Berichte über Landwirtschaft

Zeitschrift für Agrarpolitik und Landwirtschaft

BAND 99 | Ausgabe 3

Agrarwissenschaft
Forschung
Praxis

Herausgegeben vom Bundesministerium
für Ernährung und Landwirtschaft

http://buel.bmel.de

ISSN 2196-5099

Berichte über Landwirtschaft
Zeitschrift für Agrarpolitik und Landwirtschaft

The profitability of mixed cropping with winter faba bean and winter wheat

By Vanessa Bonke, Daniel Siebrecht-Schöll, Oliver Mußhoff

1 Introduction

The conservation and promotion of biodiversity are becoming increasingly important against the background of narrow cereal crop rotations in German agriculture. One way to increase biodiversity in agricultural land production is to apply mixed cropping (GABA et al., 2015; MARTIN-GUAY et al., 2018). By definition, mixed cropping is the simultaneous cultivation of two or more crops on the same land (ANDREWS and KASSAM 1976). Mixed cropping is in principle a traditional cropping system whose origins can be traced back to several thousand years ago. Among the best known crop mixtures already used by indigenous peoples in Mesoamerica are combinations of maize, bean, and pumpkin (POSTMA und LYNCH, 2012). In Germany, mixed cropping was also a widespread form of cultivation until the second half of the 19th century. Only with the increasing mechanization and the growing availability of synthetic fertilizers and pesticides did this cropping system lose its importance (HOF und RAUBER, 2003). The availability of synthetic nitrogen fertilizers has also contributed to a considerable decrease of legumes in crop rotations (MAMINE und FARÈS, 2020). On the one hand, this development has led to severe losses in biodiversity within arable fields, and within crop rotations on the other (STEIN und STEINMANN, 2018).

From today's perspective, mixed cropping thus represents an innovative way of increasing biodiversity within arable fields and crop rotations. In addition, mixed cropping with legumes and non-legumes in particular offers the possibility of saving synthetic nitrogen fertilizers. Furthermore, mixed cropping promises improved yield stability, compared to sole cropping under low-input conditions, while reducing the input of synthetic fertilizers and pesticides (GABA et al., 2015; HAUGGAARD-NIELSEN et al., 2008). Moreover, the so-called "mixing effect" which results from the interaction of the species involved, often leads to a yield advantage of the mixed stand compared to the corresponding pure stands (HOF und RAUBER, 2003; PELZER et al., 2012). Mixed cropping can also help increase soil fertility, suppress weeds, and make better use of available resources, such as nutrients, water, and light (CHEN et al., 2018;

MALÉZIEUX et al. 2009; WEZEL et al., 2014). Thus, the cultivation of legumes and non-legumes in mixed stands has the potential to contribute towards a more sustainable agriculture.

However, from a practical agricultural point of view, mixed cropping, in particular with main crops (e.g., wheat and pea, oats and lentil), presents some challenges. As the agricultural sector has evolved around dominant cereal crops in recent decades, path dependencies have emerged that have led to technological lock-in (WEZEL et al., 2014; BEDOUSSAC et al., 2015; MEYNARD et al., 2018). All stages of the value chain have been designed and optimized for sole crops: Starting with the varieties that have been bred to be grown in pure stands (SIEBRECHT-SCHÖLL, 2019) and ending with the processing firms, which are not adapted to process mixed yields. In the primary agricultural production, challenges arise because farmers have very limited experience and knowledge to draw on when adopting mixed cropping, implying that growing mixed cropping involves learning costs for a large proportion of German farmers (BONKE und MUSSHOFF, 2020). Information on the profitability of different mixed cropping combinations is limited in the scientific and practical literature (LEMKEN et al., 2017b; PELZER et al., 2012; ROSA-SCHLEICH et al., 2019). The information situation regarding the yields of mixed stands is also limited, whereas the annual state variety experiments alone continuously provide up-to-date information for pure stands in Germany. In practice, the lack of information also increases the risk for the cultivation of mixed stands.

