling dates, the three replicates (zones) of OSR were pooled, ground with a hammer mill (RETSCH SR 300, Haan, Germany), and the N content was measured (Dumas' method, with a combustion analyzer, ELEMENTAR Vario MAX cube, Hanau, Germany). In late fall, the legumes, the non-legume SPs, and the weeds were also pooled per field, ground, and prepared for N and C content measurements.

OSR grains were harvested by the farmers and weighed to calculate yield per hectare. All but three farmers sent us a sample of the harvest to assess the proportion of impurity, 1000-seed weight using a seed counter (PFEUFFER GmbH Contador, Kitzingen, Germany). The oil and protein contents of the grain were measured using a near-infrared spectrometer (BÜCHI LABORTECHNIK AG NIRFlex N-500, Flawil, Switzerland). For the three missing fields, the impurities were measured by the retailers, and seed weight and quality data were not available.

2.6 Pest damage assessment

The damages from the main pests were also assessed. First, the number of cabbage stem flea beetle (*Psylliodes chrysocephala* L.) larvae per plant was measured using the Berlese-funnel-method (Conrad et al. 2016). This measurement was performed in late winter on the aboveground parts of 30 OSR plants in each field (10 per zone).

The proportion of bushy plants and the proportion of plants with stem damaged by stem weevil (cracked stem), were assessed visually on 45 OSR plants (15 per zone) at the end of flowering. The pod loss due to pollen beetles (*Brassicogethes aeneus* (Fabricius), syn. *Meligethes aeneus* (Fab.)), cold, pod parasitism and other factors was assessed by measuring the number of healthy pods divided by the total number of buds (sum of aborted buds, peduncles without buds, aborted pods, parasitized pods, and healthy pods) on one inflorescence per zone at the end of flowering.

2.7 Analysis procedure

The regional agronomic diagnosis is classically split into three steps: (i) the description of the variability of the variable of interest, (ii) the identification of the main limiting factors that explain this variability, and (iii) the description of pedoclimatic conditions and farmer practices that impact these limiting factors (Doré et al. 1997, 2008).

Based on our research question, the analysis focused on two sets of variables of interest describing (i) the intercrop growth in late fall (dry weights (DWs) and nitrogen amounts accumulated by OSR and SPs) and (ii) the OSR grain yields and grain oil content. The fall variables of interest were directly linked with environmental factors (pedoclimatic conditions and farmer practices). The classical three-step approach was used for the yield and yield components diagnosis.

2.7.1 Statistics

In order to identify and rank the main factors involved in the variability of the variables of interest and their limiting factors, we used a mixing model approach (Burnham and Anderson 2002) based on the Akaike (1974) information criterion (AIC) using the R software (R Core Team 2021) and the MMIX package (Morfin and Makowski 2009).

The principle of this method is that all the possible linear models with k explanatory factors are computed (2^k models, no interaction factor). For each model, the Akaike weight W_i (Burnham and Anderson 2002) was calculated following Eq. 1:

$$\mathrm{W_i} = \frac{e^{-0.5(\mathrm{AIC_i}-\mathrm{AIC_{min}})}}{\sum_{i=1}^{2k} e^{-0.5(\mathrm{AIC_i}-\mathrm{AIC_{min}})}} \quad (1)$$

where AIC_i is the AIC of the ith model and AIC_{min} is the smallest AIC among the 2^k model tested. W_i is then used to calculate the relative importance of the explanatory factors x noted $w_+(x)$ following Eq. 2:

$$\mathrm{w_+(x)} = \sum_{i=1}^{2^{k-1}} \mathrm{W_i} \quad (2)$$

and the parameter estimates value θ_x of the factor x in the mixed model follows Eq. 3:

$$\theta_x = \sum_{i=1}^{2^{k-1}} \frac{\theta_i}{\mathrm{W_i}} \quad (3)$$

where θ_i is the parameter estimates, W_i is the Akaike weight of the ith model among the 2^{k-1} models that includes the explanatory factor x.

These calculations were replicated 10,000 times on bootstrap samples in order to ensure the stability of the mixed model (Prost et al. 2008). This procedure is the same as the one described by Ouattara et al. (2021) and Leclère et al. (2021).

Linear models were also used to assess the linear relationship between two variables. When such a model was presented, the normality and homogeneity of residuals were first verified using the Shapiro-Wilk test and visual assessment.

2.7.2 Factors of variability of the intercropping growth in the late fall

The variables chosen as candidate explanatory factors of SP DW and N accumulations in fall were split into three categories: (i) the climatic conditions in fall, including precipitation and the sum of temperatures, (ii) the soil variables including clay and soil mineral N contents in the late fall and (iii) the farmer practices with number of tillage operations and the SP sowing density.

