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RESEARCH ARTICLE

Yield gap analysis extended to marketable grain reveals the profitability of organic lentil-spring wheat intercrops

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Abstract

Lentil has been overlooked by organic farmers in Europe mainly because of low and unstable yields, notably due to lodging and bruchid beetles. Our study aimed to evaluate the efficiency of lentil-spring wheat intercrops to lower these reducing factors and increase yield and gross margin. A 2-year field experiment was carried out in southwestern France in 2015 and 2016 under organic farming rules. Four lentil and two wheat cultivars were grown as sole crops and intercrops. The "yield gap" concept was adapted to include grain losses due to mechanical harvest and insufficient quality. Mean total intercrop grain yield before mechanical harvest was higher than mean sole crop (1.91 ± 0.47 vs. 1.57 ± 0.29 t ha^{-1}, respectively), with a lower mean yield of lentil in intercrop than in sole crop (1.06 ± 0.28 vs. 1.61 ± 0.54 t ha^{-1}). This led to a lower mean gross margin of intercrop than that of sole cropped lentil (1772 ± 507 vs. 2371 ± 756 € ha^{-1}), before mechanical harvest. The percentage of bruchid-damaged grain did not differ significantly between intercrop and sole crop (41%). However, lentil lodging was lower in intercrop than in sole crop (15 vs. 40%), which strongly increased lentil mechanical harvest efficiency (75 vs. 50%). This led to a similar mechanically harvested yield of lentil in intercrop and sole crop (0.80 t ha^{-1}). Consequently, mean marketable gross margin of intercrops was higher than that of sole cropped lentil (949 ± 404 vs. 688 ± 393 € ha^{-1}), due to the addition of marketable wheat yield. We thus demonstrated for the first time the interest of extending the yield gap concept to consider all grain losses that influence profitability, including those linked to mechanical harvest efficiency and insufficient grain quality. Furthermore, this is a first demonstration of the higher profitability of organic lentil-wheat intercrops compared to sole crops despite the additional costs associated with grain sorting.

Keywords Lodging · Bruchid · Harvest efficiency · Gross margin

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1 Introduction

Grain legumes are among the most common crop species in human diets worldwide (Erskine et al. 2011; Stefaniak and McPhee 2015). Lentil (*Lens culinaris* Med.) is a popular legume and an important source of protein in many countries in Asia and Africa, but not in Europe, where lentil consumption remains low despite recent increasing trends. Lentil is grown mainly in North America, southern and western Asia, and North Africa (Erskine et al. 2016; Ghanem et al. 2015). Consequently, Europe imports a large percentage of the lentils its population consumes, which creates an opportunity for European producers, particularly organic producers, and for the development of agroecology and organic agriculture, which are forces driving the promotion of grain legumes (Erskine et al. 2016).

Lentil, a member of the *Fabaceae* family, can meet as a crop much (up to 80%) of its nitrogen (N) requirements through biological N_2 fixation, due to a symbiotic relationship between its roots and rhizobacteria (Reda 2015). This ability is particularly interesting in low N systems such as organic farming, in which N is often a limiting factor due to the prohibition of mineral fertilisers and the cost of organic ones. Introducing legumes into crop rotations is one way to increase sustainability, by increasing biodiversity, soil N fertility, and pest management at the cropping system level (Meynard et al. 2013; Voisin et al. 2013). Despite these potential advantages, grain legumes represented less than 2% of arable crop area in the European Union in 2014, of which lentil represented only 4.9% of the area dedicated to pulses (FAOSTAT 2014). Farmers' reluctance to grow lentil can be explained in part by its low and unstable yields under European conditions. Intercropping is the simultaneous growth of two or more species in the same field for a significant period but without necessarily sowing or harvesting at the same time (Willey 1979). In the case of lentil-spring wheat intercrops, both species reach maturity at roughly the same time and are mechanically harvested together. Lentil grains are then separated from wheat grains using successive separating and cleaning tools such as vibratory, rotary, gravity and optical sorters. Like other legume-cereal intercrops, intercrops of lentil and wheat may be an interesting way to increase lentil production, as they have been shown to increase total yield (Akter et al. 2004; Carr et al. 1995) and gross margin (Akter et al. 2004).

Among challenges to lentil production, bruchid beetles (Coleoptera: Bruchidae) may decrease grain yields greatly, particularly in organic farming. Grain damaged by bruchids is not marketable and represents net yield and income losses for farmers that can exceed 50% (Laserna-Ruiz et al. 2012), especially in organic farming. In Europe, two established bruchid species (*Bruchus lentis* and *Bruchus signaticornis*) may cause great damage to lentil (Delobel 2005; Yus-Ramos et al. 2014). Adults lay eggs on the surface of developing pods, and larvae then penetrate the pod and feed on the growing lentil grain. These two species can damage lentil only in the field, as they are univoltine and do not lay eggs on stored grain (Yus-Ramos et al. 2014). No effective biocontrol method is currently available in the field for organic farmers, which hinders development of lentil in areas where bruchid damage is high. Meanwhile, to our knowledge, the potential of lentil-spring wheat intercrops to reduce the percentage of bruchid-damaged grains has never been studied, which is of particular interest for low-input systems without chemical control. Plant diversity can promote pest regulation through a phenomenon called "associational resistance" (Tahvanainen and Root 1972; Risch et al. 1983; Letourneau et al. 2011). Associational resistance is considered to occur because of two main ecological mechanisms (Root 1973; Andow 1991; Barbosa et al. 2009): (1) resource concentration, a bottom-up perspective predicting that pests are more likely to find and remain on host plants that are concentrated, such as in dense or nearly pure stands, and (2) natural enemies, a top-down perspective based on a positive correlation between plant species richness and natural enemy abundance. In lentil-spring wheat intercrops, we hypothesise that the spring wheat creates visual or olfactory confusion, decreasing the ability of bruchids to find pods for oviposition, thus reducing grain damage and financial loss (Kinane and Lyngkjaer 2003). This hypothesis does not exclude the potential control of pests by natural enemies.

