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Strip cropping in organically managed vegetable systems: agronomic and environmental effects

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Abstract

This study evaluated the agro-environmental and economic effectiveness of strips introduced in a diversified organic vegetable system. Two experiments of three experimental years (2018, 2019, 2020) were carried out within the 4-year rotation of MOnsampolo VEgetable organic Long-Term Experiment (MOVE LTE) in Central Italy to test strip cropping *vs* pure stand. The crop combinations in the two experiments were faba bean (*Vicia faba* L.)–tomato (*Solanum Lycopersicum* L.) and common wheat (*Triticum aestivum*)–zucchini (*Cucurbita pepo L.*). We determined the productive and economic performances, disease and weed control, nutritional differences and effectiveness in returning carbon to the soil. The two strip cropping systems allowed a better use of resources, enhancing plant biomass and crop residues, particularly for tomato (+24%) and zucchini (+63%). However, the greater plant biomass did not always result in an increase in crop yields. For example, while the wheat–zucchini strip system showed a land equivalent ratio >1 in all three experimental years with a high yield performance in zucchini (+54% of yield), the faba bean–tomato system was more productive in strips only in 2018. On the contrary, this latter system contributed a carbon return >1 in all three experimental years. No significant differences between strip and pure stand systems were observed for fusarium (*Fusarium oxysporum* f. sp. *lycopersici*) and oidium (*Oidium* spp.) diseases on tomato and zucchini crops, respectively, and for weed control. Lastly, greater labor costs associated in both experiments did not affect their profitability (+21% and +319% in faba bean–tomato and wheat–zucchini experiments, respectively). Overall, our findings pointed out that farmers could increase sustainability of their cropping systems with the introduction of a well-designed strip cropping system, which can lead to the reduction of economic risks, greater potential soil carbon and more efficient use of resources on the same land.

Introduction

The European Union committed to a goal of 25% of all production be organic by 2030 under the current legislative framework to promote sustainability of food systems (European Commission, 2020; Fetting, 2020). Indeed, organic agriculture is generally considered an environmentally sustainable system since it is associated to an enhancement of biodiversity, ecosystem services and soil quality (Norton *et al.*, 2009). However, under the umbrella of organic farming, there are different production systems, including the substitution of conventional inputs by more environment-friendly options without challenging the simplified structure typical of many non-organically managed systems (Darnhofer *et al.*, 2010). Organic farms, which are in the input substitution stage (Rosset and Altieri, 1997), need to redesign their production systems, also intensifying the crop diversification processes. These are one of the most important elements in agroecological re-design (Lin, 2011; Wezel *et al.*, 2014) to improve ecosystem functionality, crop production, pest and disease control, soil quality (Duru *et al.*, 2015) and reduce the negative effects caused by agricultural specialization and industrialization (Campbell *et al.*, 2017; Robinson, 2018). More recently, crop diversification processes have been strongly promoted in Europe through the same legislative framework for sustainable food systems, which increase researches funding (Messean *et al.*, 2021), with the goal to support the producers and farmers transition toward a sustainable well-diversified European agriculture. Diversity in field can be enhanced in several ways in terms of temporal, spatial, or genetic diversification (Ditzler *et al.*, 2021). Crop diversification is relevant for organically managed vegetable production systems since they involve a wide range of crops with short growth cycles, which allow multiple crop combinations, mainly based on leafy vegetables. Temporal (rotations, multiple cropping) and genetic (multiple species, including local cultivars and landraces) diversification strategies are often implemented in organic vegetable systems, especially to preserve plant health and obtain harvestable products throughout the year (Morel and Léger, 2016).

Intercropping, defined as growing two or more crop species simultaneously on the same field, is a method to spatially diversify the system. In a well-designed intercropping system, both the variations in root and aboveground architecture affect resource (solar radiation, mineral nutrients, water) and, at spatial and temporal levels, also reduce the inter-species competition, increasing complementarity among plants. Different researches indicate that these positive effects impacted various aspects of vegetable systems, including yield and pest control (Yildirim and Guvenc, 2005; Yu *et al.*, 2015). However, despite these advantages, the application of intercropping is more complicated requiring a high level of knowledge and management skills (Theunissen, 1997).

Among different kinds of intercropping (Brooker *et al.*, 2015), strip cropping, where different crops are cultivated in parallel strips with alternate multiple-row patterns, has evolved and is designed to allow cultivation work. Strip cropping also maintains or increases labor efficiency of modern agriculture and improves crop diversification and its related ecosystem services. The strip cropping is a form of intercropping compatible with machinery. To be an easily acceptable diversification practice, strips must be adequately spaced to allow separate management regimes, but close enough to allow plants to influence each other (Ditzler *et al.*, 2021).

Even if this matter is already studied, there is a lack of information on the effects of strip cropping on different agro-ecological and economical parameters in organic vegetable production, especially in the Mediterranean environment. Therefore, the objective of our work is to quantify the effects of strip cropping in well spatially diversified vegetable systems and assess their impacts from an agro-environmental and economic perspective. Accordingly, our hypotheses are that, in an already diversified cropping system, the increased crop diversity at the field level wrought by the strip cropping will improve crop yield, enhance disease and weed control and profitability.

Material and methods

Site description, experimental design and crop management

Strip cropping technique was introduced in 2017 at the MOnsampolo VEgetable organic Long-Term Experiment (MOVE-LTE) located in Monsampolo del Tronto (AP), coastal area of Central Italy (42°53′N, 13°48′E). MOVE-LTE is characterized by a typical thermo-Mediterranean climate and its soil is Typic Calcixerepts fine-loamy, mixed thermic one (USDA, 1996). The 30-year average monthly data for the temperature and precipitation in the MOVE-LTE are reported in Supplementary Figure S1 and compared with data recorded during the strip cropping experimental years. The mean annual temperature was 15.5°C in each experimental year. Except for May, in each month it was 1.5°C higher than the 30-year mean. We also recorded a peak of +4°C in November 2020 and some exceptional frosts in February 2018. The average rainfall during the three experimental years was 650 mm. It was +140 mm compared to the 30-year average value. This rainfall resulted from strong storm events occurred in November 2018 and March 2020, even if they were alternated with dry months. MOVE-LTE is a wide field of 2112 m^2 and it is divided into four equal rotational areas. Within this LTE, the crop diversification techniques are based on 4-year rotation and the use of cover crops was applied from 2001 (Supplementary Fig. S2; Canali *et al.*, 2013; Campanelli and Canali, 2012). Nine plant species were cultivated annually (six for income and three for services provision (i.e., agroecological service crops) belonging to seven different botanical families. Every year, only two rotational areas were included in the 3-year (2017–2018; 2018–2019; 2019–2020) strip cropping experiments of this study. Specifically, the two experiments were carried out to test strip cropping (S) *vs* pure stand (P). The chosen crop combinations were faba bean (*Vicia faba L.*, local cv 'Fratterosa')–tomato (*Solanum Lycopersicum* L., local cv 'SAAB CRA') and common wheat (*Triticum aestivum*, heterogeneous material)–zucchini (*Cucurbita pepo*, F1 'Galatea'). The selected species are widely cultivated in the Mediterranean test area and in particular, the botanical families adopted in these experiments were already included in the crop rotations the MOVE-LTE. Both, leguminous crops and cereals were cultivated as agroecological service crops before tomato and zucchini, respectively.

In the MOVE-LTE, two experiments were established: (1) faba bean–tomato; (2) wheat–zucchini. Each experiment is divided into two different sub-experiments to test vegetable crops (tomato or zucchini) in S *vs* vegetable crops in P stands, and grain crops (faba bean or wheat) in S *vs* grain crops in P stands. Each sub-experiment consisted of a non-randomized block design with three adjacent blocks and two replicated treatments (S and P stands) per each block. In fact, to keep the P stand separated from the S cropping, it was not possible to completely randomize the experiments. Each block included six plots, three plots for each treatment. The four sub-experiments were analyzed separately. Size of the plot for vegetable crops was 15.2 m^2, while for grain crops it was 14.2 m^2. The experimental design was repeated each year in two fields within the rotation of MOVE-LTE. The layout of the experiments is reported in Supplementary Figure S2 in.