Politically, mixed cropping with main crops has received little attention in Germany so far. While the cultivation of catch crops as a mixture and main crops with grass undersowing have been promoted for some time (BMEL, 2015), there was no uniform consideration for mixed cropping with legumes and non-legumes as main crops at national level within the first pillar of the Common Agricultural Policy (CAP) until 2018. Only since the latest changes to the direct payment requirements of the CAP, has this type of mixed cropping received consideration within the greening requirements nationally. Specifically, this means that mixed cropping with legumes and non-legumes, in which the legume share in the mixed stand predominates, are recognized with a weighting factor of 1.0 for the provision of Ecological Focus Areas (EFA) as of the application year 2018 (BMEL, 2018). Prior to 2018, this only applied to sole cropped legumes and mixtures of legumes, for which a weighting factor of 0.7 applied during this period (BMEL, 2015). With the change of the weighting factor, a general pesticide ban for legumes as EFA was introduced simultaneously. If in compliance with the pesticide ban, mixed cropping thus competes directly with other measures that can be counted as EFA, such as fallow land or buffer strips. In some federal states, it is theoretically also possible to consider mixed cropping within the framework of agri-environmental measures for the promotion of diverse crops, but only if further restrictions are adhered to. In addition, there is the compliance with double promotion ban, which is why this possibility of promotion is suspended, for example, in Lower Saxony (ML NIEDERSACHEN, 2020). Thus, nationally for arable areas that are not eligible as EFA, mixed cropping must compete with established pure stands from an economic point of view.

Against this background, the aim of this paper is to evaluate the profitability of mixed cropping using the example of winter faba bean (*Vicia faba*) and winter wheat (*Triticum aestivum*). Based on the data from a multi-year field experiment, which took place within the framework of a collaborative project at the Georg-August-University Göttingen (IMPAC³), gross margins (GM) are calculated for different combinations of winter faba bean genotypes and winter wheat varieties. For the economic evaluation of the “mixing effect”, the relative gross margins of mixtures are also calculated. Based on this, the optimal production program is determined by means of linear programming, where in addition to the "classic" production methods, mixed cropping with winter faba bean and winter wheat is also taken into account as a production method. The whole-farm model allows the implementation of a sensitivity analysis for the stability ranges of the mixed cropping GM, which enables implications regarding the profitability of mixed stands beyond the concrete calculated GM. The results can serve as a first orientation for the profitability of this mixed cropping combination for conventional agriculture and illustrate where more research is needed to be able to implement mixed cropping in the German agricultural practice in the future.

2 Data Basis IMPAC³ Field Experiments

As part of the IMPAC³ project, field experiments were conducted with winter faba beans and winter wheat in mixed and in pure stands. The objective of the experiment was to identify traits in the involved species that are associated with the yield advantage of mixed cropping. The experiment was therefore designed to maximize interactions between the participating mixed cropping partners in order to study these effects. Mixed stands and pure stands of

- eight different winter faba bean genotypes (*Vicia faba*, Vf 1-8) and
- three winter wheat varieties (*Triticum aestivum*, Ta 1-3) were grown.

The winter faba beans were experimental inbred lines from the breeding program of the Norddeutsche Pflanzenzucht Hans-Georg Lembke KG, Hohenlieth (NPZ) and the Department of Plant Breeding, Department of Crop Sciences, Georg-August-University Göttingen (ROTH und LINK, 2010). For wheat, two line varieties were used (Genius = Ta1 and Boxer = Ta2) and one hybrid variety (Hybery = Ta3). The experimental plots were laid out as a substitutive cropping model in alternating rows, i.e., a percentage of the seeding rate in pure stand of winter faba bean was replaced by an equal percentage of the seeding rate in pure stand of winter wheat. The reference point is always the seeding rate of the pure stand of the involved species, which corresponds to 100 %. It should be noted that the seeding densities (seeds/m²) of different species often differ greatly (HOF und RAUBER, 2003). The seeding density of the winter faba bean in pure stand was 40 seeds/m² and that of the winter wheat pure stand was 320 seeds/m². The seeding rate in the mixed stand was 50 % of the seeding rate of the pure stands in each case (20 seeds/m² winter faba bean, 160 seeds/m² winter wheat) (SIEBRECHT-SCHÖLL, 2019). It should be noted that the hybrid wheat variety was also sown with the seeding density of 320 seeds/m² in pure stand and 160 seeds/m² in the mixed stand. The equally high seeding density is due to the experimental design and research objective. However, variety trials show that "Hybery" with a seeding density of 160 seeds/m² in pure stands achieves very high yields under practical conditions (ZIPPERT et al., 2013). The experimental setup was explicitly not designed to maximize yields. No nitrogen fertilization took place in the mixed and pure stands of the experiment.