Lodging is another common issue for lentil which results from a combination of genotypic and environmental factors (Ball et al. 2006). Lentil shoots collapse if unfavourable weather (e.g. rain and wind) occurs before harvest (Sidahmed and Jaber 2004). Impacts of lodging on grain yields may be limited in southern and western Asia, where most lentil is harvested by hand. However, in areas where lentil harvest is mechanical, such as North America or Europe, when lentil lodges, combine harvesters may fail to pick up plants leaning too much toward the ground, leading to large grain loss in the field, sometimes up to 100% (Carr et al. 1995). Even in countries were lentil is traditionally harvested by hand, mechanisation is gradually taking over because of increasing scarcity and costs of human labour (Erskine et al. 2016; Reda 2015), making them susceptible to reduced yields from lodging. Factors besides lodging influencing grain loss during mechanical harvest are numerous, such as weather conditions, field topography, ground roughness, management practices, crop maturity, type of combine harvester used and its settings and height of cut (Erskine and Goodrich 1988; Ibrahim et al. 1993). Erskine and Goodrich (1988) concluded that lentil should be as tall as possible at maturity for mechanical harvest to be efficient because more grain would be harvested. The presence of wheat shoots in intercrops may act as stakes, keeping lentil shoots relatively upright and high (Carr et al. 1995; Erskine et al. 1991; Sidahmed and Jaber 2004); in this way, intercropping could decrease grain loss due to lodging by increasing mechanical harvest efficiency (Fig. 1).

As increasing lentil production in Europe is desirable to lower importations and feed the increasing demand for organic products, it is important to provide information about agronomic issues and thus the economic feasibility of more sustainable agronomic solutions such as intercropping. Indeed, farmers are more likely to adopt new agricultural practices if they are economically promising or risk-limiting. In many studies, including several focusing on lodging and economic performance, lentil was hand-harvested. By not considering potential grain loss due to mechanical harvest, however, these studies may have overestimated yields, as mentioned by Wang et al. (2013), especially in areas where lentil would likely be mechanically harvested. Knowledge is lacking about effects of mechanical harvest with a combine harvester on sole cropped and intercropped lentil. In this study, our objective was to address three research questions: Do lentil-spring wheat intercrops have higher total

Fig. 1 Sole cropped lentil (left) and lentil-spring wheat intercrop at harvest (middle), and mechanical harvest of the intercrop (right). Orange marks on the ladders are spaced 10 cm apart. These pictures highlight that spring wheat in intercrops reduces lentil lodging at physiological maturity by maintaining plants relatively upright, allowing the combine harvester to pick up most shoots. Field pictures at harvest stage of sole cropped lentil, lentil-spring wheat intercrop and mechanical harvest of an intercrop

grain yield, mechanical harvest efficiency, and/or profitability than sole cropped lentil in organic farming? We thus developed an original approach to analyse the issues of lodging and bruchids in lentil, by adapting the "yield gap" concept developed by Evans (1994) and revised by Van Ittersum et al. (2013). Yield gap analysis identifies and quantifies "limiting" and "reducing" factors of a crop (Van Ittersum et al. 2013). In our adaptation, we added two downstream stages to estimate all grain losses down to the "marketable" yield.

2 Materials and methods

2.1 Improving the yield gap concept

The yield gap concept was adapted by adding two downstream stages to the established yield gap sequence to estimate all grain losses from "attainable" yield down to marketable yield, which is composed of only grain that can be conditioned and sold for human consumption (Fig. 2). Attainable yield is that obtained in the presence of limiting factors (e.g. water, N). "Actual" yield is the yield after the occurrence of biotic reducing factors and is estimated by hand-harvest, assuming that all grain produced in the field is collected. In this study, actual yield is composed of three distinct fractions: (1) sound, marketable grain, (2) bruchid-damaged, non-marketable grain, and (3) "small grain", non-marketable for human consumption. "Mechanically harvested" yield, which corresponds to actual yield minus grain loss in the field during mechanical harvest, is also composed of sound grain, bruchid-damaged grain and small grain. Finally, marketable yield corresponds to mechanically harvested yield minus grain discarded after the sorting process because it falls below quality and sanitary standards (i.e. small grain and bruchid-damaged grain in our study). Note that we hereafter call "sorting process" the combination of both the separation of grains from the two intercropped species (whenever relevant) and the cleaning process where all contaminants, debris and below-standard grain fractions are discarded. Separation and cleaning occur at the same time on the grain sorting chain.

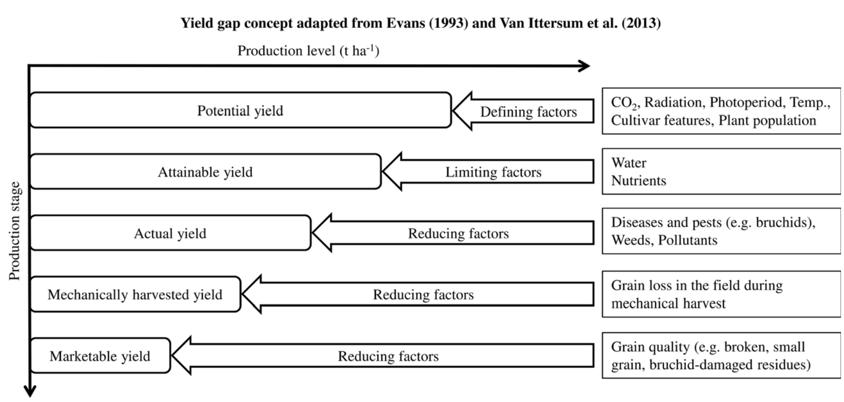


Fig. 2 Extension of the yield gap concept to the marketable yield. Agronomic production is influenced by growth-defining, limiting and reducing factors. Attainable yield is that obtained in the presence of limiting factors. Actual yield is that obtained after the occurrence of biotic reducing factors and when a crop is hand-harvested. Two subsequent production stages were added: (1) mechanically harvested yield, which equals actual yield minus a reducing factor due to loss in the field during mechanical harvest, and (2) marketable yield, which is composed of only human-edible grain and corresponds to mechanically harvested yield minus a reducing factor due to discarding grain that falls below quality and sanitary standards

2.2 Site, soil and climate

A 2-year field experiment was carried out at the Institut National de la Recherche Agronomique station in Auzeville—southwestern France, 43°31′ N, 1°30′ E—in 2015 and 2016. In 2015, soil was sandy clay loam (25% clay, 23% silt and 52% sand) with total soil water content at sowing of 294 mm (0–120 cm soil depth). In 2016, soil was loam (30% clay, 30% silt and 40% sand) with total soil water content at sowing of 286 mm (0–120 cm). Soil mineral N at sowing was low, with 31 and 20 kg N ha^{-1} in 2015 and 2016, respectively (0–120 cm). The sum of daily mean temperatures over the growing period was above the 20-year mean of the experimental site (3060 vs. 2901 °C day^{-1}, respectively, on a 0 °C basis) in 2015, but lower (2766 °C day) than it in 2016. Moreover, mean daily maximum temperature during a key lentil developmental period—from flowering to maturity—was higher in 2015 than in 2016 (29 vs. 26 °C, respectively). Total rainfall during the growing period was similar in both years (305 and 286 mm in 2015 and 2016, respectively) and similar to the 20-year mean (282 mm). Rainfall in 2015 had heterogeneous distribution, however, with 57% of that during the growing period concentrated in only two storm events (early May and mid-June), without any rain in between. These conditions may have led to water stress for plants from mid-May to mid-July. Conversely, rainfall in 2016 had homogenous distribution throughout the growing period, and we assumed that no water stress occurred.