For OSR DW and N accumulation in the late fall, the explanatory factors of these three categories were the same, except the SP sowing density that was replaced by the OSR sowing density and the row spacing. The SP DW in the late fall was also added. This last factor was used as an indicator of SP competition with the OSR.

2.7.3 Yield and oil content candidate-limiting factors

The yield-limiting factors considered here were (i) climatic limiting factors such as precipitation, sum of temperatures, and relative sunshine duration over the 45 days before the end of flowering; (ii) nitrogen nutrition index (NNI; Lemaire and Gastal 1997) at the end of flowering; and (iii) the impact of pests on yields, including the weed DW at the end of flowering, the proportion of bushy OSR plants, the proportion of OSR stems damaged by stem weevils and the percentage of pod loss. NNI was calculated using the critical dilution curve of Colnenne et al. (1998) extrapolated beyond flowering as in Justes et al. (2000).

The most impacting limiting factors were then linked with pedoclimatic factors and farming practices.

3 Results and discussion

3.1 Service plant growth in fall

The SP DW in the late fall was highly variable, ranging from 0.04 to 2.64 t ha^{-1} with a mean value of 0.62 ± 0.65 t ha^{-1} (Fig. 2a). In all the fields that reached more than 0.5 t ha^{-1} of SP DW, the non-legumes were dominant within the SP mixture. Non-legume SPs achieved biomass of up to 2.12 t ha^{-1}. However, non-legume SPs DWs were lower than 0.51 t ha^{-1} in 75% of the fields within the network. Legume SP DWs ranged from 0.03 to 1.05 t ha^{-1} and 75% of farmers' fields accumulated less than 0.25 t ha^{-1} of legume SPs (Fig. 2c). The SP mixture N contents ranged from 2.2 to 4.9% and N accumulation from 2 kg ha^{-1} to 79 kg ha^{-1} with a mean of 17 ± 18 kg ha^{-1} in aboveground parts (Fig. 2b).

SP DWs measured in the field network were in most cases lower than existing references. For example, in the large experimental network of Verret et al. (2017), legume SPs intercropped with OSR produced on average 0.81 t ha^{-1}, when in the current study, only a third of the fields reached this value. However, the SP DWs and N contents had a similar range of variation to that reported by Lorin et al. (2015, 2016): 0.1 t ha^{-1} to 2.8 t ha^{-1} for legume SP DWs and less than 5 kg N ha^{-1} to more than 75 kg N ha^{-1}.

Both the fall precipitation and the buckwheat sowing density had a dominant and positive impact on the SP DW. The relative importance ($w_+(x)$) calculated for these two factors was 0.96 for both factors after bootstrap (Table 2).

The precipitation during fall was highly variable and ranged from 24 to 88 mm in 2018, and from 88 to 216 mm in 2019. The low precipitation in 2018 explained why the SP DW was lower in 2018 than in 2019, with mean SP DW of 0.48 ± 0.62 t ha^{-1} and 0.81±0.66 t ha^{-1}, respectively (Fig. 2a). In particular, the mixtures without buckwheat did not exceed 0.31 t ha^{-1} in 2018. The impact of precipitation on SP DW was consistent with previous observations in field experiments that showed very low SP DW in dry site (Bousselin et al. 2024).

All the fields sown with a mixture containing buckwheat produced at least 0.37 t ha^{-1}, whereas among the 13 fields without buckwheat, only 3 fields produced more than 0.37 t ha^{-1}of SP DW (Fig. 2 a). Buckwheat represented on average 43% of SP mixture overall biomass (proportion of SP fresh weight) which was more than twice as higher as its mean relative sowing density within the SP mixture (15.4% of the SP mixture). Indeed, buckwheat has a strong ability to compete thanks to its fast early growth, as reported by Cheriere et al. (2020) in intercropping with soybean. While buckwheat is known to be sensitive to drought (Creamer and Baldwin 2000), Tribouillois et al. (2016) also showed that it needs a lower water potential for germination than other species such as legume SPs, niger or OSR. It could also explain why mixtures with buckwheat sustained higher DW than others in 2018. The dominance of the non-legume species within the SP mixture was consistent with results obtained from cover crop intercropping studies (Brennan et al. 2011; Lawson et al. 2015), and may lead to increasing the competition with OSR (Verret et al. 2017; Bousselin et al. 2024).

Buckwheat was dominant but the species composition remained highly variable even among fields in which the same mixture made of buckwheat, niger, grass pea, lentil, Berseem clover, and vetch was sown (Fig. 2c). This was consistent with the large differences of biomass and species composition observed by Bousselin et al. (2024) for a given complex SP mixture intercropped with OSR across contrasting growing conditions.

In the late fall, the soil mineral nitrogen content had a positive impact on the SP DW. This factor had a lower relative importance than the two first factors (fall precipitation and buckwheat sowing density) and was less stable across bootstrap samples ($w_+(x)$) = 0.78; Table 2).