Experiment 1. Hairy vetch of the existing rotation was replaced by faba bean to obtain a multiple cropping system based on faba bean–tomato. This experiment consisted of two sub-experiments with the same layout to test: (*a*) faba bean for dry grains in S with tomato *vs* faba bean for dry grain in P; (*b*) tomato in S with faba bean for dry grains *vs* tomato in P. Strips were 2.0 and 2.8 m wide for faba bean (dry grain production) and tomato, respectively. In the whole experimental area (both S and P stands) of the two sub-experiments, faba bean was sown in October with a density of 150 kg ha^{-1}. In S and P tomato areas, the faba bean was harvested in May for fresh pod production, while in the remaining experimental areas it was left for dry grain production until harvest (July). After harvest of fresh product, the faba bean residues were flattened by the In-Line Roller Crimper technology (ILRC; Canali *et al.*, 2013) and tomato was transplanted in May, with a density of 28,500 plant ha^{-1} in both S and P, on the obtained mulch without soil tillage.

Experiment 2. Also this experiment consisted of two sub-experiments to test: (*a*) wheat grain in S with zucchini *vs* wheat grain in P stands; (*b*) zucchini in S with wheat grain *vs* zucchini in P stand. In the experimental field area, common wheat was sown in late October to early November at a density of 200 kg ha^{-1}. Strips were 2.0 and 2.8 m wide for wheat (dry grain production) and zucchini, respectively. In S and P zucchini areas, the wheat was terminated at flowering (April–May) by the ILRC, while in the remaining areas it was left for dry grain production until July. Zucchini was transplanted (13,400 plants ha^{-1} both in P and S) on the wheat mulch without soil tillage. In 2019, zucchini was harvested in June, July and August, while only in June and July during the other experimental years.

Agronomic management practices adopted during the experimental years for the crops of both experiments are reported in Supplementary Table S1.

Measurements

At harvest dates, one square meter faba bean fresh pods, faba bean dry grain, wheat dry grain and their related crop aboveground residues were manually collected from each experimental plot. The same occurred both for tomato and zucchini residues at final harvesting time, collected from four tomato and three zucchini plants from each plot. Weeds were manually collected in an area of 0.25 m^2 per each plot, at each weeding operation and at the end of the crop harvest. Total weed biomass as the sum of the different sampling times per plot was considered in the study. Vegetable fruits were manually collected throughout the season. All mature tomato and zucchini fruits were collected sampling the four and three central crop plants from each plot, respectively. They were selected according to local market standards to obtain both fresh marketable and non-marketable yields. At each harvest time, the fruit samples collected at plot level were subsampled and frozen. Subsamples from different harvest times were combined to constitute the final fresh samples. Fresh biomass were dried at 105°C for 24 h to obtain the dry weight and then analyzed for nitrogen (N) concentration by a LECO Nitrogen analyzer model FP-528 (St. Joseph, MI, USA). Furthermore, carbon (C) concentrations in crop residues, non-marketable yield and weed biomass were assessed using a LECO TOC Analyzer, model RC-612 (LECO Corporation, 1987).

The effect on the dry grains faba bean was evaluated in terms of grain yield and 100-seed weight, on wheat in terms of grain yield, 1000-seed weight, hectoliter weight (ISO 7971-3, 2019) and gluten content (AACC Method 38–10.01, 1999), and on vegetable summer crops in terms of marketable yield, fruit weight and number of marketable fruits.

During the second and third experimental year, an in-depth study was carried out by measuring the soil mineral N (SMN, NO_3^--N + NH_4^+-N, 0–30 cm soil depth, 3 soil core sampling per plot, combined to finally obtain one sample per plot for subsequent analyses), by collecting soil samples at 49 and 73 days after transplanting (DAT) in 2019 and 2020, respectively. These DAT corresponded to beginning of fruit setting and beginning of harvest for tomato, respectively, and with 26 and 30 DAT in 2019 and 2020 for zucchini, respectively, which corresponded with beginning of fruit setting in both years.

The SMN was extracted by 2 M KCl (1:10, w/v) and measured by continual flow colorimetry, according to Krom (1980) and Henriksen and Selmer-Olsen (1970) for NH_4^+-N and NO_3^--N, respectively.

Evaluation of fusarium (*Fusarium oxysporum* f. sp. *lycopersici*) infection on tomato or oidium (*Oidium* spp.) on zucchini, two key diseases, was carried out in each treatment and in all plots, and on the same 16 and 13 selected plants for tomato and zucchini, respectively.

Data on fusarium symptoms were collected three times in each experimental year (2018: July 3rd, July 24th, August 20th; 2019: July 5th, July 26th, August 23th; 2020: July 15th, July 28th, August 17th), while oidium symptoms were assessed two times in each year (2018: July 3rd, July 24th; 2019: July 22th, August 22th; 2020: July 15th, August 3rd). The disease incidence was expressed as percentage of infected plants relative to the total number of plants observed. The severity index represents the mean symptom intensity (Madden and Hughes, 1999) and it was expressed assigning five levels of an empirical scale, from 0 (healthy plant) to 4 (100% of the infected leaves). The infection index or McKinney index (McKinney, 1923) includes both the incidence and severity of the disease. It expresses the weighted means of the disease as a percentage of the maximum possible level and it was calculated using the following equation:

$$\text{Infection index} = [\Sigma(d \times f)/\ (n \times D)] \times 100$$

where d is the level of empirical scale, f is the frequency of each level, n is the total number of plants examined and D is the highest level of the disease intensity that occurs on an empirical scale.

Advantage, competition and economic indices

The advantage of S cropping over the P system and the effect of competition between the two intercropped species were calculated for the 3 years of the two experiments as mean values of each treatment using the land equivalent ratio (LER) and competitive ratio (CR) indices.

The LER (Mead and Willey, 1980) indicates the efficiency of S cropping in the use of environmental resources to obtained yield compared with the P system. Any value greater than 1.0 indicates a yield advantage for strip cropping. LER was calculated as

$$\text{LER} = \sum\left(\frac{Ysi}{Ypi}\right)$$

where Ys is the yield of each crop in the S cropping, and Yp is the yield of each crop in the P stand.

For each i-th crop, a ratio is computed to determine the partial LER for it. The partial LERs are then summed to achieve the total LER.

The CR (Willey and Rao, 1980) was used as an indicator to evaluate the competitive ability of different crops in strip cropping. Considering the two crops in each experiment, it was calculated as

$$\text{CR crop1} = \frac{\text{Partial LERcrop1}}{\text{Partial LER crop2}} \times \frac{\text{Pcrop2}}{\text{Pcrop1}}\ ;\ \text{CR crop2} = \frac{\text{Partial LERcrop2}}{\text{Partial LER crop1}} \times \frac{\text{Pcrop1}}{\text{Pcrop2}}$$

where Pcrop1 is the sown proportion of crop 1 in intercropping with crop 2 and Pcrop2 is the sown proportion of crop 2 in intercropping with crop 1.

A CR value >1 for a crop indicates that it is more competitive than the other in the intercropping system (Zhang *et al.*, 2011).

The same concepts and formulas of LER and CR were also applied to N uptake and organic C returned to soil.

According to Salehi *et al.* (2018), N-ABG-LER and N-LER were calculated for each experiment using N uptake (kg N ha^{-1})

of the aboveground crop biomass and yields, respectively, to determine the nutritional advantage of intercropping. The N-ABG-CR and N-CR were similarly calculated to evaluate the competitive ability of different crops in the use of N resources.

The effectiveness of the S cropping system in returning C to the soil was computed through C-LER using the amount of C input ($\mathrm{Mg\ C\,ha^{-1}}$) from crop residues, mulch, non-marketable yield and weed biomass in each treatment of the two experiments. The greater or lesser contribution to soil C between the two intercropping crops was evaluated with C-CR calculation.

Gross margin (GM) was used to determine the profitability of both S and P of the following crop combinations: (i) faba bean for dry grain–faba bean for fresh pod production+tomato transplanting; (ii) common wheat–zucchini. The economic analysis was calculated each year and both in S and P systems as follows:

$$\mathrm{GM} = \sum \left((Yi \times \mathrm{Pi}) - Ci \right)$$

where Yi is the marketable yield of the i-th crop, Pi is the market price for the i-th crop and Ci is the total direct expenses for the i-th crop.