2.3 Experimental design

The experiment was a randomised block design with three replicates. Four lentil cultivars (cv.)—Anicia, Beluga, Flora and Rosana, yielding green, black, yellow and red grains, respectively—and two spring wheat (*Triticum aestivum*) cultivars—Valbona and Togano—were each grown as (1) sole crops with an objective of 300 and 450 plants m^{-2} for lentil and wheat, respectively, and as (2) two-species intercrops—in eight cultivar pairs—in a partial additive design with a plant density ratio of 100% of sole cropped lentil:17% of sole cropped spring wheat. Spring wheat's low plant density in intercrop was chosen to limit its competition with lentil. Lentil was planted at 100% density to maximise its yield in intercrop and thus the intercrop's profit, given the much higher price of lentil compared to that of wheat. Crops were sown on 12 March 2015 and 23 March 2016. Each plot consisted of 10 rows, 10 m long in 2015 and 8 m long in 2016, spaced 16.5 cm apart. In intercrop plots, the two species were homogeneously mixed within each row to maximise the ability of wheat shoots to act as stakes. Mean plant density after emergence among all treatments reached 95% in 2015 and 101% in 2016 of the plant density objective. The experiment was conducted under organic farming rules; thus, neither synthetic pesticides nor chemical fertilisers were applied. Besides bruchids on lentil, no other significant yield-reducing biotic factors such as diseases or weeds were observed on any of the sole crops or intercrops.

2.4 Measurements, calculations and statistics

2.4.1 Actual yield measured by hand-harvest

To avoid edge effects, an area of 1.98 m^2 (2 m long, 0.99 m wide) of the six inner rows of each plot was hand-harvested at lentil maturity, around mid-July in both years. Spring wheat always reached maturity before lentil, but no wheat grain was lost despite the delay in harvest, due to its indehiscence. Lentil shoots were carefully hand-harvested to prevent pod opening and grain loss, and attached root fragments were discarded. Spring wheat was cut at ground level. Crops were threshed separately using a research-designed thresher (brand Roland Chateau du Loir, France) ensuring little grain damage or loss. Grain was then processed through an air separator to separate heavier sound grain from lighter grain (i.e. small grain and, for lentil, bruchid-damaged grain). Grain fractions were subsequently oven-dried for 48 h at 80 °C for dry weight determination.

2.4.2 Mechanical harvest efficiency measurement

To estimate lentil grain loss in the field during mechanical harvest using a combine harvester, an experiment was performed in 2016 with lentil cv. Anicia, both in sole crop and in intercrop with spring wheat cv. Valbona. It consisted of two identical lines of plots in which treatments were randomly placed and replicated three times, contiguous to those used previously to estimate the actual yield by hand-harvest. In one line, crops were hand-harvested following the same protocol as previously described, and in the other line, crops were mechanically harvested with a research-designed combine harvester as a prototype of classic combine harvesters (Fig. 1). The combine harvester cutter-bar was placed as low as mechanically possible—i.e. 5 cm above the ground—to simulate farming practice conditions. Machine settings—sieve size and fan speed—were first calibrated in additional dedicated lentil plots to maximise mechanical harvest efficiency. The area mechanically harvested by the combine harvester was measured for each plot (mean = 11 m^2). Grain dry weight was determined as for hand-harvested plots, except that grain from the combine harvester was already threshed and only had to be air-cleaned. Finally, mechanical harvest efficiency was calculated as a function of the fraction of sound grain.

2.4.3 Lentil height, stem length, lodging and lowest pod height at harvest

Lentil plant height (cm) at harvest was measured 1 day before harvest in each hand-harvested plot using a ruler placed vertically at six randomly chosen places in the six inner rows. Lentil stem length (cm) was defined as the distance from the collar to the top of slightly stretched-until-straight shoots. Each lentil plant sampled for estimating bruchid-damaged grain in 2016 was measured, and the lodging (%) was estimated as follows:

$$\text{Lodging} = \left(\frac{\text{Lentil stem length} - \text{Lentil height at harvest}}{\text{Lentil stem length}}\right) \times 100$$

Height of the lowest lentil pod was measured in 2016 for lentil cv. Anicia in sole crop and in intercrop with spring wheat cv. Valbona in each plot of the hand-harvested line of plots used to estimate mechanical harvest efficiency, on one plant—randomly chosen—every 10 cm over a 50-cm-long row segment. This operation was repeated three times per plot.

2.4.4 Estimation of bruchid-damaged grain rate, total grain loss due to bruchids and attainable yield

Evaluating grain loss due to bruchids by using insecticide-sprayed plots as a control was not considered an option for our experiment, since the plots were too small to prevent dispersal of bruchids from non-sprayed plots to sprayed plots, even with repeated spraying. Therefore, we estimated grain loss due to bruchids by measuring the percentage of damaged grains in each plot and the mean one-grain mass of bruchid-damaged grains. Twenty plants—five times four consecutive plants in the six inner rows—were collected from each hand-harvested plot. Plants from each plot were manually threshed, and the grain was immersed in a basin of water. Sound grain sinks to the bottom, while bruchid-damaged grain floats to the surface. The water was stirred to separate the grains completely. A sieve was used to collect floating grain and then submerged grain. Each grain that had floated was then pressed with a finger to confirm that it was bruchid-damaged, as bruchid-damaged grain cracks when pressed. Bruchid-damaged and sound grains were then dried and counted separately using a grain counter. This original method provided quick and accurate estimates of the bruchid damage rate for a large sample of grain and also the ability to detect bruchid-damaged grain from which adult insects had not yet emerged, something which cannot be done visually. Sound and bruchid-damaged grain from 16 plots in 2015 were oven-dried for 48 h at 80 °C to determine the one-grain weight for each lentil cultivar.