The N accumulated by SPs was affected by the same environmental factors as the DW and followed the same trends (Fig. 2a, b; Table 2). Both the fall precipitation and the buckwheat presence had the highest relative importance among all factors (0.94 and 0.93, respectively; Table 2). To a lesser extent, the soil mineral N content in the late fall may also explain the observed variability ($w_+(x) = 0.79$).

The SP C:N ratios were also highly variable, from 8.9 to 20.8, and correlated with the legume proportion in the mixture ($R^2 = 0.57$; $P < 0.001$; Fig. 2d). However, the accumulation of N by SPs followed the same trends as SP DW (Fig. 2a, b).

Finally, the weed DW was low in late fall, between a minimum of 0 t ha^{-1} and a maximum of 0.29 t ha^{-1}, and lower than 0.08 t ha^{-1} in 75% of the studied fields. Weeds accumulated on average 3.2±3.4 kg N ha^{-1} and up to a maximum of 11.7 kg N ha^{-1}. Therefore, the weed growth in fall was very limited compared to the levels that were observed in early winter by Valantin-Morison and Meynard (2008) on their organic OSR field network: 0.4 t ha^{-1} and 11.6 kg N ha^{-1} on average.

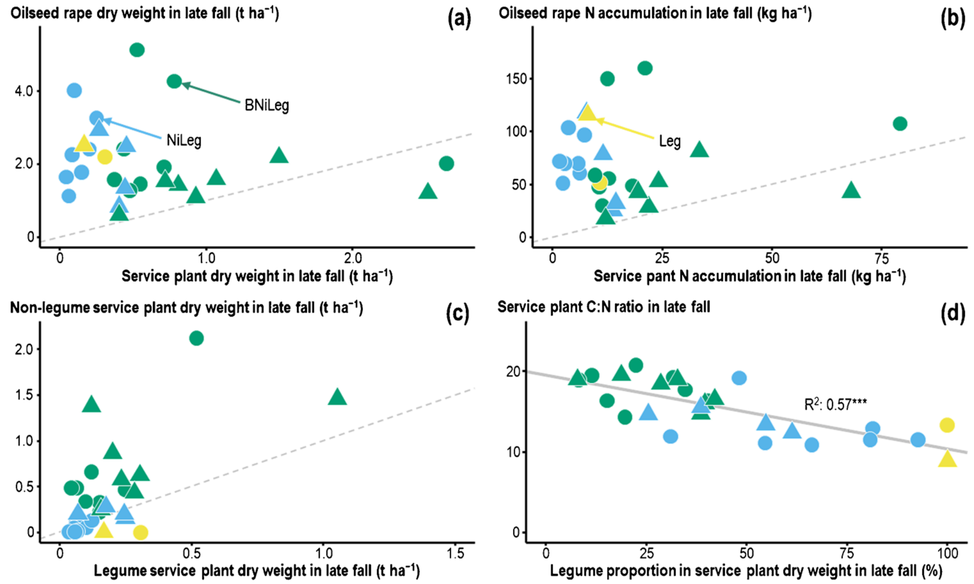

Fig. 2 Distribution of oilseed rape and service plant dry weight, N content and C:N ratio in the late fall (n=28). The circles represent the fields of the year 2018-2019, triangles represent the fields of the year 2019-2020. BNiLeg: service plant (SP) mixture with buckwheat, niger and other SP species, NiLeg: mixture without buckwheat with niger and other SP species, Leg: mixture or pure stand of legume SPs. The dashed grey lines are the 1:1 lines, the full grey line is the trend of the linear regression.

3.2 Oilseed rape growth in fall

The OSR DW amounted to 2.00 t ha^{-1} on average, from 0.61 t ha^{-1} to 5.13 t ha^{-1} (Fig. 2a), while its N content varied from 2.2 to 5.3%. Consequently, the OSR nitrogen uptake was also highly variable, ranging from 17 to 160 kg N ha^{-1} with a mean of 68±37 kg N ha^{-1} (Fig. 2b). In the late fall, the OSR density amounted to 42 ± 13 pl m^{-2} on average, ranging from 21 to 70 pl m^{-2}.

Thus, these results are in accordance with the survey of Cadoux et al. (2015), which also reported large DW variability for OSR sole crop (from 0.1 to 3.6 t ha^{-1}). However, in our study, three fields reached very high DWs above 4.0 t ha^{-1}. In terms of OSR N accumulation the observed variability was in agreement with the early winter OSR N accumulation recorded in the field network of organic OSR sole crop studied by Valantin-Morison and Meynard (2008), which ranged from less than 10 kg N ha^{-1} to more than 180 kg N ha^{-1}.

Among the potential explanatory factors of OSR DW in the late fall, none appeared to be dominant in the field network. The relative importance of all factors was low and unstable across the bootstrap samples. The same was found for the quantity of N accumulated by OSR (Supplementary material Table S3).