Field experiments were conducted in three growing seaons (2014/15, 2015/16, and 2016/17) at two contrasting sites (Reinshof and Deppoldshausen) in southern Lower Saxony. The Reinshof site (51°29'N, 9°55'E, at 157 m a.s.l.) is characterized by fertile deep soil in a flood plain. The topsoil consists of 21 % clay, 68 % silt and 11 % sand and is a high yielding site. The Deppoldshausen site (51°34'N, 9°58'E at 342 m a.s.l.) can be described as a marginal yielding site. The topsoil in Deppoldshausen consists of 55 % clay, 43 % silt and 2 % sand and is characterized by a high stone content (SIEBRECHT-SCHÖLL, 2019).

Figure 1 illustrates as an example the grain yields achieved in the experiment for the year 2016 for the high yielding site Reinshof and the marginal yielding site Deppoldshausen, which serve as the basis for the calculations in the following. Detailed yield results for the experiments can be found in SIEBRECHT-SCHÖLL (2019). The column blocks in Figure 1 are grouped by faba bean genotypes (Vf1-8), plus a block for the mean across all faba bean genotypes (mean Vf1-8, left block) and a block for the wheat pure stands (Pure Stand Ta, right block). For each faba bean genotype, the yields of the mixed stands with the three different wheat varieties (blue=Ta1, yellow=Ta2, green=Ta3) and the pure stand faba bean (red) are shown. Similarly, the last block on the right shows the pure stand yields of the three winter wheat varieties according to the assigned color (Pure Stand Ta). The total yield of mixed stand (whole column) is composed of the faba bean yield (red hatched part of the column) and the wheat yield (non-hatched part of the column). In 2016, the yield level is between 30 and 50 decitonne/hectare (dt/ha) total grain yield of the mixed stands (Fig. 1, entire column), which can be separated into winter faba bean yield and winter wheat yield. By weight, winter faba bean clearly outweighs winter wheat in total grain yield. Depending on the environmental conditions in a given year, the proportion of the two species in the yields will vary in the mixed stand. Yields at the Reinshof site were comparatively low in this year because a storm had caused lodging on the faba beans, which was more pronounced at this site.

For both sites, it is shown that the mixed stand combinations with the hybrid wheat (Fig. 1, mixed stand with Ta3) provide the highest yields in most cases. This ratio is also observed in the other years (SIEBRECHT-SCHÖLL, 2019). In terms of resource use efficiency and yield maximization, the hybrid wheat consequently also shows itself to be particularly advantageous in the mixed stand.