The total grain mass lost due to bruchids (t ha^{-1}) equalled the sum of (1) the mass of bruchid-damaged grain residues (measured) and (2) the mass of grain consumed by bruchids (unknown). It was estimated for each plot as follows:

$$\begin{aligned}&\text{Total grain mass lost due to bruchids}\\&= \text{Number of bruchid-damaged grains} \times \text{Mass of one sound grain}\\&= \frac{\text{Mass of bruchid-damaged grain residues}}{\text{Mass of one bruchid-damaged grain}} \times \text{Mass of one sound grain}\end{aligned}$$

The mass of grain consumed by bruchids (t ha^{-1}) for each plot was calculated as follows:

$$\begin{aligned}&\text{Mass of grain consumed by bruchids}\\&= \text{Total grain mass lost due to bruchids} - \text{Mass of bruchid-damaged grain residues}\\&= \text{Mass of bruchid-damaged grain residues} \times \left(\frac{\text{Mass of one sound grain}}{\text{Mass of one bruchid-damaged grain}} - 1\right)\end{aligned}$$

Finally, the attainable yield (t ha^{-1}) for each plot was calculated as the sum of the actual yield and the mass of grain consumed by bruchids after cleaning process. In support of these equations, we assumed that bruchid larvae damaged developing lentil grains late enough during the crop reproductive phase so that lentil plants could not compensate for the damage and that lentil yield components (e.g. number of grains, mass of one sound grain) remained similar to those achieved in the absence of bruchids.

2.5 Economic parameters

Actual and marketable gross margins (€ ha^{-1}) were calculated for both lentil and spring wheat in both sole crop and intercrop, considering the actual and marketable yields (t ha^{-1}), respectively, as follows:

$$\text{Gross margin} = \text{Grain yield} \times \text{Selling price} - \text{Sowing seed quantity} \times \text{Seed cost} - \text{Grain yield} \times \text{Sorting cost}$$

For intercrops, we then summed the gross margins of both lentil and spring wheat. In calculations, we considered only the selling price, seed cost and sorting cost—costs that differed between crops—which corresponds formally to a partial gross margin. For simplification, however, we hereafter use "gross margin". Note that, for the actual yield—composed of sound and damaged grains—our calculation of gross margin assumes that damaged grains are not removed and therefore sold at the same price as sound grains. We deliberately included these damaged grains in actual yield calculation to further demonstrate that extending the yield gap concept to consider all grain losses that influence profitability, including those due to mechanical harvest and damaged grain disposal, is essential to reveal the real profitability of lentil spring wheat intercrops.

Seed costs and grain selling prices were provided by the agricultural cooperative Qualisol, located in southwestern France, which commercialises lentil produced by farmers in both sole crop and intercrop. Seed costs were 3150 € t^{-1} for lentil cv. Anicia, Flora and Rosana; 6000 € t^{-1} for lentil cv. Beluga; and 1030 € t^{-1} for each spring wheat cultivar. Selling prices were 1792 € t^{-1} for lentil cv. Anicia, Flora and Rosana; 2800 € t^{-1} for lentil cv. Beluga; 448 € t^{-1} for sole cropped spring wheat; and 504 € t^{-1} for intercropped spring wheat because its protein content exceeded 14%. Note that Beluga has higher market demand but lower potential yield than those of other lentil cultivars, which justifies its relatively higher seed cost and selling price. To estimate grain sorting costs, we used those also furnished by the agricultural cooperative Qualisol: 11, 11, 45 and 67 € t^{-1} per pass of, respectively, rotary cleaner, vibratory separator, gravity separator and optical sorter. Note that even when sole cropped, lentil needs to be thoroughly sorted (two passes of each tool for a total of 268 € t^{-1}) to remove all stones, dust, and broken and bruchid-damaged grain from marketable grain. Intercrop grain mixtures are sorted similarly to sole cropped lentil but with four passes of optical sorter (total of 402 € t^{-1}). As a comparison, the sole cropped wheat grains only need one pass of each cleaner/separator and no optical sorting (total of 67 € t^{-1}).

2.6 Statistical analysis

Shapiro-Wilk and Levene's tests were used to test the normality of the data and the homoscedasticity of its variance, respectively. Pairwise t tests were used to compare treatments for all dependent variables (e.g. grain yield, N accumulated) using the "t.test" function of R software via Rstudio (version 1.0.136). If necessary, data were square log-transformed to obtain a normal distribution. Unequal variance was accounted for in the t test if Levene's test indicated heteroscedasticity. When possible, one-tailed t tests were performed. All results are presented as mean $\pm$ 1 standard deviation.

3 Results and discussion

3.1 Effect of intercrops on actual yield

Considering all cultivars together, the mean actual yield of intercrops (lentil + spring wheat) was significantly higher than that of sole cropped lentil (Fig. 3a) in both 2015 (1.57 and 1.29 t ha^{-1}, respectively; $P < 0.01$) and 2016 (2.26 vs. 1.93 t ha^{-1}, respectively; $P < 0.01$). Mean actual yield of sole cropped spring wheat (1.46 and 1.60 t ha^{-1} in 2015 and 2016, respectively) was less than or equal to that of intercrops in almost all treatments, but the difference was significant only in 2016 ($P = 0.26$ and $P < 0.001$ for 2015 and 2016, respectively). There was no significant effect of cultivar or year on actual yield of spring wheat, allowing actual yields of the two wheat cultivars to be averaged together. Although actual yields of lentil included bruchid-damaged grain and small grain, the trends observed were the same when only the sound grain fraction of actual yield was considered (data not shown). Note that the amount of small grain turned out to be negligible.

These results indicate a grain yield advantage in intercrop vs. in sole crop under a wide range of conditions: two years with contrasting climates, four lentil varieties and two wheat varieties. This increase led to a land equivalent ratio (LER)—the relative land area of sole crops required to produce the same yield achieved in intercrop, and with the same species proportion in total grain (Willey and Osiru 1972)—ranging from 1.02–1.54 (mean = 1.24 ± 0.14) based on the actual yield. The LER illustrates the ability of lentil-spring wheat intercrops to increase total yields in low-input systems and organic farming, as reported in other studies (Carr et al. 1995) and for other legume-cereal intercrops (e.g. Bedoussac et al. 2015; Fletcher et al. 2016). The intercrop's better performance can be explained by complementary use of N niches by lentil and spring wheat. As cereal forces legume to meet more of its N requirements by fixing N_2 (e.g. Bedoussac et al. 2015), the lentil does not totally compete with spring wheat for soil mineral N when intercropped (e.g. Naudin et al. 2009). Furthermore, our results suggest that the lower the yield of sole cropped lentil, the higher the yield advantage in intercrop (Fig. 3a), indicating that this species mixture could also be a way to ensure a minimum grain yield for organic farmers among years, especially when lentil yields are low, for example due to dry spring conditions. Moreover, when lentil yields were high, intercrops produced more than sole cropped spring wheat, probably because N was limiting in both experimental years (Tosti et al. 2016). Our results also agree with those of Bedoussac and Justes (2010), who observed that total grain yields of cereal-wheat intercrops were higher than those of sole cropped wheat when N availability remained low, such as in stockless organic farming.