To allow a comparison between S and P, GM was calculated considering: (a) 1 ha cultivated in S with the same widths (2.8 and 2.0 m) and management described in the experiments; (b) 1 ha cultivated in P stands in a proportion of 42% for one crop (faba bean for dry grain or common wheat) and 58% for the other one (faba bean for fresh pod production + tomato or zucchini). These percentages represent the total area included in all the strips in the intercropping system. The crop management in P was the same as reported in the experiments.

Yields and direct costs (Supplementary Tables S2 and S3) were those incurred in carrying out the experiments, while selling prices were set according to a team of organic farmers who reviewed the MOVE LTE procedures and results. They were: €1 $\mathrm{kg^{-1}}$ for faba bean dry grains; €2 $\mathrm{kg^{-1}}$ for faba bean fresh pods, tomatoes and zucchini; €0.45 $\mathrm{kg^{-1}}$ for wheat grains.

Statistical analysis

Statistical analyses were performed with R software (R Core Team, 2021). Crop and soil variables described above, such as fruit (marketable and non-marketable) and grain yield, crop aboveground residues, weed biomass, marketable fruit and seed weight, marketable fruit numbers and SMN measurements for each sub-experiment, were statistically analyzed by analysis of variance (ANOVA). A mixed model using *lme* function of *nlme* R package (Pinheiro and Bates, 2022) was built with treatment (T, 2 levels: S—strip; P—pure), year (Y) and the interaction of T × Y as fixed effects. The block factor was included in the random part of the model with the block (B) nested within the rotational areas. Since the experimental layout was characterized by non-randomization, we introduced spatial correlation structures in the model to account for the lack of independence among samples (Pinheiro and Bates, 2000; Navarro-Miró *et al.*, 2022). Models without and with different (exponential, Gaussian and spherical) spatial correlation structures were compared considering Akaike's and Bayesian information criteria. For each dependent variable, the selected best model was always without any spatial correlation structure. When necessary, data were transformed by the function $y = \log(x)$ or $y = \sqrt{x}$ to ensure the normality and homoscedasticity of the residuals checked graphically and through statistical tests in R. We used *shapiro.test* function to test normality (Shapiro and Wilk, 1965) and *leveneTest* function from *car* package for homoscedasticity of the variance (Levene, 1960). Mean comparison was carried out according to post-hoc Tukey's test using the R package *emmeans* (Lenth, 2022). Reported means and standard errors are from non-transformed data.

The non-parametric clustered Wilcoxon rank-sum test was performed using the R package *clusrank* (Jiang *et al.*, 2020) to evaluate the effect of strip cropping on incidence, severity and infection index of fusarium and oidium diseases on tomato and zucchini, respectively, across the multiple years of the sub-experiments. In order to compare disease observations in both S and P treatments on the same date and in the same experiment block, data were clustered by observation date and experiment block.

Advantage, competition and economic indices described in 2.3 sub-paragraph were instead assessed across the multiple years of the two experiments evaluating average values and the coefficient of variation (CV), obtained by dividing the standard deviation by the mean, multiplied by 100.

Results

Faba bean–tomato experiment

The ANOVA showed that variability between years affected most of the results of the faba bean for dry grain sub-experiment (Fig. 1). Faba bean grain yield was not significantly different between treatments (mean values of 2.59 ± 0.30 and 2.57 ± 0.34 $\mathrm{Mg\,ha^{-1}}$ for S and P, respectively), while a significant T × Y interaction was observed (Fig. 2a). The yield was greater in 2019 (4.43 ± 0.27 $\mathrm{Mg\,ha^{-1}}$) followed by 2020 (2.33 ± 0.17 $\mathrm{Mg\,ha^{-1}}$) and 2018 (0.98 ± 0.11 $\mathrm{Mg\,ha^{-1}}$). However, only in 2018, grain yield in S resulted in greater yield than in P (+31%; 1.28 ± 0.16 $\mathrm{Mg\,ha^{-1}}$ *vs* 0.68 ± 0.08 $\mathrm{Mg\,ha^{-1}}$). No factor significantly affected crop aboveground residues (Fig. 1b) and weed biomass (Fig. 1c), which reported a mean annual value of 3.86 ± 0.13 and 1.83 ± 0.16 $\mathrm{Mg\,ha^{-1}}$, respectively. The 100-seed weight (Fig. 1d) was significantly affected by the year, varying between 150.62 ± 9.86 g in 2018 and 207.59 ± 4.27 g in 2019.

Results obtained for tomato sub-experiment are reported in Figure 2. The marketable yield (Fig. 2a) and the number of marketable fruits (Fig. 2f) were significantly influenced both by Y and the T × Y interaction. Mean annual values of marketable yield ranged between 36.13 ± 4.16 $\mathrm{Mg\,ha^{-1}}$ in 2018 and 63.01 ± 3.57 $\mathrm{Mg\,ha^{-1}}$ in 2020 but there was a significant greater value in S than P systems only in 2018 (+103%, 48.42 ± 4.94 *vs* 23.85 ± 3.40 $\mathrm{Mg\,ha^{-1}}$). No significant differences were obtained between treatments for the moisture content of fresh tomatoes (93.81 ± 0.14% in P, and 94.00 ± 0.20% in S). Number of marketable fruits ranged between 77,779 ± 7461 $\mathrm{n\,ha^{-1}}$ in 2019 and 341,270 ± 17,616 $\mathrm{n\,ha^{-1}}$ in 2020 showing a greater value of 90% in S compared to P only in 2018, for marketable yield.

Non-marketable yield (Fig. 2b) was not affected by any factor. On average, the S system resulted in greater crop residues than P by +24% (3.64 ± 0.17 *vs* 2.93 ± 0.25 $\mathrm{Mg\,ha^{-1}}$) (Fig. 2c). Weed biomass (Fig. 2d) was 34% greater in S compared to P systems (5.01 ± 0.38 *vs* 3.75 ± 0.34 $\mathrm{Mg\,ha^{-1}}$). Marketable fruit weight (Fig. 2e) was affected only by Y ranging between 0.16 ± 0.004 kg in 2019 and 0.19 ± 0.006 kg in 2020.

SMN content during tomato ripening (July) was not affected by any factor. There were no differences between treatments both in 2019 (68.89 ± 7.57 and 67.75 ± 9.89 $\mathrm{kg\ N\,ha^{-1}}$ in S and