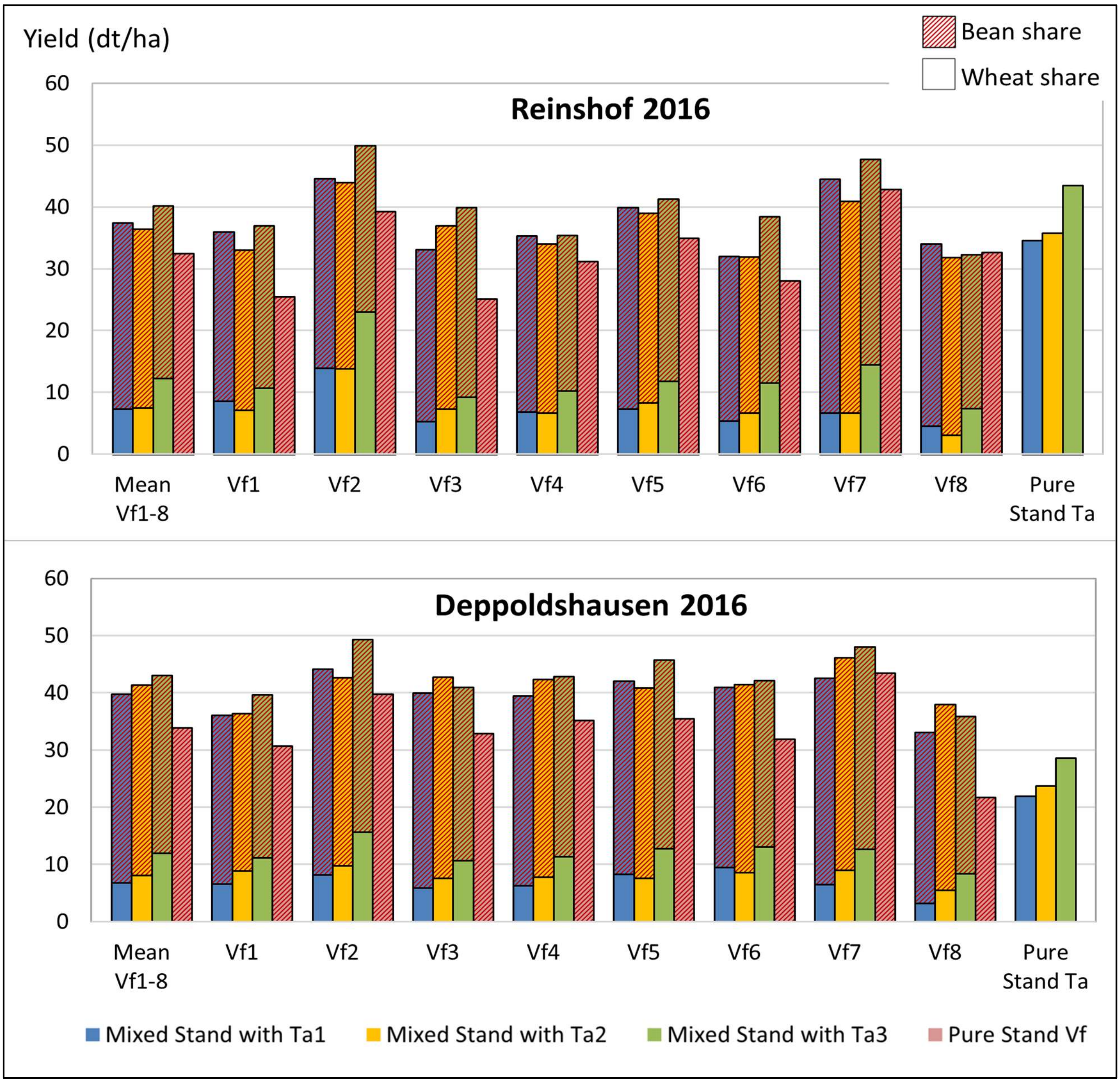


Figure 1: Mean values of the total grain yield (dt/ha, entire column) for the year 2016 for mixed stands with winter faba bean (*Vicia faba,* Vf, red hatched) and winter wheat (*Triticum aestivum,* Ta, not hatched) and their corresponding pure stands of winter faba bean (Pure Stand Vf, red column hatched) and winter wheat (Pure Stand Ta, right block, not hatched) for the sites Reinshof and Deppoldshausen
Source: Own illustration based on SIEBRECHT-SCHÖLL (2019)

3 Economics of Mixed Cropping

3.1 Gross Margins

3.1.1 Methodical Approach

For the calculation of GM based on the results of the field experiments, various planning assumptions had to be made, which affect the results and their resilience. To determine the market performance, first the grain yields of the individual experimental plots (g/10.5 m²) had to be converted into yields per hectare (dt/ha). The average annual prices of the Agrarmarkt Informations-Gesellschaft (AMI) for Lower Saxony East (free warehouse) for conventionally produced products were used to calculate the market performance (AMI, 2020). Here, it was assumed that wheat in the mixed stand is of higher protein quality and can be sold as bread wheat, while the wheat in pure stand can only be sold as fodder wheat (Hof und Schmidtke, 2006). Other revenues, such as direct payments, were not taken into account, as these are paid independently of the chosen crop and thus do not count as decision-relevant revenues.

The calculation of the variable costs is largely based on the data of the Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL). However, to account for the field experiment design and focus of the trial, seed costs were approximated separately for the individual varieties and genotypes using regionally available seed prices (Table 1, Raiffeisen Waren GmbH, 2019). Here, the seed prices for winter wheat correspond to the actual regional prices for the varieties used. A uniform price was assumed for the different winter faba bean genotypes, as these are non-approved varieties from experimental breeding research. The seed price for the winter faba bean variety "Hiverna" was used here, plus a premium of 2 Euro/dt. This premium results from the difference in seed prices between "Hiverna" and the newly approved variety "Augusta" from 2018.