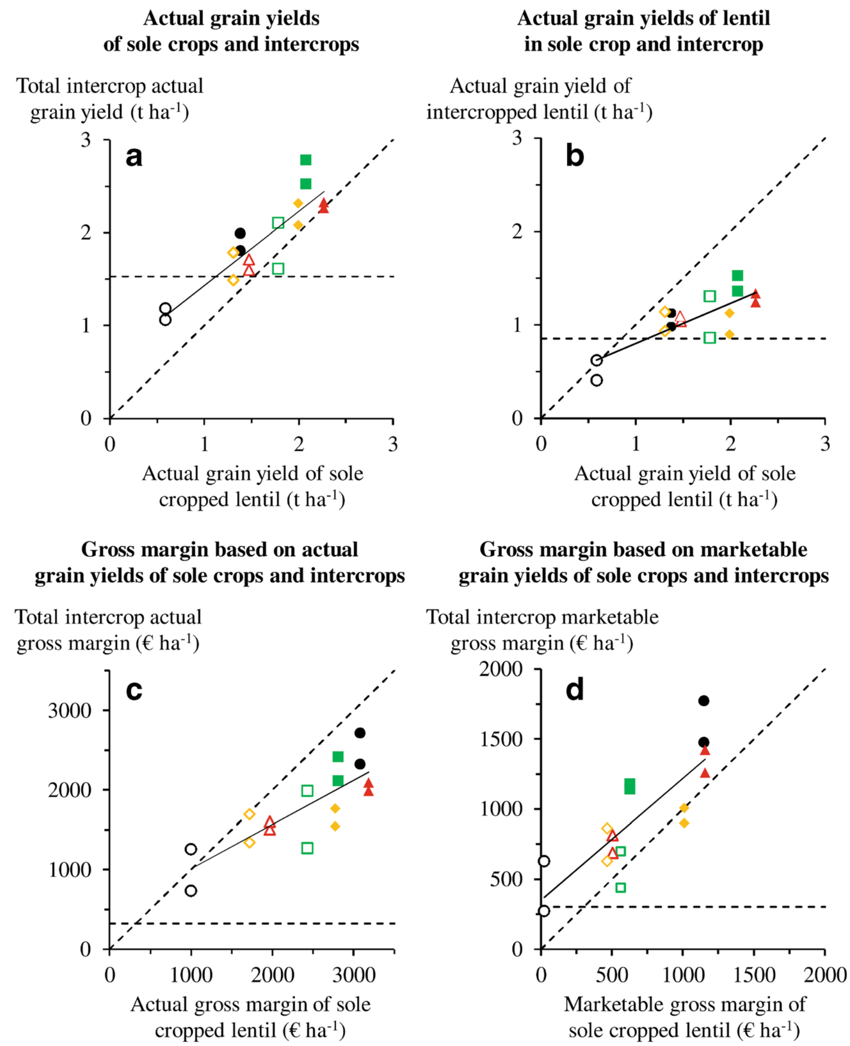


Fig. 3 Yields and gross margins of lentil-spring wheat intercrops compared to those of sole cropped lentil. **a** Actual grain yield (t ha^{-1}) of the intercrop (lentil + spring wheat) vs. that of sole cropped lentil ($y = 0.80x + 0.63$; $R^2 = 0.78$***). **b** Actual grain yield of intercropped lentil (t ha^{-1}) vs. that of sole cropped lentil ($y = 0.43x + 0.37$; $R^2 = 0.63$***). **c** Actual gross margin (€ ha^{-1}) of the intercrop (lentil + spring wheat) vs. that of sole cropped lentil ($y = 0.54x + 458$; $R^2 = 0.64$***). **d** Marketable gross margin (€ ha^{-1}) of the intercrop (lentil + spring wheat) vs. that of sole cropped lentil ($y = 0.87x + 351$; $R^2 = 0.67$***). ***P values < 0.001. Symbol colour and shape indicates the lentil cultivar (green square = Anicia, black and circle = Beluga, orange diamond = Flora, red triangle = Rosana). Symbol filling indicates the experimental year (open = 2015, closed = 2016). $N = 16$. Dashed horizontal lines indicate the mean yield or gross margin of spring wheat in sole crop (both cultivars and years combined) (**a**, **c**, **d**) or in intercrop (**b**)

Mean actual yield of lentil was significantly lower in intercrop than in sole crop (Fig. 3b) in both 2015 (0.93 vs. 1.29 t ha^{-1}, respectively; $P < 0.01$) and 2016 (1.20 vs. 1.93 t ha^{-1}, respectively; $P < 0.001$). This highlights that spring wheat added at a low density (17% of sole crop density) was still dense enough to decrease the associated lentil yield, illustrating strong interspecific competition of spring wheat with lentil. Similar trends were observed in several previous studies of lentil-wheat intercrops (Akter et al. 2004; Carr et al. 1995; Wang et al. 2013). Actual yield of lentil in sole crop and intercrop was significantly higher in 2016 than in 2015 ($P < 0.001$ and $P < 0.01$, respectively) (Fig. 3b). Actual yield of intercropped lentil tended to be higher when that of sole cropped lentil was high, i.e. when conditions were favourable for lentil growth. These results can be explained in part by favourable temperature and rainfall conditions around flowering and early pod filling stages in 2016, greatly increasing the number of pods per plant (data not shown) and thus the yield, unlike in 2015, which had a dry spring.

3.2 Effect of intercropping on gross margin from actual yield

Mean actual gross margin of intercrops was significantly lower than that of sole cropped lentil but higher than that of sole cropped wheat (Fig. 3c) in 2015 (1427, 1778 and 304 € ha^{-1}, respectively; $P < 0.05$) and 2016 (2117, 2965 and 346 € ha^{-1}, respectively; $P < 0.001$). Despite the higher total yield of intercrops, the decrease in lentil yield in intercrop compared to that in sole crop was not economically offset by the actual yield of spring wheat in intercrop, given a selling price of lentil ca. four times that of spring wheat. Therefore, as lentil contributes more to intercrop gross margin, one should favour lentil yield to maximise gross margin of the actual yield of intercrops. Our results show that when hand-harvested—which corresponds to the actual yield—intercrop is less profitable than sole cropped lentil. Finally, actual gross margins ranged widely over the 2 years of experiments, from 734 to 2715 € ha^{-1} for intercrops and 1002–3188 € ha^{-1} for sole cropped lentil. Thus, intercrops with lentil can achieve high, albeit lower, actual gross margins, even with a strong decrease in the actual yield of lentil. Akter et al. (2004) observed an economic advantage in the actual yield of lentil-wheat intercrops for management strategies including irrigation, fertilisation and chemical control of biotic stresses. However, since lentil is intended to human food and harvested with combine harvesters, one should include the potential grain losses due to non-edible seeds (e.g. bruchid-damaged grains) and losses on field due to mechanical harvest to reveal marketable yield and marketable gross margin that reflect more accurately the reality of farmers.