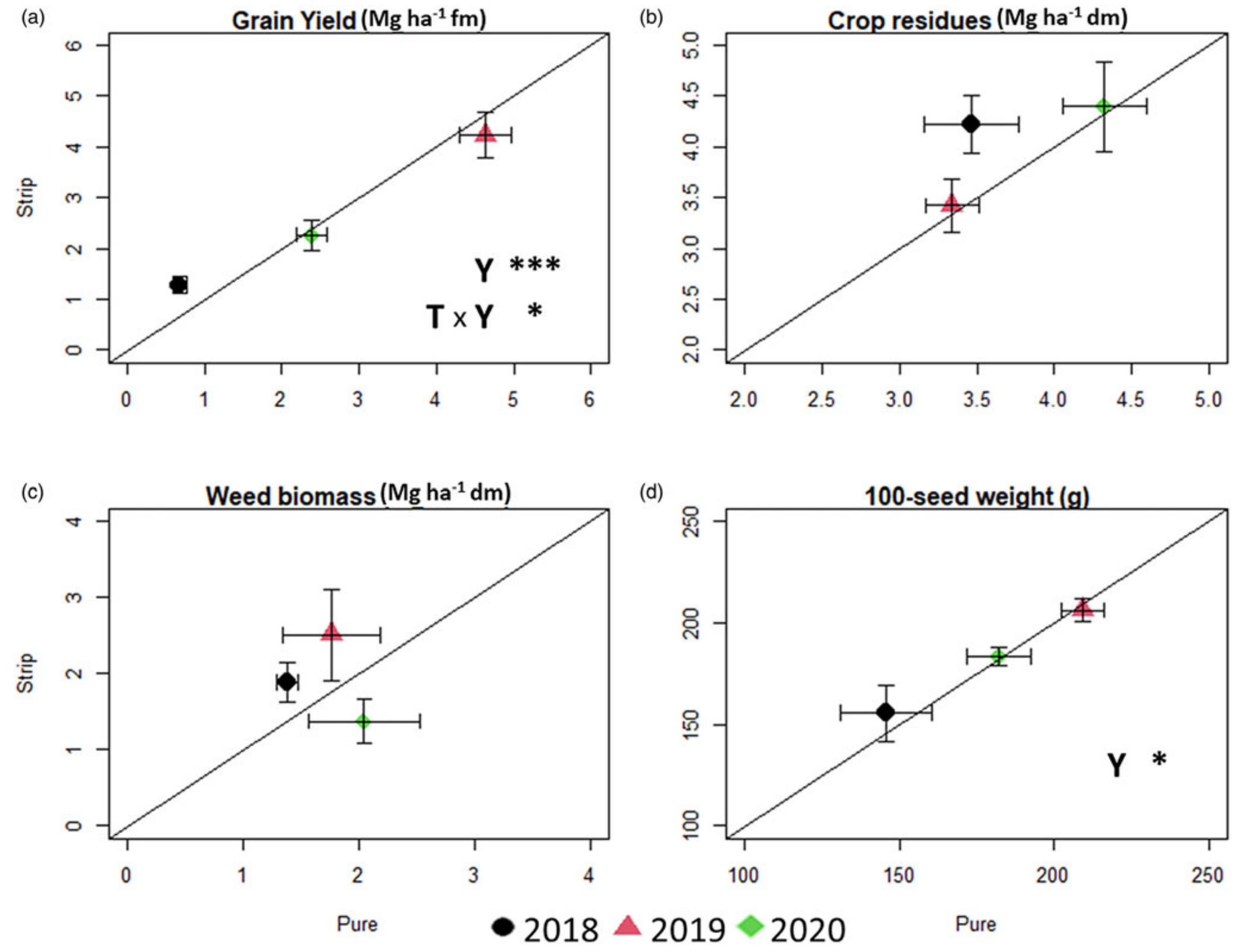

Figure 1. Mean annual treatment values of the tested variables (a–d) of the sub-experiment faba bean for dry grain in strip (*y*-axis) *vs* faba bean for dry grain in pure stand (in the *x*-axis). Vertical bars are the standard errors for the strip and the horizontal bars for the pure stand. Lines ($x = y$) in the graphs represent the performance boundary where observations in strip equal to those in pure treatment. Factors (treatment—T, year—Y) of the ANOVA models with significant *P* values of the *F* tests (*significant at $P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$) are reported for each response variable.

P, respectively) and 2020 (89.59 ± 14.74 and 80.00 ± 8.66 kg N ha^{-1} in S in P, respectively).

In the multi-year comparison of fusarium disease in S *vs* P, the clustered Wilcoxon rank-sum tests across all years showed no differences between the treatments for all variables ($P = 0.3792$ for incidence, 0.3855 for severity and 0.453 for the infection index). Disease incidence (Fig. 3a) was lower for S than for P in 15 out of 27 paired observations by −13%. On average, S resulted in no difference, compared to P by −3% (66.18% in S and 68.29% in P). The severity (Fig. 3b) was lower (−4%) for S than for P in only five out of 27 paired observations, showing a trend toward a greater value of +11% for the S treatment (1.61 for S *vs* 1.45 for P). The infection index incidence (Fig. 3c) was lower (by −16%) for S than for P in eight paired observations but only a trend toward greater infection of +9% for S treatment compared to P (26.8 for S *vs* 24.6 for P).

Total LER calculated for yield in the faba bean–tomato system (Table 1) was above 1 only in 2018, showing an annual average of 1.27 even if with a high inter-annual variability (CV = 48%). Similarly, total LER calculated for N uptake of yield was >1 in 2 out of 3 years, ranging between 0.85 in 2019 and 2.02 in 2018. Total LER calculated for N uptake of crop aboveground biomass and for the amount of C input left on soil resulted in >1 in all the experimental years with an annual mean of 1.25 (CV = 20%) and 1.20 (CV = 4%), respectively. The two crops did not show any pattern of competition, except for the N uptake of aboveground biomass where the value of N-ABG-CR of tomato was >1 in all the experimental years, with a mean of 1.22 and CV = 13%.

Although the faba bean–tomato S system showed the costs greater by 3% compared to the pure, its average resulted greater mean annual gross margin than P by about +21% (€40,376 *vs* €33,270 ha^{-1}). Furthermore, P presented a greater GM variability across the experimental years (Supplementary Table S4) compared to S (CV = 70% in P and CV = 38% in S).

Wheat–zucchini experiment

The crop yield of the wheat dry grain sub-experiment was affected by T and the Y (Fig. 4a), with an annual mean value of 2.76 ± 0.65 Mg ha^{-1} in 2020 and 3.54 ± 0.83 Mg ha^{-1} in 2019, and a lower mean value of −18% in S compared to P (2.81 ± 0.54 and 3.41 ± 0.66 Mg ha^{-1} in S and P, respectively). Crop aboveground

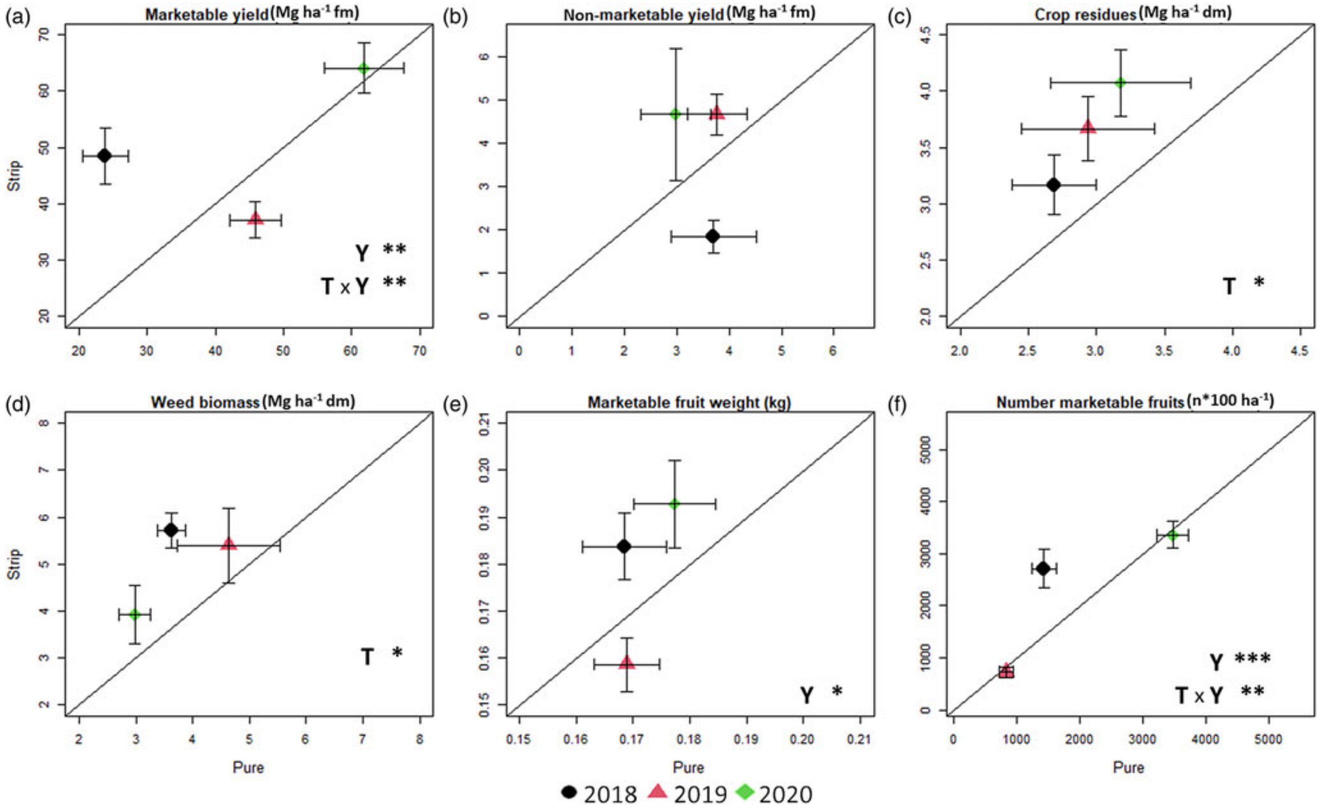

Figure 2. Mean annual treatment values of the tested variables (a–f) of the sub-experiment tomato in strip (*y*-axis) *vs* tomato in pure stand (in the *x*-axis). Vertical bars are the standard errors for the strip and the horizontal bars for the pure stand. Lines ($x = y$) in the graphs represent the performance boundary where observations in strip equal to those in pure treatment. Factors (treatment—T, year—Y) of the ANOVA models with significant *P* values of the *F* tests (*significant at $P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$) are reported for each response variable.