Table 1:
Utilized Seed Prices 2014-2016

Seed Prices	2014	2015	2016
Wheat			
Wheat Ta1 Genius (€/dt)	58.90	58.75	58.00
Wheat Ta2 Boxer (€/dt)	58.60	58.25	58.00
Wheat Ta3 Hybery (€/500,000 seeds)	67.50	67.50	67.50
Faba bean			
Vf1-Vf8 (€/dt)	99.50	100.00	98.40

The seed quantity (in kg/ha) was calculated on the basis of the seeding rates (winter faba beans: 40 seeds/m² in pure stand, 20 seeds/m² in mixed stand; winter wheat: 320 seeds/m² in pure stand, 160 seeds/m² in mixed stand), based on the thousand-seed weights (TSW) plus a safety margin. Different seed costs for the faba beans are thus implicitly taken into account despite the same price based on different TSW.

The cultivation steps correspond, as far as possible, to the steps carried out in the field experiment and vary between the sites (Reinshof: medium soil, Deppoldshausen: heavy soil). A field size of 5 ha and a farm-to-field distance of 2 km were assumed for the cost calculation. The working steps for the soil cultivation are identical for pure and mixed stands. For the sowing of the mixed stand, it is assumed that this took place in two passes for the calculation. In contrast, sowing in the field experiment was carried out in one pass using a second seed hopper, which is however not readily available in practice on farms. In the pre-emergence stage, an application of crop protection products (CPP) was carried out in each year, in particular a weed treatment with herbicides. For mechanical weed control, two passes with the harrow and one pass with the hoe are assumed. For fertilization, the share of maintenance fertilization for chalk is taken into account. In the pure stands and in the mixed stand, the harvest was carried out in one pass with a combine harvester and is equally accounted for in the costs.

For the mixed stand, additional costs arise for the separation of the mixed yield. This is assumed to be carried out by the farmer by means of wind sifting and is included in the calculation in the form of direct costs. Separation costs of 1.43 Euro/dt were approximated here, which consist of machine and labor costs, based on the data of the KTBL. MAMINE und FARÈS (2020) report separation costs of 1.50 Euro/dt for mixed yields of peas and wheat in France. Thus, the approximated costs seem plausible.

On the basis of the field experiment data, 160 individual GM were calculated per location and year (4 replicates á 40 experimental plots). In the following, the used calculation scheme for the mixed stands and pure stands for the mean yield is presented for one example each. The presentation of all individual GM is omitted; a graphical representation of the GM for all the different mixed stand combinations is given on the basis of the mean values for the two locations Reinshof and Deppoldshausen and the respective harvest years 2015-2017, which result from the individually calculated GM.

Table 2 shows an example of the scheme used for the GM of the mixed stand. Separation costs are based on the achieved yield of the respective mixed stand. Seed costs and interest costs vary between the different mixed stand combinations. Variable machinery costs vary with location. The GM shown is the GM based on the mean yield of a mixed stand in 2016.

Table 2:
GM Scheme Shown for the Mean Yield of the Mixed Stand Vf7/Ta1, Reinshof, 2016

Revenue/Costs	Quantity	unit	Price	unit	Amount in €/ha
Bread wheat (mean)	6.71	dt/ha	15.52	€/dt	104.14
Faba bean (mean)	37.81	dt/ha	17.64	€/dt	666.97
Sum Revenues					771.11
Wheat Ta1 seed	86.00	kg/ha	0.5875	€/kg	50.53
Faba bean seed	130.00	kg/ha	1.00	€/kg	130.00
Chalk	1.00	t/ha	40.70	€/t	40.70
CPP (Herbicide)	5.00	l/ha	12.76	€/l	63.80
Hail insurance	720.00	€/ha	0.01337	€/€	9.63
Water	1.20	m^3/ha	1.80	€/m^3	2.16
Interests (3 Month)	297.50	€/ha	0.00742	€/€	2.21
Separation costs	44.52	dt/ha	1.43	€/dt	63.66
Sum Direct Costs					363.70
Direct Cost Free Revenues					**408.42**
Variable machine costs					208.43
Interests (3 Month)	208.43	€/ha	0.00742	€/€	1.55
Sum Variable Costs					572.67
Gross Margin					**198.44**

Table 3 shows the scheme used for the calculation of GM for the wheat pure stands. Separation costs are omitted here and machinery costs are lower because the second pass for seeding is not needed. Hail insurance costs are lower for wheat.