3.3 Effects of intercrops on bruchid damage, lodging and mechanical harvest efficiency

3.3.1 Effect of intercrops on bruchid damage

Among all cultivars and years, mean percentage of bruchid-damaged grain was not significantly different for lentil in intercrop and sole crop (40 ± 15 vs. $42 \pm 14\%$, respectively). Both treatments had a high mean percentage of bruchid-damaged grain in 2015 (49%) and a lower one in 2016 (33%). No difference in the bruchid damage was observed among cultivars except for Anicia, which was more sensitive (mean = 63 and 52% in 2015 and 2016, respectively, for sole crop and intercrop combined). Leroi et al. (1990) observed no significant difference in bruchid damage to cowpea intercropped with maize and that in sole crop. In contrast, Karel et al. (1982) and Olubayo and Port (1997) observed a significant decrease in bruchid infestation rate in cowpea-maize intercrops. These studies were carried out in East Africa, which has different bruchid species than those established in Europe. This result emphasises, however, that increased plant diversity in the field can decrease bruchid infestation rate. Under our conditions, we estimated that mean yield loss due to bruchids was 0.69 and 0.93 t ha^{-1} in 2015 and 0.52 and 0.93 t ha^{-1} in 2016 for lentil in intercrop and sole crop, respectively. The presence of *B. lentis* and *B. signaticornis* has been confirmed in southwestern France (Yus-Ramos et al. 2014), but to our knowledge, this is the first report of major damage by bruchids in this area in a scientific publication. Currently, the abundance of bruchids in southwestern France, coupled with the lack of effective agronomic or biological methods to control them, seriously hinders development of lentil in organic agriculture there. Unfortunately, our experiment cannot help to identify factors influencing bruchid damage, as it was not designed to do so, and no clear trend in damage was observed. Moreover, bruchid ecology is not well-known, but we can hypothesise that bruchid infestations are influenced by temperature or degree-days during the growing season, as well as by crop rotations, landscape pattern and biodiversity.

3.3.2 Effect of intercrops on lentil height at harvest, stem length and lowest pod height

Mean lentil height at harvest (Fig. 4a) was higher in intercrop than in sole crop, non-significantly in 2015 (28 vs. 23 cm, respectively; $P = 0.23$) but significantly in 2016 (36 vs. 25 cm, respectively; $P < 0.01$). Akter et al. (2004) observed a similar increase in lentil height in intercrop. Mean lentil height at harvest in intercrop was lower in 2015 than in 2016 ($P < 0.05$), while no difference was observed in sole crop ($P = 0.38$). In 2016, mean lentil stem length (Fig. 4b) was similar between intercrop and sole crop (42 cm; $P = 0.75$). Thus, the mean lodging was 15% in intercrop and 40% in sole crop (Fig. 4c). These results suggest a strong decrease in lentil lodging due to having spring wheat in the intercrop. Furthermore, mean height of the lowest pod was also significantly higher in intercrop than in sole crop (22 vs. 12 cm, respectively; $P < 0.001$; data not shown). Thus, sowing wheat at 17% of its sole cropped density in intercrop was sufficient to significantly increase lentil height and lowest pod height at harvest. Moreover, the lower the height of sole cropped lentil at harvest, the larger its difference with the height of intercropped lentil (Fig. 4a). Carr et al. (1995) observed an increase of 3.5 cm in the height of the lowest lentil pod (albeit smaller than our result) in intercrop compared to that in sole crop. Thus, intercrops could be a way to significantly decrease lentil lodging, thus increasing pod height and creating conditions in which combine harvesters are more likely to gather more of the actual yield of lentil.

3.3.3 Effect of intercrops on mechanical harvest efficiency

Our mechanical vs. hand-harvest experiment performed in 2016 (Fig. 5) confirmed that the mean hand-harvested yield of sound lentil grain was lower in intercrop than in sole crop (1.01 ± 0.19 vs. 1.29 ± 0.13 t ha^{-1}, respectively; $P < 0.05$). In contrast, the mean yield of mechanically harvested lentil was similar in intercrop and sole crop (0.75 ± 0.11 vs. 0.64 ± 0.06 t ha^{-1}, respectively; $P = 0.81$). Consequently, mechanical harvest efficiency was clearly higher for lentil in intercrop than in sole crop (75 vs. 50%, respectively, $P < 0.05$). The greater mechanical harvest efficiency in intercrop can be attributed mainly to the higher mean pod height in intercrop, confirming the importance of maintaining pod height as high as possible. The slight increase in the lowest pod height observed by Carr et al. (1995) decreased grain loss of lentil in intercrop by only 3% compared to that in sole crop. They provided no data on lentil lodging, however, making comparison with our experiment impossible. Breeding lentil cultivars for high mechanical harvest efficiency appears to be a viable long-term strategy for