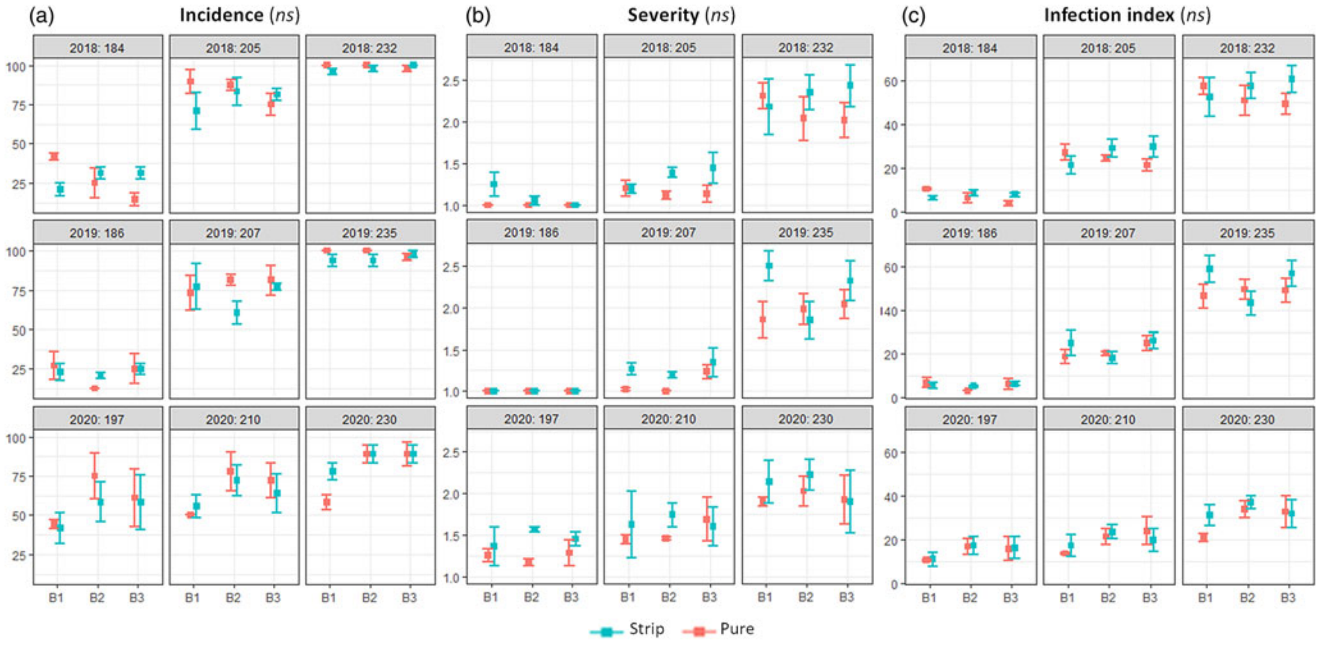

Figure 3. Incidence (a), severity (b) and infection index (c) of fusarium on tomato in strip compared to the pure treatment for each observation date (reported in Julian day) across all experiment years (2018–2020). Data are paired by cluster (observation date and experiment block—B1, B2, B3). Points in the graphs show mean values with bars indicating standard errors. *ns*: non-significant *P* values ($P > 0.05$) resulting from Wilcoxon rank test.

Table 1. Partial and total land equivalent ratio (LER) and competitive ratio (CR) of faba bean for dry grains–tomato experiment calculated for crop yields, nitrogen uptake of crop aboveground biomasses (N-ABG), nitrogen uptake of crop yields (N) and the amount of carbon input (C) coming from crop residues, not-marketable yield and weed biomass during the three experimental years

		Partial LER faba bean	Partial LER tomato	Total LER	CR faba bean	CR tomato
Yield	2018	0.79	1.18	1.97	0.93	1.08
	2019	0.38	0.47	0.85	1.13	0.89
	2020	0.40	0.60	1.00	0.91	1.09
	CV	44%	50%	48%	12%	11%
N-ABG	2018	0.57	0.96	1.53	0.82	1.23
	2019	0.42	0.62	1.04	0.95	1.06
	2020	0.40	0.77	1.18	0.72	1.39
	CV	19%	22%	20%	14%	13%
N	2018	0.78	1.25	2.02	0.86	1.16
	2019	0.39	0.47	0.85	1.15	0.87
	2020	0.37	0.68	1.05	0.76	1.32
	CV	45%	50%	48%	22%	20%
C	2018	0.56	0.68	1.25	1.14	0.88
	2019	0.45	0.76	1.21	0.81	1.23
	2020	0.39	0.76	1.15	0.71	1.41
	CV	19%	6%	4%	25%	23%

CV, coefficient of variation (%).

residues (Fig. 4b) were significantly affected only by the year, showing high interannual variability with a minimum annual mean value in 2018 (9.45 ± 0.45 Mg ha^{-1}) and a maximum in 2019 (16.40 ± 1.53 Mg ha^{-1}). There was a significant T × Y interaction with weed biomass (Fig. 4c) ranging from 0.08 ± 0.03 Mg ha^{-1} (S in 2020) to 0.39 ± 0.14 Mg ha^{-1} (S in 2019) with a mean of 0.18 ± 0.03 Mg ha^{-1}. The Y was significant for seed weights (Fig. 4d), and hectoliter weights (Fig. 4e), with a mean of 43.3 ± 0.5 g, 74.2 ± 0.3 kg hl^{-1}, respectively. Gluten percentage in dry matter (Fig. 4f) was not affected by any factor with a mean annual value of 10.73 ± 0.21%.

In the zucchini sub-experiment, S resulted in greater marketable yields (Fig. 5a) than P by about +54% (22.85 ± 1.47 *vs* 14.83 ± 0.87 Mg ha^{-1}) and annual mean yields ranged from 15.54 ± 1.09 Mg ha^{-1} in 2019 to 23.46 ± 1.59 Mg ha^{-1} in 2018. Conversely, no differences in moisture content of fresh zucchini were observed between treatments (95.24 ± 0.09 and 95.30 ± 0.11% in P and S, respectively). Non-marketable yield (Fig. 5b) was affected by T and the T × Y interaction ranging from 0.0 Mg ha^{-1} (S 2018) to 0.96 ± 0.3 Mg ha^{-1} (P 2020) with a lower mean annual value by −67% in S compared to P. On average, S crop residues (Fig. 5c) were greater by 63% than P (0.70 ± 0.06 *vs* 0.43 ± 0.04 Mg ha^{-1}), while weed biomass (Fig. 5d) was only affected by Y ranging between 1.25 ± 0.11 Mg ha^{-1} in 2018 and 5.47 ± 0.42 Mg ha^{-1} in 2020. The marketable fruit weight (Fig. 5e) was influenced by T and Y with a greater mean value by 11% in S compared to P (0.20 ± 0.04 *vs* 0.18 ± 0.04 kg). Treatment affected the number of marketable fruits (Fig. 6f). On average, S resulted in greater marketable fruit numbers than P by about +44% (102,822 ± 6623 *vs* 71,247 ± 3117 n ha^{-1}).

The Y ($P = 0.0057$) and T × Y ($P = 0.0119$) interaction of the SMN content were significant for the zucchini sub-experiment. Data showed a difference between the treatments only in 2020 (11.27 ± 1.59 and 18.35 ± 1.68 kg N ha^{-1} for S and P, respectively), while no differences were found in 2019 (36.6 ± 8.16 and 27.48 ± 3.54 kg N ha^{-1} for S and P, respectively).