Interactions between factors or multiple factors are likely to be involved in OSR DW and N accumulation variability, in the late fall. Indeed, field network designs are not totally adapted to study interactions between factors (Doré et al. 2008). According to empirical observation of the field network, in some fields neither SPs nor OSR grew well in fall, due to water limitation. However, based on our results, OSR and SPs did not respond the same way to environmental conditions. It was also noticeable that the SP DW was not a key driver of OSR DW variability, even if non-legumes were dominant in SP DWs and were reported as having a high impact on OSR DW by Verret et al. (2017).

3.3 Impact of winter on the intercropping

The OSR DW in the late winter was correlated with the OSR DW in the late fall ($R^2 = 0.42$; $P < 0.001$). The OSR DW did not differ between the late fall and the late winter in the fields observed during the season 2019–2020. In 2018–2019, some fields with less than 2 t ha^{-1} of OSR DW in the late fall showed a slight DW increase over winter (Supplementary material Fig. S1). The fields with OSR fall biomass higher than 3 t ha^{-1} had a strong DW loss over winter. Indeed, Dejoux et al. (2000) have reported that OSR producing a very high amount of biomass also loses dry weight as dead leaves throughout winter.

The winter of 2019–2020 was the mildest winter since registration started in the area in 1864 according to MeteoSwiss (2020). However, in both years, the SPs were almost completely killed in the late winter. The maximum SP DW in late winter was 0.1 t ha^{-1}.In more than 50% of the studied fields, SP DW was lower than 0.01 t ha^{-1} at this stage. The DW of non-legume SPs was null in the late winter in all the fields of the network.

3.4 Oilseed rape grain yield and oil content

The OSR final grain yield (reported at 6% H_2O) was highly variable in the field network and ranged from 0.4 to 5.0 t ha^{-1} (Fig. 3a). In 2019, the yield reached 2.1±1.3 t ha^{-1} on average vs 2.8±2.9 t ha^{-1} in 2020 (Fig. 3a). The grain yield was strongly related to the number of grains per square meter ($R^2 = 0.97$; $P < 0.001$; Fig. 3a), which

Table 2 Relative importance of pedoclimatic conditions and crop management on service plants in growth in the late fall. $w_+(x)$: relative importance of the explanatory variable x calculated on the sample, $w_+(x)_{boot}$: relative importance of the explanatory variable x calculated on 10,000 bootstrap samples the values higher than 0.7 are bolded, Estimates: the estimate of the parameter of the x variable in the mixed models, SD, standard deviation of the estimate. GDD, growing degree-day; LF, late fall; Sd, proportion of sowing density (proportion or sum of proportion of the pure recommended density of each species); SP, service plant.

Limiting factor (x)	Service plant dry weight in late fall (t ha^{-1}) (n = 28)				Service plant N amount in late fall (kg ha^{-1}) (n = 28)			
	$w_+(x)$	$w_+(x)_{boot}$	Estimates	SD	$w_+(x)$	$w_+(x)_{boot}$	Estimates	SD
Intercept	1.00	**1.00**	−0.65	0.52	1.00	**1.00**	−18	17
Fall precipitation (mm)	0.99	**0.96**	0.0061	0.0017	0.99	**0.94**	0.16	0.052
Fall GDD (°C d)	0.27	0.47	−0.000018	0.00031	0.30	0.48	−0.0027	0.011
Soil clay content (%)	0.35	0.61	0.42	1.1	0.40	0.62	19	38
Soil mineral N LF (kg ha^{-1})	0.95	**0.78**	0.0082	0.0036	0.97	**0.79**	0.26	0.10
Number of tillage operations	0.27	0.45	0.0020	0.049	0.28	0.46	0.12	1.5
Sd buckwheat SP (%)	1.00	**0.96**	0.031	0.0082	0.98	**0.93**	0.74	0.26
Sd other non-legumes SP (%)	0.29	0.45	−0.0013	0.0065	0.30	0.47	−0.038	0.20
Sd legumes SP (%)	0.31	0.45	−0.00070	0.0025	0.29	0.45	−0.015	0.071

ranged from 7100 to 117,400 grain m^{-2} whereas it was negatively linked to the 1000-seed weight ($R^2 = 0.25$; $P < 0.05$; Fig. 3b). The 1000-seed weight ranged from 3.9 to 5.8 g in the field network (Fig. 3b). Even though the OSR plant density in the late winter ranged from 23 to 72 pl m^{-2}, this did not affect OSR grain yield.