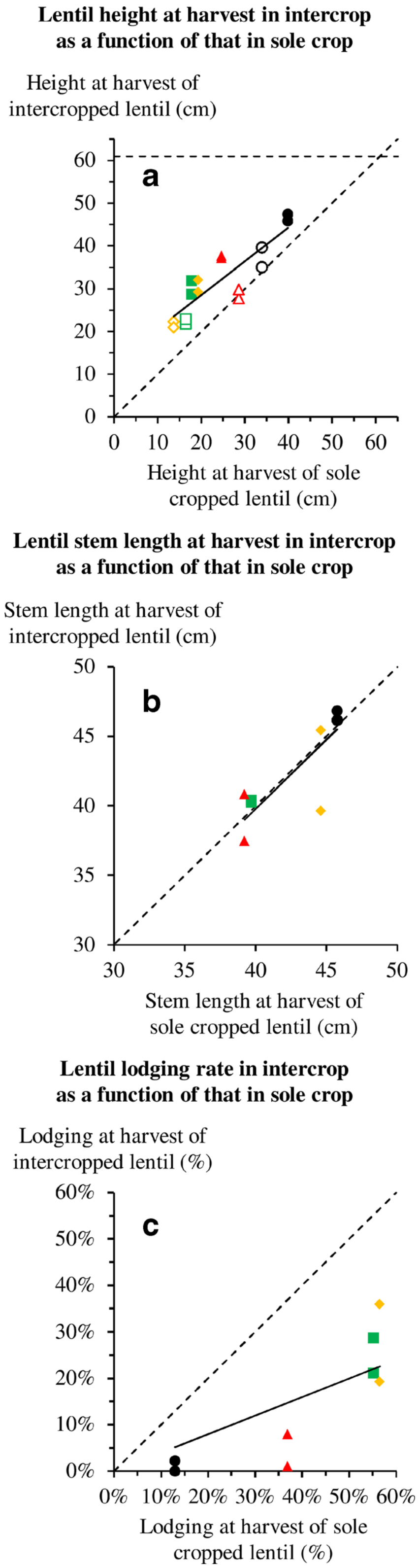


Fig. 4 Height, stem length and lodging of lentil intercropped with spring wheat compared to those of sole cropped lentil. **a** Height at harvest (cm) of intercropped vs. sole cropped lentil ($y = 0.79x + 12.7$; $R^2 = 0.75$***). **b** Stem length at harvest (cm) of intercropped vs. sole cropped lentil ($y = 0.99x$; $R^2 = 0.61$**). **c** Lodging at harvest (%) of intercropped vs. sole cropped lentil ($y = 0.40x$; $R^2 = 0.61$**). *P values; **$P < 0.01$; ***$P < 0.001$. Intercropped lentil height at harvest exceeded that of sole cropped lentil in almost all treatments (mean = 32 vs. 24 cm, respectively), while lentil stem length was similar (mean = 42 cm). Lentil intercropped with spring wheat had a lower lodging than sole cropped lentil (mean = 15 vs. 40%, respectively. Symbol colour and shape indicate the lentil cultivar (green square = Anicia, black circle = Beluga, orange diamond = Flora, red triangle = Rosana). Symbol filling indicates the experimental year (open = 2015, closed = 2016). $N = 16$. The dashed horizontal line indicates the mean yield of intercropped spring wheat (both cultivars and years combined)

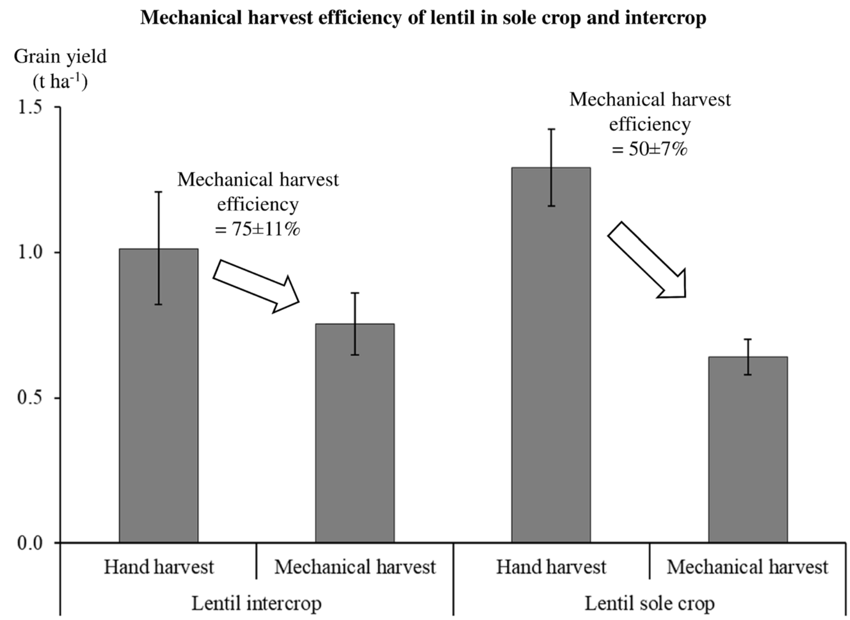
issues related to mechanical lentil harvest. Moreover, it would be interesting to determine the minimum relative density of spring wheat needed to increase mechanical harvest efficiency of lentil in intercrop and simultaneously decrease its strong interspecific competition with lentil. We hypothesise that densities below 17% of its sole crop density can reach these objectives, notably due to the ability of spring wheat to compensate for low density by growing more shoots. However, reducing wheat density at sowing could increase at least two risks: (1) that farmers would fail to obtain good spatial distribution of wheat seeds, even using a pneumatic precision drill, and (2) that unfavourable climatic conditions would decrease wheat density even further by decreasing its emergence rate.

3.4 Effect of intercrop gross margin from marketable yield

We applied mechanical harvest efficiency to the actual yields to estimate mechanically harvested yields. We first assumed that mechanical harvest efficiency was the same for all lentil cultivars in both years, which seemed acceptable based on our observations of lentil height at harvest and stem length. These observations suggested that, even though mechanical harvest efficiency can vary among cultivars and years, the relative difference in mechanical harvest efficiency between lentil in intercrop and sole crop remains large. We then assumed that loss of spring wheat grain during mechanical harvest was negligible, as confirmed by our field observations after harvest, and did not significantly affect marketable gross margins. Next, we assumed that mechanical harvest efficiency was the same for all grain fractions of actual yield (i.e. marketable, bruchid-damaged and small). Finally, the marketable yield was used to calculate marketable gross margin to compare intercrop vs. sole crop profitability.

Mean marketable gross margin (Fig. 3d) was significantly higher for intercrops (lentil + spring wheat) than sole cropped lentil or sole cropped wheat in both 2015 (629, 390 and 283 € ha^{-1}, respectively; $P < 0.05$) and 2016 (1269, 987 and 325 € ha^{-1}, respectively; $P < 0.05$). Furthermore, marketable gross margins, like actual gross margins, ranged widely over the

Fig. 5 Mean harvested yields of hand-harvested and mechanically harvested lentil in intercrop and sole crop, used to calculate mechanical harvest efficiency. The field experiment was performed in 2016 with lentil cv. Anicia and spring wheat cv. Valbona, considering only sound grain ($N = 3$ for each). Mechanical harvest efficiency was higher for lentil in intercrop than in sole crop, leading to similar yields of sound grain. Error bars represent 1 standard deviation



2 years (273–1773 and 23–1158 € ha^{-1} for intercrops and sole crops, respectively). The lowest marketable gross margin of intercrops was higher than that of sole cropped lentil ($P < 0.05$), meaning that intercrops can act as "harvest insurance" for farmers, especially when sole crop yields are low. On the other hand, the highest marketable gross margin of intercrops was also higher than that of sole cropped lentil ($P < 0.001$). Consequently, when lentil yield is high in sole crop, intercropping lentil may still be a way to increase gross margins. Intercropped lentil was thus found to be more profitable than sole cropped lentil in our experiments, under both favourable and unfavourable climatic conditions in organic farming. The decrease in lentil lodging due to support by wheat is an example of the "within-season benefit" concept developed by Fletcher et al. (2016) and helped to assess agronomic and economic performances of intercrops.