Table 3:
GM Scheme Shown for the Mean Yield of the Wheat Pure Stand Ta1, Reinshof, 2016

Revenue/Costs	Quantity	Unit	Price	Unit	Amount in €/ha
Fodder wheat (mean)	34.56	dt/ha	15.14	€/dt	523.24
Sum Revenues					523.24
Wheat Ta1 seed	172.00	kg/ha	0.5875	€/kg	101.05
Chalk	1.00	t/ha	40.70	€/t	40.70
CPP (Herbicide)	5.00	l/ha	12.76	€/l	63.80
Hail insurance	620.00	€/ha	0.00822	€/€	5.10
Water	1.20	m^3/ha	1.80	€/m^3	2.16
Interests (3 Month)	212.00	€/ha	0.00742	€/€	1.57
Sum Direct Costs					212.81
Direct Cost Free Revenues					**310.43**
Variable machine costs					199.09
Interests (3 Month)	199.09	€/ha	0.00742	€/€	1.48
Sum Variable Costs					413.38
Gross Margin					**109.86**

Table 4 illustrates the scheme for calculating the GM of winter faba bean pure stands (Vf7, Reinshof 2016). Hail insurance costs turn out to be the highest here. Variable machine costs are minimally higher than in the winter wheat pure stands due to weight differences of the seed.

Table 4:
GM Scheme Shown for the Mean Yield of the Faba Bean Pure Stand Vf7, Reinshof, 2016

Revenue/Costs	Quantity	Unit	Price	Unit	Amount in €/ha
Faba bean (mean)	42.87	dt/ha	17.64	€/dt	756.23
Sum Revenues					756.23
Faba bean seed	260.00	kg/ha	1.00	€/kg	260.00
Chalk	1.00	t/ha	40.70	€/t	40.70
CPP (Herbicide)	5.00	l/ha	12.76	€/l	63.80
Hail insurance	780.00	€/ha	0.01851	€/€	14.43
Water	1.20	m³/ha	1.80	€/m³	2.16
Interests (3 Month)	326.66	€/ha	0.00742	€/€	2.42
Sum Direct Costs					383.51
Direct Cost Free Revenues					**372.72**
Variable machine costs					199.43
Interests (3 Month)	199.43	€/ha	0.00742	€/€	1.48
Sum Variable Costs					584.42
Gross Margin					**171.81**

3.1.2 Gross Margins for the Reinshof Site

Figure 2 illustrates the GM for the different mixed stand combinations and the corresponding pure stands grouped by faba bean genotypes (Vf1-8). The GM of the mixed stands with the respective wheat variety (blue=Ta1, yellow=Ta2, green=Ta3) and of the faba bean pure stand (red) are differentiated by color. Similarly, the right column block shows the GM of the wheat pure stands (Pure Stand Ta) according to the assigned color. For 2015, the Reinshof site shows that the GM of the different mixed stands are all positive. The best average GM of the different mixed stands is provided by Vf3 and Ta1 (249.98 Euro/ha, Vf3 blue column) in that year, which is also above the GM of the corresponding pure stands of Vf3 (233.21 Euro/ha, Vf3 red column) and Ta1 (243.47 Euro/ha, Pure Stand Ta blue column). In comparison with the corresponding winter faba bean pure stands, it can be seen that the mixed stands have partially higher GM, but partially also lower GM. The winter wheat pure stands Ta1 and Ta2 show clearly positive GM, which in almost all cases are higher than those of the corresponding mixed stands. The overall highest GM is on average provided by the winter wheat pure stand Ta2 (278.82 Euro/ha). Mixed stands with Ta3 as well as the Ta3 pure stands perform the lowest overall. This is mainly due to the fact that Ta3 is a hybrid wheat variety whose seed costs are far higher than those of the other pure line wheat cultivars. Positive yield effects cannot compensate for the higher seed costs in these pure and mixed stands. However, the seed density used for the hybrid wheat (320 seeds/m²) was much higher than would be the case in practice. Should the hybrid wheat also show similarly positive yields at a seed density of 160 seeds/m² in the pure stands (ZIPPERT et al., 2013) and correspondingly 80 seeds/m² in the mixed stand, this would considerably improve the profitability. Reducing the seed quantity by half would also halve the seed costs, which can have a massive influence on the relative competitiveness considering the overall low GM level.