In their experimental network in French conventional farming conditions, Cadoux et al. (2015) observed a minimum OSR yield of 1.3 t ha^{-1}. Here, 25% of the fields showed yields below 1.3 t ha^{-1}. Our results are thus closer to those observed by Valantin-Morison and Meynard (2008) in France (from 0.1 to 2.7 t ha^{-1}) and by Charles et al. (2020) in Switzerland for OSR grown under organic conditions. The yield difference we observed between 2019 and 2020 was consistent with national averages reported by the official statistics: 3.1 t ha^{-1} vs 3.7 t ha^{-1} respectively (SBV-USP 2021). Globally, the OSR yields were, on average 1 t ha^{-1} lower than the national average (SBV-USP 2021).

The grain yield distribution within the field network was also in agreement with the farmers' observations about low yield in intercropping systems reported by Baux and Schumacher (2019). It highlights the gap between experimental results showing a similar or improved yield in intercropping compared to OSR sole crop (Cadoux et al. 2015; Verret et al. 2017) and the farmers' results in the Swiss context. It justifies further investigation of the limiting factors involved and the potential path to fill this gap.

The 1000-seed weight did not contribute much to the yield, which was almost completely explained by the number of grains per m^2. This was consistent with the review of Diepenbrock (2000) who also reported the small impact of this component on yield and its negative correlation with yield.

The grain quality was less variable than the yield. The seeds' oil content ranged from 48 to 58% with a median of 52% (in proportion of dry matter) while the protein content ranged from 16 to 24% (Fig. 3c). Oil and protein contents were strongly and negatively correlated ($R^2 = 0.96$; $P < 0.001$). The oil content was rather high compared to the existing reference and its variability was comparable (Gauthier et al. 2017; Rathke et al. 2005). The oil and protein contents were closely and negatively correlated as observed in other studies focusing on OSR or other oil crops (Leclère et al. 2021; Rathke et al. 2005). Only the oil content, which is the main quality criterion, was then investigated.

3.5 Limiting factors affecting oilseed rape grain yield and oil content

The damage of spring insects appeared as the main factor explaining yield variability. Stem damage caused by stem weevils came first ($w_+(x) = 0.96$; Table 3), and to a lesser extent the pod loss mostly due to pollen beetles also contributed to yield variability ($w_+(x) = 0.79$). Within our field network, no field with more than 40% of stems damaged by stem weevil achieved a yield higher than 2.7 t ha^{-1} and no field with more than 30% pod loss reached yields of 3.1 t ha^{-1} or more. This result is consistent with the fact that stem weevils were already a damaging species for OSR in Switzerland when its cultivation started on a large scale in the 1940s before insecticides were used in cropping systems (Derron et al. 2015). This observation was not due to specific conditions as, according to the extension office of the canton of Vaud, the captures of stem weevils were close to the standard with a peak in the last week of February (Jaquiéry 2020). As for the pollen beetles, the pressure was higher than the standard both years, especially in 2019 (Jaquiéry 2020).

Studies in Europe often pointed out flea beetles as a major issue (Andert et al. 2021; Zheng et al. 2020). Although peaks of captures of flea beetles were twice higher than the standard in the area for the two years of our experiment (Jaquiéry

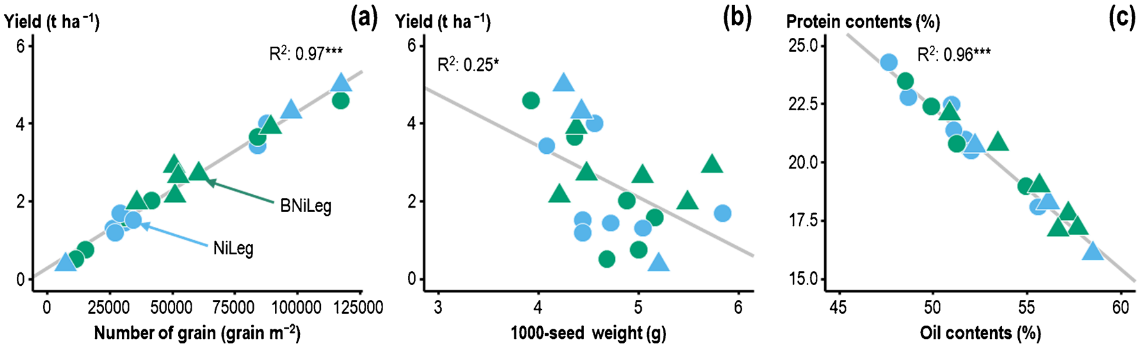

Fig. 3 Dispersion of oilseed rape grain yield, yield components and grain content ($n = 22^a$). Yield: oilseed rape grain yield reported at 6% H_2O. The circles represent the fields of the year 2018-2019, triangles represent the fields of the year 2019-2020. For service plants mixture: BNiLeg: service plant (SP) mixture with buckwheat, niger and other SP species, NiLeg: mixture without buckwheat with niger and other SP species. The full grey lines are the trends of the linear regressions. ^{a}All the fields for which yield and seed sample were available.