In the multi-year comparison of oidium disease on tomato in S *vs* P stands (Fig. 6), the clustered Wilcoxon rank-sum tests across all years showed no differences between the treatments for all variables ($P = 0.9424$, 0.7778 and 0.9534 for incidence, severity and infection index, respectively). The disease incidence (Fig. 6a) was lower for S than for P in only three out of 18 paired observations, showing a similar mean value in S (33.60%) and in P (33.61%). The severity (Fig. 6b) was lower (by −29%) for S than for P in seven out of 18 paired observations, showing a trend toward a lower value of −13% for the S treatment (0.57 for S *vs* 0.64 for P). The infection incidence (Fig. 6c) was also lower (by −32%) for S than for P in seven paired observations, with no differences (11.0 for S *vs* 12.3 for P).

Total LER calculated for yield in the wheat–zucchini experiment (Table 2) was above 1 in all the experimental years showing a mean annual value of 1.25 (CV = 8%). Likewise, total LER calculated for N uptake both of yield and crop aboveground biomass also resulted in >1 in all the experimental years with an annual mean of 1.26 (CV = 9%) and 1.29 (CV = 12%), respectively. Total LER calculated C input was less than 1 in all 3 years (mean value of 0.91, CV = 0.2%). CR values (Table 2) showed that zucchini was more competitive than wheat in the intercropping system except for the amount of C input where the value of C-CR of wheat was >1 in 2 out of 3 years.

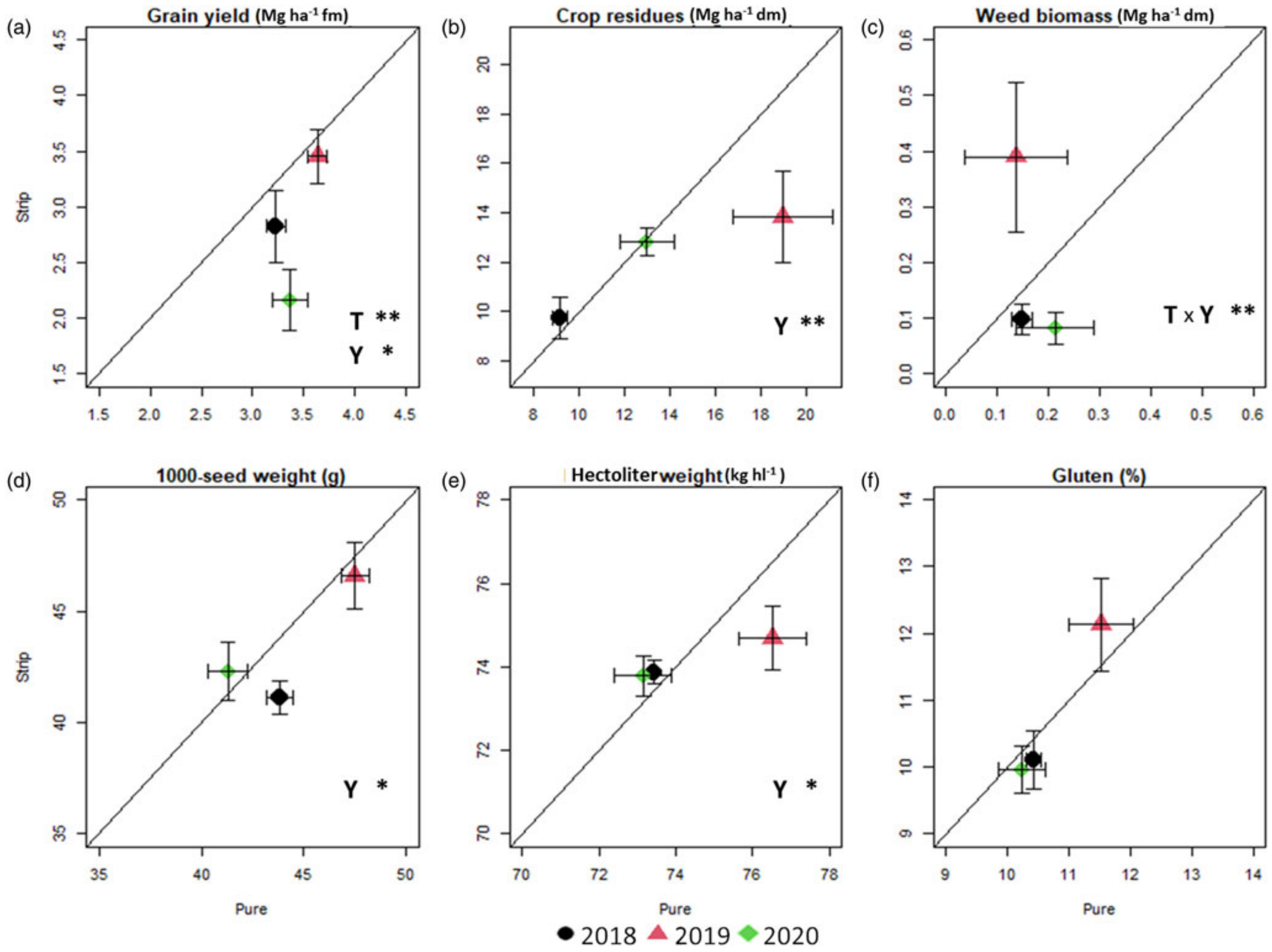

Figure 4. Mean annual treatment values of the tested variables (a–f) of the sub-experiment wheat for dry grain in strip (*y*-axis) *vs* wheat for dry grain in pure stand (in the *x*-axis). Vertical bars are the standard errors for the strip and the horizontal bars for the pure stand. Lines ($x = y$) in the graphs represent the performance boundary where observations in strip equal to those in pure treatment. Factors (treatment—T, year—Y) of the ANOVA models with significant *P* values of the *F* tests (*significant at $P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$) are reported for each response variable.

Despite the greater production costs (4%), the wheat–zucchini S system resulted in greater mean annual gross margins than P (€11,193 *vs* €2673 ha^{-1}, Supplementary Table S4) and greater GM stability (CV = 55% in S and CV = 149% in P).

Discussion

Crop yield

The diversified rotation of the MOVE-LTE, the use of cover crops and long-standing agroecological environment parameters, which characterized our experiments, are resilient and positively influenced crop performances. In the faba bean–tomato experiment, the yield of the two crops, seed/fruit weight and fruit number were more affected by inter-annual variability than by the strip treatment. El-Gaid *et al.* (2014) observed no interspecific competition when tomato was intercropped with common bean, while Ramkat *et al.* (2008) reported a beneficial effect with species other than faba bean. Other studies showed that faba bean is less competitive when intercropped with vegetable crop species increasing, or no change, the yields of the associated crops such as carrot, cabbage and oil crops (Schröder and Köpke, 2012; Lepse *et al.*, 2017). Our study confirms both yield and total LER benefits from intercropping only in 2018. In this year, a severe frost and a snowfall event at the beginning of February damaged the faba bean plants. Subsequently, when the temperatures increased, some pathogens (in particular *Ascochyta fabae* and *Botrytis fabae*) infected the already damaged plant tissues, thus reducing crop yields both in S and P. In any case, a greater yield in the S treatment occurred in this experimental year, since the diseases which infected faba bean tissues damaged by snow and frost events may have been reduced in the S cropping system, through protection from the tomato crop, leading to greater production than the P. At the same time, the tomatoes in S may have indirectly benefited from reduced inter-specific competition, thus showing a greater yield than the P system. Our results suggest a greater resilience of S than P in adverse weather and under biotic stress conditions. In agreement with Mead and Willey (1980), a more general evaluation of the effect of intercropping systems on crop performances and yield is needed, and a long period of observations of interannual variability and annual differences should be taken into account.