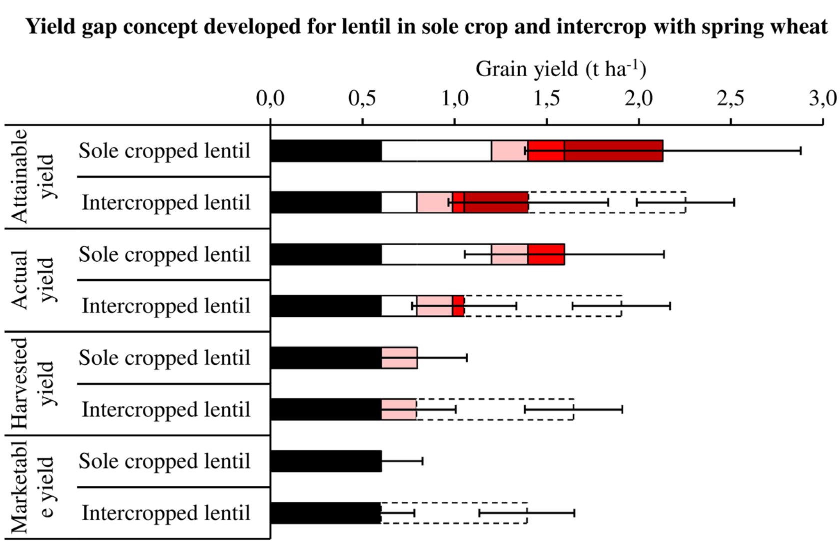


Fig. 6 Yield gap analysis for lentil intercropped with spring wheat and sole cropped lentil. For all cultivars and years combined, total grain loss from attainable to marketable yield was 58% for intercropped lentil and 72% for sole cropped lentil, leading to similar marketable yields. Bars indicate the mean mass of grain yield or loss for a given production stage: dark red bars for grain eaten by bruchids, red bars for bruchid-damaged grain residues eliminated from actual yield during mechanical harvest, light red bars for bruchid-damaged grain residues discarded by the final grain cleaning process, respectively, white bars for sound grain lost during harvest, dashed-outline bars for wheat grain and black bars for the marketable yield of lentil. The mass of small grain lost during mechanical harvest and cleaning stages is not represented because of its insignificant weight compared to those of the other grain fractions. $N = 16$ for intercropped lentil and $N = 8$ for sole cropped lentil. Error bars represent 1 standard deviation

3.5 Yield gap analysis of all cultivars and years combined

Finally, we used our adaptation of the yield gap concept to detail lentil grain losses along the agronomic production stages in sole crop and in intercrop, for all cultivars and years combined. Mean attainable yield was 1.41 and 2.14 t ha^{-1} for lentil in intercrop and sole crop, respectively (Fig. 6). Mean attainable yield of sole cropped lentil was high and even higher with cv. Anicia in 2016 (3.11 t ha^{-1}). This yield is consistent with that (3.0 t ha^{-1}) observed by Wang et al. (2013) in an experiment conducted with cv. Anicia in organic farming in Germany without water stress. This strengthens our assumption that our growing conditions were favourable (i.e. no water stress) for lentil in 2016.

Although bruchids consumed ca. 25% of the attainable yield of lentil in both intercrop and sole crop, we observed a mean actual yield in both intercrop and sole crop that was relatively higher than the mean worldwide lentil yield (ca. 1.0 t ha^{-1}, Erskine et al. (2011)). Subsequently, 25 and 50% of the actual yield were lost during the mechanical harvest of lentil in intercrop and sole crop, respectively. Finally, a large mass of bruchid-damaged grain residues, representing 25% of the mechanically harvested yield of lentil in both intercrop and sole crop, had to be removed from the mechanically harvested yield to obtain the marketable yield (Fig. 6). Note that additional downstream stages can be added if higher grain quality is required by agro-food industries.

Ultimately, the marketable yield of lentil in intercrop was only 42% of its attainable yield but was higher than that in sole crop, which was only 28% of its attainable yield. Intercropped lentil approaches attainable yield more closely than sole cropped lentil (and with less risk), but both systems currently lay far below optimum performances. The yield gap analysis (Fig. 6) illustrates that grain loss at mechanical harvest was an important issue for lentil but clearly highlights that bruchids were the major reducing factor in our experiments, as is the case for organically farmed lentil in southwestern France.

4 Conclusion

This study illustrates the ability of lentil-spring wheat intercrops to yield more total grain than sole cropped lentil in low-input organic farming, confirming previous results for legume-cereal intercrops. Our study shows that false conclusions can be drawn when analysing intercrops based on only simple indicators and without representing the practical reality. We showed that lentil-spring wheat intercrops could be significantly less profitable than sole cropped lentil when considering the grain yield before mechanical harvest, as profit from spring wheat in intercrop did not economically offset the loss of lentil yield, due to lentil's much higher price. We demonstrated, however, that the presence of spring wheat reduced lentil lodging and allowed a higher percentage of pods to be mechanically harvested. Consequently, after sorting and cleaning grain, the intercrops had significantly higher marketable yield than sole cropped lentil, and led to higher marketable gross margins thus demonstrating that these intercrops can be more profitable. Unfortunately, intercropping did not significantly decrease bruchid damage, which was high in both experimental years. Intercropping can limit risk when yields of sole cropped lentil are low and increase gross margins when they are high.

Our adaptation of the yield gap concept may be used for future studies of legume-cereal intercrops or any other cropping system. The conceptual framework of the yield gap—including a novel definition for mechanically harvested and marketable grain yields—is designed to mimic farmers' real working conditions and thus greatly increase the application potential of scientific results, as farmers can relate the results directly to their practices. The addition of these two reducing factors is particularly relevant for lentil because of its high susceptibility to lodging and bruchid damage and its production as human food. These new production stages complement yield gap analysis and allow for full stepwise quantification of grain losses from attainable yield down to marketable yield. Consequently, farmers would be more likely to adopt more sustainable agricultural practices such as intercropping. Further research is needed, however, particularly to analyse factors that can influence intercrop performances, such as the type of combine harvester and traits of lentil cultivars that can affect mechanical harvest efficiency. From an economic viewpoint, questions remain about how to reduce the cost of grain cleaning and sorting tools, which would increase economic performance of intercrops. Finally, we show that effective biocontrol methods and lentil cultivars tolerant to bruchids are still needed, as bruchids greatly decrease lentil yield in organic farming, especially in areas where they are established, such as southwestern France.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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