2020), they were no major yield-limiting factor in our field network. In our study, the proportion of bushy plants was low. Despite the number of larvae per plant in late winter was 16.5 on average (ranging from 0.1 to 44.7), the percentage of bushy plants was only 14% on average and was higher than 50% in only two locations. The field with the highest number of larvae per plant (44.7) also had the highest OSR biomass in late fall and achieved the highest yield (5.0 t ha^{-1}). This is not surprising, as Ortega-Ramos et al. (2022) highlighted in their review that linking the number of larvae per plant with damage and yield loss is very difficult.

Nitrogen nutrition index (NNI) at the end of flowering also affected yield ($w_+(x)$ = 0.84; Table 3). It ranged from 0.72 to 1.76 with a mean of 1.28 ± 0.23. The NNI was positively correlated with OSR grain yield ($R^2 = 0.43$; $P < 0.001$). This result is in accordance with Valantin-Morison and Meynard (2008) who demonstrated that nitrogen is a key limiting factor. However, the early flowering OSR NNI observed in this study was much lower than ours (Valantin-Morison and Meynard 2008). The instability of the relative importance of this factor across bootstrap samples could be explained by the low number of fields with nitrogen deficiency, in our study only one field had a NNI lower than 0.9 (Table 3).

To a lesser extent, the weed DW at the end of flowering also affected the OSR yield ($w_+(x)$ = 0.75). However, weed DW relative importance ($w_+(x)$) was rather unstable across bootstrap samples; further investigations are needed to fully confirm its impact. In their organic field network, Valantin-Morison and Meynard (2008) found weed DW to be a strong limiting factor of OSR yield. Here, only a fifth of the fields in the network received one or more herbicide applications during OSR growth: on average 0.28 vs more than 1 application on average for conventional Swiss OSR growers (de Baan et al. 2015). However, converse to organic farmers, our growers used herbicide on other crops; therefore, weed management during the crop rotation was easier.

The relative sunshine duration ($w_+(x)$ = 0.72) also appeared as a limiting factor, whereas precipitation and the sum of temperature during the 45 days before the end of flowering did not have an impact on yield variability. Indeed, the incoming radiation during flowering was mentioned as a limiting factor of grain yield in literature (Baux et al. 2015; Weymann et al. 2015). Relative sunshine duration was also the main limiting factor of oil content ($w_+(x)$ = 0.97; Table 3), even if oil content was rather stable and relative sunshine duration only explained a part of its variability (R^2 = 0.46; $P < 0.001$). The literature on the effect of radiation on oil content is heterogeneous (Kirkegaard et al. 2018; Pritchard et al. 2000; Weymann et al. 2015).

3.6 Causes of variability of the identified limiting factors

The number of insecticide applications in spring was identified as the only key-factor explaining stem damaged by stem weevil ($w_+(x)$ = 0.81; Table 4). The OSR DW in late winter is sometimes considered as an asset to reduce sensitivity to insect pests, and the number of frost events after 1 March is considered as affecting stem damage by stem weevils (Agridea 2021). Within the field network, these two factors were not clearly identified as affecting stem weevil damages (Table 4).

Insect management practices were very extensive within the field network: 19 of the 27 studied fields did not receive

Table 3 Relative importance of oilseed rape grain yield and oil content limiting factors. $w_+(x)$: relative importance of the explanatory variable x calculated on the sample, $w_+(x)_{boot}$: relative importance of the explanatory variable x calculated on 10,000 bootstrap samples the values higher than 0.7 are bolded, Estimates, the estimate of the parameter of the x variable in the mixed models; SD, standard deviation of the estimate; Yield, OSR grain yield reported at 6% H_2O; Flo, over the 45 days before the late flowering sampling; GDD, growing degree-day; OSR, oilseed rape; NNI, nitrogen nutrition index; EFlo, end of flowering; DW, dry weight. [a]All the fields for which yield was available. [b]All the fields for which the yield and the seed sample were available.

Limiting factor (x)	Oilseed rape grain yield (t ha^{-1}) ($n = 24^a$)				Oilseed rape grain oil content (%) ($n = 21^b$)			
	$w_+(x)$	$w_+(x)_{boot}$	Estimates	SD	$w_+(x)$	$w_+(x)_{boot}$	Estimates	SD
Intercept	1.00	**1.00**	−1.9	1.7	1.00	**1.00**	37	5.3
Precipitation Flo (mm)	0.59	0.67	0.0042	0.0054	0.34	0.51	0.0046	0.013
GDD Flo (°C d)	0.45	0.58	0.0018	0.0038	0.36	0.54	−0.0038	0.0096
Relative sunshine duration Flo (%)	0.76	**0.72**	0.037	0.031	1.00	**0.97**	0.33	0.094
OSR NNI EFlo (t ha^{-1})	0.95	**0.84**	2.2	1.0	0.49	0.60	−0.29	0.45
Weed DW EFlo (t ha^{-1})	0.84	**0.75**	−0.27	0.19	0.33	0.43	0.46	1.7
Bushy plant (%)	0.37	0.58	−0.26	0.66				
Stem damaged (%)	1.00	**0.96**	−2.4	0.63				
Pod loss (%)	0.90	**0.79**	−1.8	1.0				