In our systems, the N soil availability was not limited due to the nitrogen-fixation of the legume crops in the rotation,

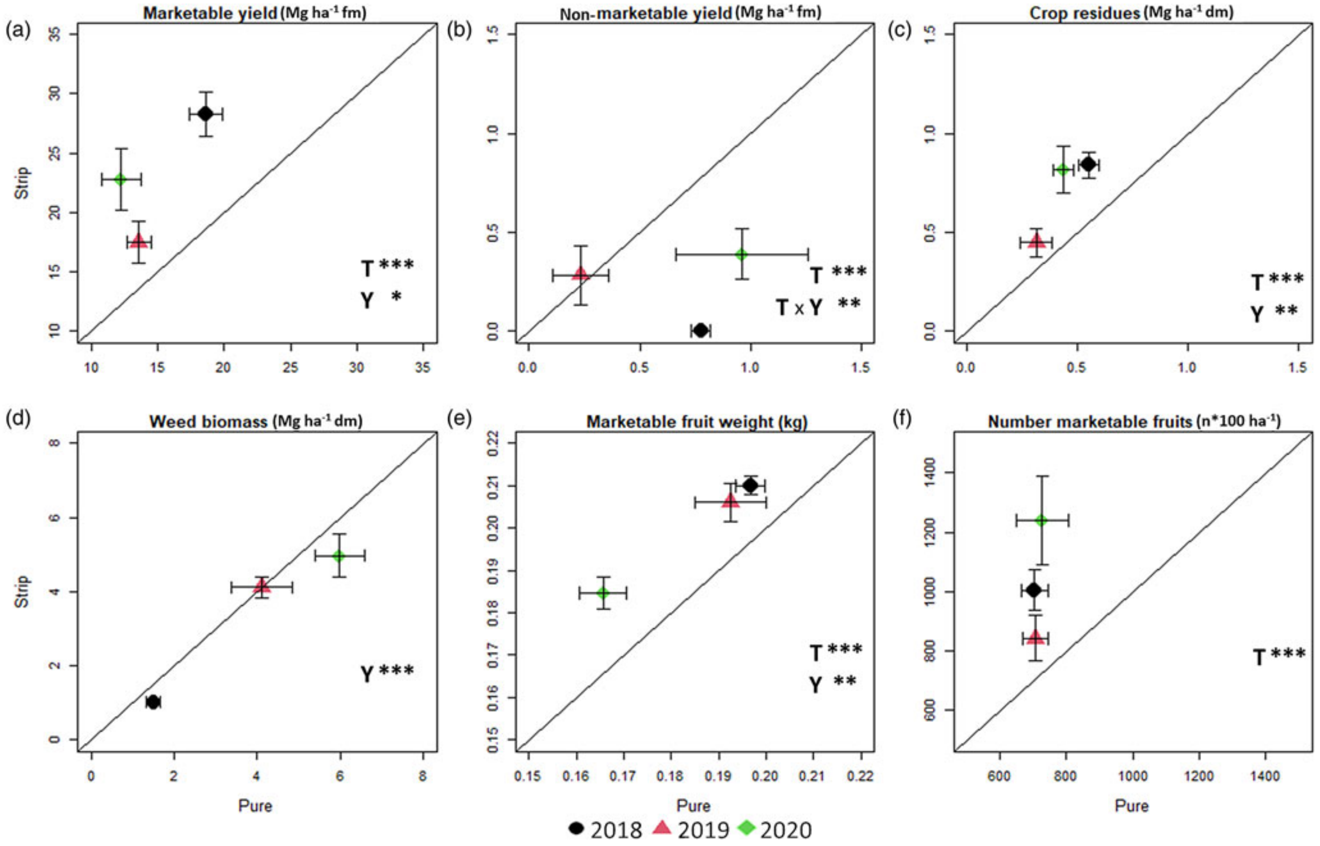

Figure 5. Mean annual treatment values of the tested variables (a–f) of the sub-experiment zucchini in strip (*y*-axis) *vs* zucchini in pure stand (in the *x*-axis). Vertical bars are the standard errors for the strip and the horizontal bars for the pure stand. Lines ($x = y$) in the graphs represent the performance boundary where observations in strip equal to those in pure treatment. Factors (treatment—T, year—Y) of the ANOVA models with significant *P* values of the *F* tests (*significant at $P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$) are reported for each response variable.

mineralization of the flatted legume crop residues and inputs from organic fertilization. However, a temporal competition among the two crops for N use is expected, even when N is not a limiting resource. In general, the faba bean–tomato system determined a nutritional advantage in the S arrangement compared to P ones with a greater total N uptake. In particular, this is due to the aboveground crop biomasses (N-ABG-LER > 1 in all the experimental years) and a greater competitive ability of tomato in the use of the resource (N-ABG-CR > 1), even if in presence of a greater tomato crop residues in S than in P. The aboveground interactions are considered very important for plant growth (Keating and Carberry, 1993; Zhang *et al.*, 2008; Zhu *et al.*, 2015) and, due to competition for light, they affect the intercropping systems. In our study, the faba bean in S may have influenced the growth of the tomato plants leading to a greater crop residues. In fact, the intercropping crops, characterized both by the non-synchronous patterns of canopy development and life cycles, can result in a greater development of leaf area during the growing season and intercept more total light energy in S than in P treatment, allowing greater biomass production (Trenbath, 1986). However, the different tomato shape and biomass in S did not affect yields and quality, as well as the non-marketable yield, which was also unaffected by treatment. Other aspects not explored in this work could be investigated in further studies to understand the greater availability of other nutrients (phosphorus and Fe) mobilized by faba bean root exudates (Li *et al.*, 2014; Brooker *et al.*, 2015).

In the wheat–zucchini experiment, the crops in S took more N in all the experimental years (N-ABG-LER and N-LER > 1) and therefore they utilized resources (nutrient, water, light) better than the P, since the LER always was >1. The benefits in yield occur when crops of a intercropping system compete only partly for the same resources, and the inter-specific competition is less than intra-specific (Vandermeer, 1989). Wang *et al.* (2009) observed that wheat as an intercrop promoted cucumber growth and yield. Few studies were carried out with wheat as an intercrop in vegetable systems (Aziz *et al.*, 2015), and this is the first time that these items are investigated both in a well-diversified organic vegetable system and in Mediterranean environment. In our experiment of zucchini, marketable and non-marketable yields, fruit weight and number and plant residues were strongly influenced by wheat as an S crop. Generally, zucchini yield seems to be increased through the decline of wheat production. This effect is also known as compensation (Willey, 1979) with the two crops referred as dominant and dominated species. However, wheat yield reduction in S was also due to lodging problems observed in field and caused by storm events especially during the earing stage (May) throughout the three experimental years (Supplementary Fig. S1). These problems could be reduced during the operational farms by increasing the strip width and/or using cultivars with lower stem height.

Peet (1999) suggested providing as much light as possible to zucchini, since it is a plant rarely saturated at the bottom of the canopy. In our study, the shading effect of wheat did not seem to have influenced the capacity of the zucchini to use intercepted

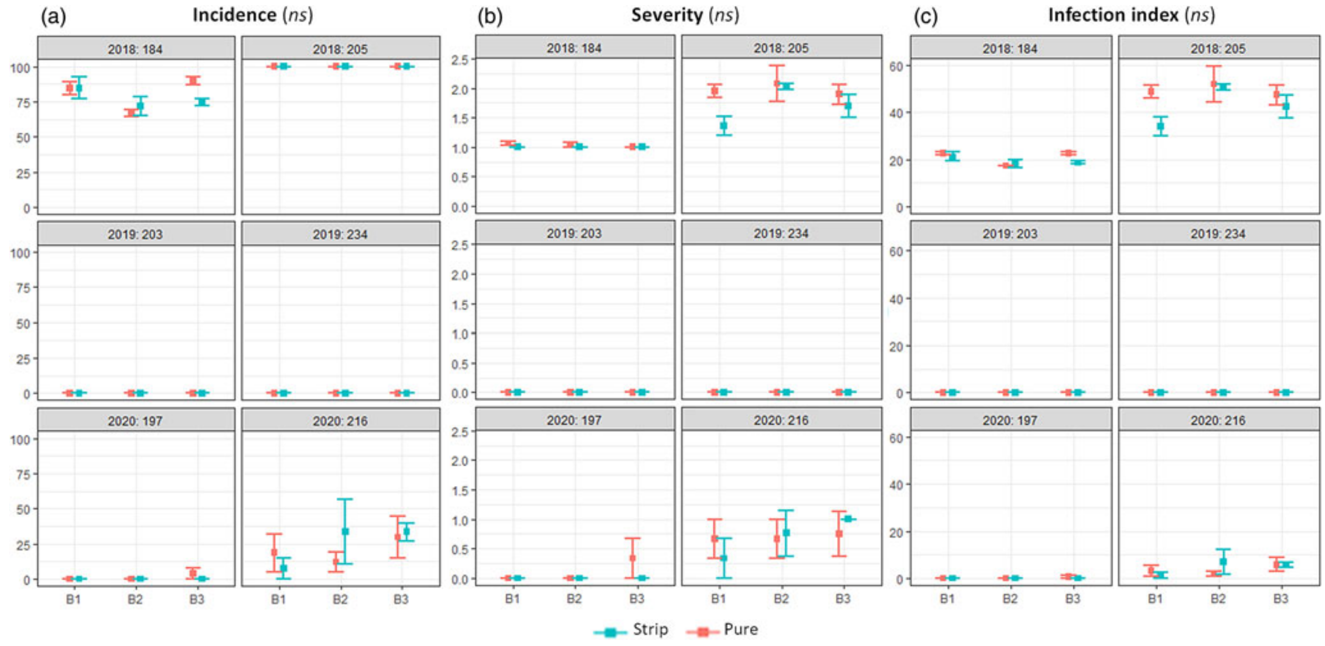

Figure 6. Incidence (a), severity (b) and infection index (c) of oidium on zucchini in strip compared to the pure treatment for each observation date (reported in Julian day) across all experiment years (2018–2020). Data are paired by cluster (observation date and experiment block—B1, B2, B3). Points in the graphs show mean values with bars indicating standard errors. *ns*: non-significant *P* values ($P > 0.05$) resulting from Wilcoxon rank test.