For 2016, the GM are very uneven and overall lower (Fig. 2). Among other things, this is due to the considerably lower sales prices in 2016, which were however in Lower Saxony still far above the German national average for wheat (AMI, 2020). In addition, it should be noted that a storm in this year led to heavy lodging of the faba beans in the experiment (SIEBRECHT-SCHÖLL, 2019). Thus, differences between the various faba bean genotypes in particular become evident here, which are partly due to better lodging resistance. The GM of the mixed stand are above those of the corresponding bean pure stands for the most part, but a clear advantage over the wheat pure stands cannot be seen. For the mixed stands with combinations of Vf2 and Vf7, the overall highest GM can be recorded. Thereby, the combination of Vf7 and Ta1 achieved the highest GM this year (198.08 Euro/ha). Which is higher than both the corresponding wheat pure stand Ta1 (109.41 Euro/ha) and the corresponding faba bean pure stand Vf7 (171.99 Euro/ha).

In 2017 (Fig. 2), the GM of the mixed stands are all clearly in the positive value range at the Reinshof site. Compared to the previous year, the prices for wheat and faba bean have increased essentially. The winter faba bean pure stands are inferior to their corresponding mixed stands in all cases and this despite the decidedly higher selling price of faba bean. This year, mixed stands with Ta2 perform best overall. The highest GM are provided by the combinations with Vf3 (370.90 Euro/ha) and Vf4 (358.55 Euro/ha). However, the highest GM overall was on average achieved by the pure stand of Ta2 (427.26 Euro/ha), despite the, per assumption, lower selling price for fodder wheat.

Overall, it should be reiterated that the pure stands in the experiment were also yields from unfertilized cultivation. Thus, the yield level for the wheat in the pure stand is considerably lower than the average yields produced in conventional agriculture. From a practical point of view, the comparison between the mixed stands and their corresponding pure stands is only of very limited relevance.