any insecticide application in spring. Although the insect pest damages were variable among insecticide-free locations, insecticide use consistently decreased stem damage and pod loss. Two of the eight fields that reserved insecticide in spring showed high damages in 2019, because of late spraying that was targeting pollen beetles and did not affect stem weevils. Thus, the large yield variability was mostly explained by the extensive practices of OSR intercropping growers. This confirms that the production of this oil crop is still highly dependent on insecticide use (Andert et al. 2021; Derron et al. 2015; Zheng et al. 2020). It also highlights the lack of impact of frost-sensitive SPs on spring insect damage that was also reported by Emery et al. (2021) in field trials. Finding SP species that could contribute to spring insect control such as non-frost sensitive ones (Emery et al. 2021; Järvinen et al. 2023) or using other means to control insects such as regional synchronization of rotation as suggested by Zheng et al. (2020) and Hausmann et al. (2023) would be necessary to allow sustainable OSR production without using insecticides in spring.

OSR NNI at the end of flowering was first explained by the N fertilization rate ($w_{+}(x) = 0.95$; Table 4), and to a lesser extent by OSR nitrogen uptake and soil mineral N content in the late winter ($w_{+}(x) = 0.86$ and 0.81 respectively). The SP N accumulation in fall and its C:N ratio did not appear as key factors explaining OSR NNI variability across fields. However, the accumulation of N by SPs in the late fall had the highest relative importance ($w_{+}(x) = 0.87$) to explain soil mineral N content in the late winter among the following factors: soil mineral N content in the late fall, OSR N loss over winter, winter precipitation, winter sum of temperatures, and SP C:N ratio (Supplementary material Table S4). In our field network, the soil mineral N content in late winter ranged from 9 to 67 kg ha^{-1} with an average value of 39 kg ha^{-1}.

Our results are consistent with the fact that spring N fertilization and soil N content are important factors for OSR N supply and grain yield (Rathke et al. 2005, 2006) and that OSR nitrogen uptake in early stages is less decisive and can be compensated in later stages (Colnenne et al. 2002). Within our network, SPs accumulated a low amount of N in most cases. The SP total biomass was mostly dominated by non-legumes which resulted in only a small and indirect link with nitrogen nutrition of the OSR and the N accumulation of SPs. Lorin et al. (2016) demonstrated an effect of SPs on the OSR N nutrition, but this effect was rather low compared to the variability we observed here. The reference of 30 kg N ha^{-1} reduction of N fertilization without yield loss (Lorin et al. 2016; Verret et al. 2017) was established based on pure legume SPs that accumulated on average 0.81 t ha^{-1} (Verret et al. 2017).

3.7 Practical implications

In our field network, the effect of SPs was not reported to be a strong driver of OSR N nutrition in spring. It could be due to N fertilization rate applied by farmers which was close to the recommendation for OSR sole crops. Consequently, level of N nutrition of OSR in most fields was good. The low SP growth and the high proportion of non-legumes during the two cropping seasons studied also probably reduced the potential of SP mixture to provide N supply to OSR. Increasing the legume proportion and most of all species able to fix high quantities of N such as faba bean or pea (*Pisum sativum* L.) in the SP mixtures may be an option to improve SP N supply service (Lorin et al. 2016; Verret et al. 2017).

The weed control service was not assessed directly in our study, however, in fall, the weed DW was low even though less than a third of the fields received an herbicide application. Weeds were not among the main factor explaining

Table 4 Relative importance of factors influencing stem weevil damage and oilseed rape nitrogen nutrition index. $w_{+}(x)$, relative importance of the explanatory variable x calculated on the sample; $w_{+}(x)_{boot}$, relative importance of the explanatory variable x calculated on 10000 bootstrap samples the values higher than 0.7 are bolded, Estimates, the estimate of the parameter of the x variable in the mixed models; SD, standard deviation of the estimate. NNI, nitrogen nutrition index; OSR, oilseed rape; DW, dry weight; LW, late winter; Nb, number of; d, day; SP, service plant; LF, late fall; Spring N fert., N fertilization applied after winter. [a]All the fields were included except the one that was destroyed prior end of flowering. [b]All the fields are included but the field destroyed prior sampling and the two fields where the late fall soil sampling was not possible.