solar energy. Therefore, other factors should be investigated in further studies including wheat altering the microclimate within the canopy of the sheltered crop by modifying temperature and reducing air movement, which leads to less evaporation and more relative humidity compared to the open sites (Farrell and Altieri, 1995).

The main difficulties experienced in S systems management were related to the lack of proper mechanical equipment adequate to operate in the narrow spaces created for the strips. For this reason, some operations were performed manually, thus increasing the costs of the strip cropping systems in both experiments. However, this did not affect the profitability due to greater

Table 2. Partial and total land equivalent ratio (LER) and competitive ratio (CR) of wheat for dry grain–zucchini experiment calculated for crop yields, nitrogen uptake of crop aboveground biomasses (N-ABG), nitrogen uptake of crop yields (N) and the amount of carbon input (C) coming from crop residues, waste yield and weed biomass during the three experimental years

		Partial LER wheat	Partial LER zucchini	Total LER	CR wheat	CR zucchini
Yield	2018	0.37	0.88	1.25	0.58	1.73
	2019	0.40	0.75	1.15	0.74	1.35
	2020	0.27	1.08	1.35	0.35	2.89
	CV	19%	19%	8%	36%	40%
N-ABG	2018	0.42	0.88	1.30	0.66	1.51
	2019	0.35	0.77	1.12	0.63	1.58
	2020	0.40	1.04	1.44	0.53	1.90
	CV	9%	15%	12%	12%	12%
N	2018	0.44	0.92	1.36	0.66	1.52
	2019	0.39	0.74	1.13	0.74	1.36
	2020	0.28	1.00	1.28	0.39	2.59
	CV	22%	15%	9%	31%	37%
C	2018	0.44	0.46	0.91	1.31	0.76
	2019	0.32	0.58	0.90	0.76	1.32
	2020	0.41	0.50	0.91	1.13	0.89
	CV	16%	12%	0.2%	27%	30%

CV, coefficient of variation (%).

production and more stable performances in the strip systems. According to Mead and Willey (1980), intercropping systems generally not only guarantee greater yields compared to pure stands but they appear to be more stable over time, thus resulting in a reduction of economic risk. This aspect is fully confirmed both by our experiments characterized by a greater and more stable gross margin in S compared to P during the three experimental years.

Disease and weed control

Fusarium and oidium are two of the most common diseases both in the experimental site and in the Mediterranean area (Panno *et al.*, 2021). Specifically, there is an important source of inoculum for fusarium in the soil experiment. In fact, since it is a soil-borne pathogen, the fusarium can survive in the soil as chlamydospores for long periods (Hassan, 2020). Moreover, the tomato variety used in the experiment, as well as the most important genotypes cultivated in this area, is lack of any resistance to this adversity. Panno *et al.* (2021) reported that yield losses due to fusarium can reach to 45–55% and extend up to 70% in case of favorable conditions with high temperatures and humidity. The mechanisms by which intercrops can impact these diseases are related to several factors including host plant density reduction, and microclimate modification, which modifies pathogen dispersal by rain, wind and vectors and its establishment. According to Boudreau (2013), the disease incidence reduction in intercrops, commonly in a range of less than 30–40%, primarily due to foliar fungi, was documented in 73% of more than 200 studies.

In our study, this effect was not recorded both for fusarium and oidium. In particular, for oidium, a possible explanation may lie in the fact that incidence and severity were very low during the experimental years (in 2019 oidium was absent). This result is in agreement with other studies, which reported no disease reduction in intercrops at low disease levels (Naudin *et al.*, 2009; Schoeny *et al.*, 2010). For fusarium, the large amount of inoculum present in the soil and the non-resistant tomato variety used generated a high incidence and severity of the disease at the end of the production cycles both in S and P. The S faba bean–tomato system did not modify the microclimatic conditions as optimally for the development of this disease.

In our study characterized both by a diversified system and presence of rolled cover crops that help to suppress weeds (Navarro-Miró, 2019), the strip cropping did not affect weed biomass growth, except in the tomato sub-experiment where weed biomass was greater in S than P. This is due to the designed strips, which were narrow shaped to maximize the spatial diversification of the system. Therefore, the proximity of tomato to a N-fixing crop (i.e., faba bean) would have increased the soil N supply in favor of weeds and tomato residues, even if there were no significant changes in SMN content between S and P. Moreover, a possible lower inter- than intra-specific competition (tomato–faba bean *vs* tomato–tomato) for resources would have increased the growth of the tomato system, including weeds.

Carbon input contribution

If the crops of an intercropping system are properly chosen, the interspecific complementarities in shoot architecture and the different crop duration cycles can improve radiation capture over time, allowing the production of greater plant biomasses compared to the P stands (Trenbath, 1986; Bedoussac and Justes, 2010).

This can also allow an increase of soil organic carbon, which is strictly related to the amount of C soil inputs provided when crop residues are not removed from the field. Indeed, although there are different factors related to crop residues influencing C accumulation and regulating mineralization and humification processes (mainly C/N ratio of residues and their placement in the soil), the crop residues left in the soil have long been identified as the most ecological and economic way of conserving soil (Datta *et al.*, 2019). In our study, the effectiveness of carbon return to the soil in the faba bean–tomato S system was greater than the P stands, as the C-LER was >1 in all years. This higher contribution to soil C was probably due to the tomato crop greater residues and weed development in S than in P. Despite the higher zucchini residues in S, the wheat–zucchini strip system had lower productivity than in P (C-LER always <1) (Table 2). This result is due to the low zucchini crop residues compared to wheat ones, which tend to be greater in pure stands.

Conclusions

The overall outcomes of our study pointed out that, through well-designed strip cropping spatial arrangements, the farmers can increase sustainability of a diversified organic cropping system due to the more effective use of resources on the same land, a greater potential C-sink and reduction of economic risk. Particularly, our researches both on faba bean–tomato and wheat–zucchini systems have pointed out that strip cropping in an already well-diversified system can lead to environmental and economic advantages. The temporal differentiation that characterizes crop components of the two strip cropping systems allows a better use of resources on the same land, which results in an increase of plant biomass. This greater biomass does not always translate into an increase in yields. While the wheat–zucchini strip system had an LER > 1 in all three experimental years with strong dominance of the zucchini (+54% of marketable yield), the faba bean–tomato system was more productive in strips only under adverse weather conditions. The long and diversified rotation of the system has also led to adequate disease control, with no differences between the treatments. A disadvantage from the introduction of strips was greater inputs. However, these greater costs did not affect the profitability of the strip cropping systems (+21 and +319% in faba bean–tomato and wheat–zucchini, respectively) due to a greater production obtained for more income-generating vegetable crops in most of the assessed years.

Our findings confirm that large-scale implementation of organically managed and diversified cropping systems based on rotations, multicropping and intercropping, including strip-cropping, represent an effective strategy to meet the challenges of environmental and economic food production, thus supporting the ambitions of the Farm to Fork and the Green Deal strategies under the current EU legislative framework for agri-food system.

Further studies are however necessary for deeper investigation of competition mechanisms among the strip-intercrop components of the systems to better understand the influence of factors underpinning the system performances and, accordingly, to fine tune strip cropping design.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170523000248.

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Competing interest. None.

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