Limiting factor (x)	Stem damaged (%) ($n = 27^{a}$)				Limiting factor (x)	NNI of oilseed rape at the end of flowering ($n = 25^{b}$)			
	$w_{+}(x)$	$w_{+}(x)_{boot}$	Estimates	SD		$w_{+}(x)$	$w_{+}(x)_{boot}$	Estimates	SD
Intercept	1.00	**1.00**	0.51	0.17	Intercept	1.00	**1.00**	0.12	0.24
OSR DW LW (t ha^{-1})	0.41	0.52	−3.2	6.1	N OSR LW (kg ha^{-1})	0.95	**0.86**	0.0027	0.0012
Nb d below 0 °C	0.61	0.65	−0.0093	0.011	N SP LF (kg ha^{-1})	0.54	0.65	0.002	0.0027
Nb insecticide	0.84	**0.81**	−0.12	0.075	C:N ratio SP LF	0.42	0.59	−0.0044	0.0084
					Soil N LW (kg ha^{-1})	0.95	**0.81**	0.0055	0.0023
					Spring N fert (kg ha^{-1})	1.00	**0.95**	0.0056	0.0013

yield variability and only strongly affected OSR weakened by low fall growth cumulated with heavy insect damages. This was the main difference with the diagnosis of Valantin-Morison and Meynard (2008) where weeds and their impact on nitrogen nutrition of OSR were the main divers of final yield. In our field network, in addition to the weed control at the rotation level, the N fertilization practices are likely to explain this gap.

In the early stages, abiotic factors also had a key impact on the intercropping growth. According to the climate projection CH2018 (Fischer et al. 2022), the summer precipitation in Western Switzerland should decrease (Sørland et al. 2020). The adaptation of the sowing date to weather conditions, such as early sowing when a rain event is coming, might be a strategy to enhance the SP growth and their subsequent ecosystem services provision. The choice of species that are less sensitive to drought is also possible to ensure a minimum growth of SPs, as it was observed with mixtures including buckwheat. Winters are also likely to become warmer in the future. Even though this was not a problem during the warmest winter, recorded (2019–2020), in the long term, it could lead to SP destruction problems. Such a situation would force farmers to use herbicides to kill SPs or reduce the choice of SP to very frost-sensitive species or cultivars such as Mediterranean varieties or move to other type of intercropping strategy.

4 Conclusion

The aim of this study was to identify, rank, and explain the factors explaining the growth of OSR and SP in early stages as well as grain yield variability in OSR-SP intercropping systems. It is the first implementation of the regional agronomic diagnosis framework that focused specifically on intercropping in temperate cropping systems. The yields observed in this study were low on average and very low in many situations. The results made it clear that yield variability of OSR-SPs complex intercropping was driven by other factors than SPs growth. The extensive insect management practices, favored by the local subsidy policies, were the main factor leading to crop failure and low yields. This result highlights the gap between the potential of this agroecological practice and the ecosystem services expected by farmers.

To a lesser extent, spring fertilization practices and the enhancement of OSR N accumulation in fall could also contribute to fill the yield gap, through enhancement of OSR N nutrition. In fall, the SP DWs observed in Swiss OSR-SPs intercropping fields were lower than our initial expectations. A dry fall strongly limited SP DWs and therefore the SP potential to provide ecosystem services. Non-legumes, especially buckwheat, dominated SP DWs. Including this species in complex SP mixtures could improve the SP DW production and therefore contribute to its potential to control weed. However, it also reduces SP niche complementarity with OSR for N nutrition. Modifying SP mixtures by reducing buckwheat use and increase the sowing density of legume service plants could contribute to better manage trade-offs between expected services.

Finally, these results demonstrate the value of such approaches to explain the variability of agroecological practices which is needed for (i) focusing on most impactful research topic for further research, (ii) enhance better valorization of ecosystem services, and (iii) further upscaling of these practices.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-024-00972-6.

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Authors' contributions Xavier Bousselin: conceptualization, methodology, formal analysis, data curation, visualization, investigation, writing—original draft preparation, writing—reviewing and editing; Mathieu Lorin: supervision, conceptualization, methodology, investigation, writing—reviewing and editing; Muriel Valantin-Morison: funding acquisition, supervision, conceptualization, methodology, investigation, writing—reviewing and editing; Joëlle Fustec: funding acquisition, supervision, conceptualization, methodology, investigation, writing—reviewing and editing; Nathalie Cassagne: supervision, writing—reviewing and editing; Alice Baux: funding acquisition, supervision, conceptualization, methodology, investigation, writing—reviewing and editing

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Data availability The datasets generated and analyzed during the current study are available in the Zenodo repository, https://doi.org/10.5281/zenodo.11382721.

Code availability The R scripts used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflicts of interest The authors declare no competing interests.

Disclaimer UFA Samen, Florin, and Nutriswiss were not involved in the study design, data collection, analysis, and interpretation of data, nor were they involved in writing the report and decision to submit the article for publication.

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