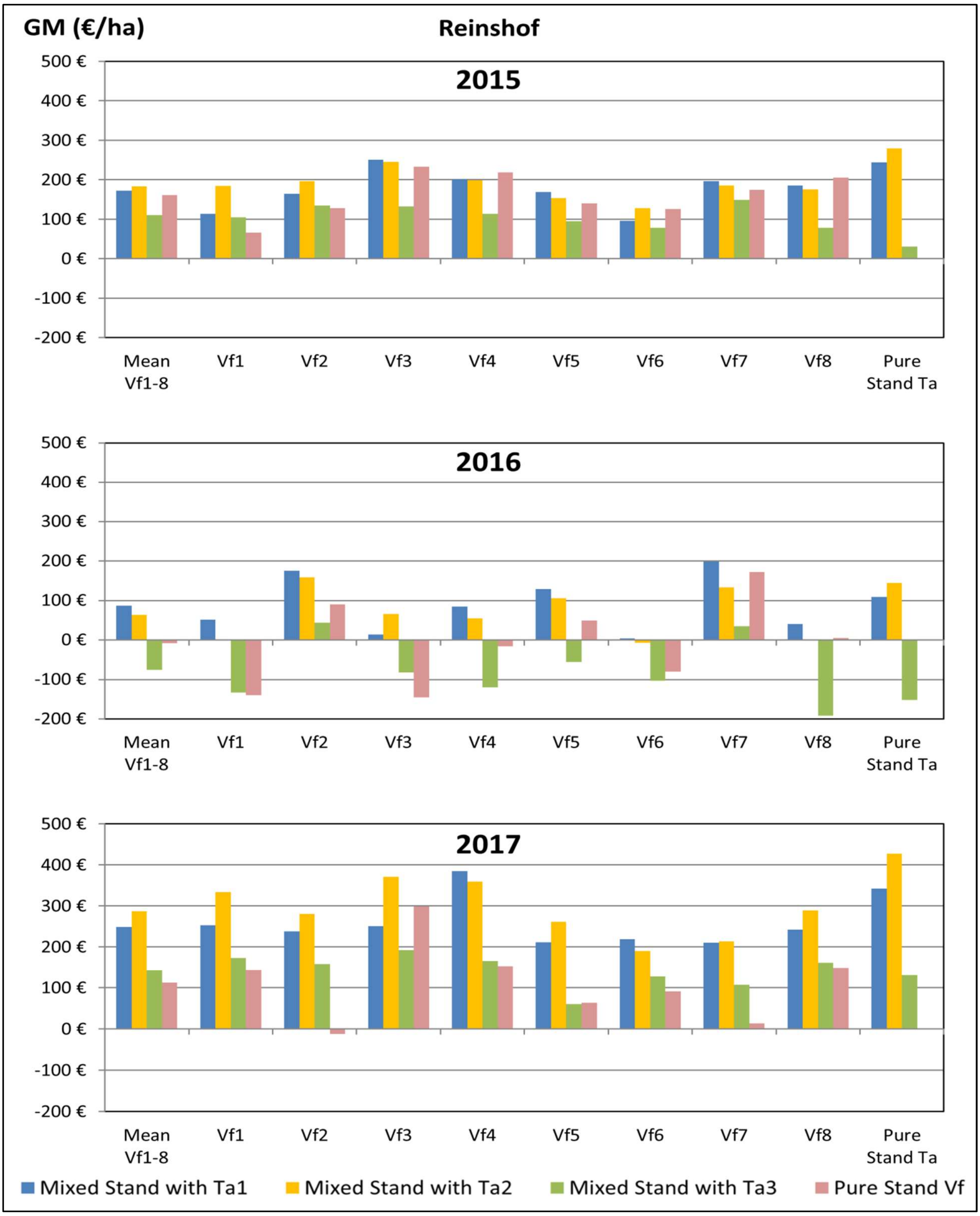


Figure 2: Mean values of the GM (Euro/ha) for the site Reinshof for mixed stands with winter faba bean (*Vicia faba*, Vf) and winter wheat (*Triticum aestivum*, Ta) grouped after faba bean genotypes (Vf1-8) as well as their corresponding pure stands for winter faba bean (Pure Stand Vf, red columns) and winter wheat (Pure Stand Ta, right block) for different years

3.1.3 Gross Margins for the Deppoldshausen Site

The gross margin level at the Deppoldshausen site is overall lower than at the Reinshof site (modified axis scaling in Fig. 3). In addition, the GM are very heterogeneous. Both were to be expected due to the poorer site characteristics.

For 2015, none of the wheat pure stands were able to generate a positive GM (right block, Pure Stand Ta), with Ta3 achieving by far the lowest GM. The faba bean pure stands (red columns) mostly achieve positive GM, with genotype Vf8 (132.71 Euro/ha) providing the highest mean among the faba bean pure stands. The mixed stands also show at least a positive GM in most cases and all perform better than the wheat pure stands. The overall highest GM on average in the mixed stands is provided by the mixed stand of Vf6 and Ta1 (164.98 Euro/ha).

For the year 2016, the GM of the wheat pure stands at the Deppoldshausen site are all negative again. The GM of the bean pure stands are very heterogeneous, again partly due to the increased occurrence of lodging, which was however not as pronounced as it was at Reinshof (SIEBRECHT-SCHÖLL, 2019). The GM of the mixed stands with Ta1 and Ta3 are superior to their corresponding wheat and bean pure stands in almost all cases. The overall highest GM is here provided on average by the combination of Vf7 and Ta2 (213.44 Euro/ha).

For 2017, the wheat pure stands provide very low or negative GM. While pure stand Vf8 provides the highest overall positive GM at this site (226.13 Euro/ha), those of Vf2 and Vf6 are in the negative value range. The mixed stands show mostly positive GM and are superior here again compared to the wheat pure stands and in most cases also compared to the faba bean pure stands.

Over the years, it can be seen for the Deppoldshausen site that the mixed stands result in considerably higher GM on average than the wheat pure stands and in most cases also higher than the faba bean pure stands. This indicates that the mixed stands seem to be particularly suitable for marginal sites. The results between years and between the different varieties vary strongly and do not allow a clear identification of the best mixed cropping combination from an economic point of view based on GM.

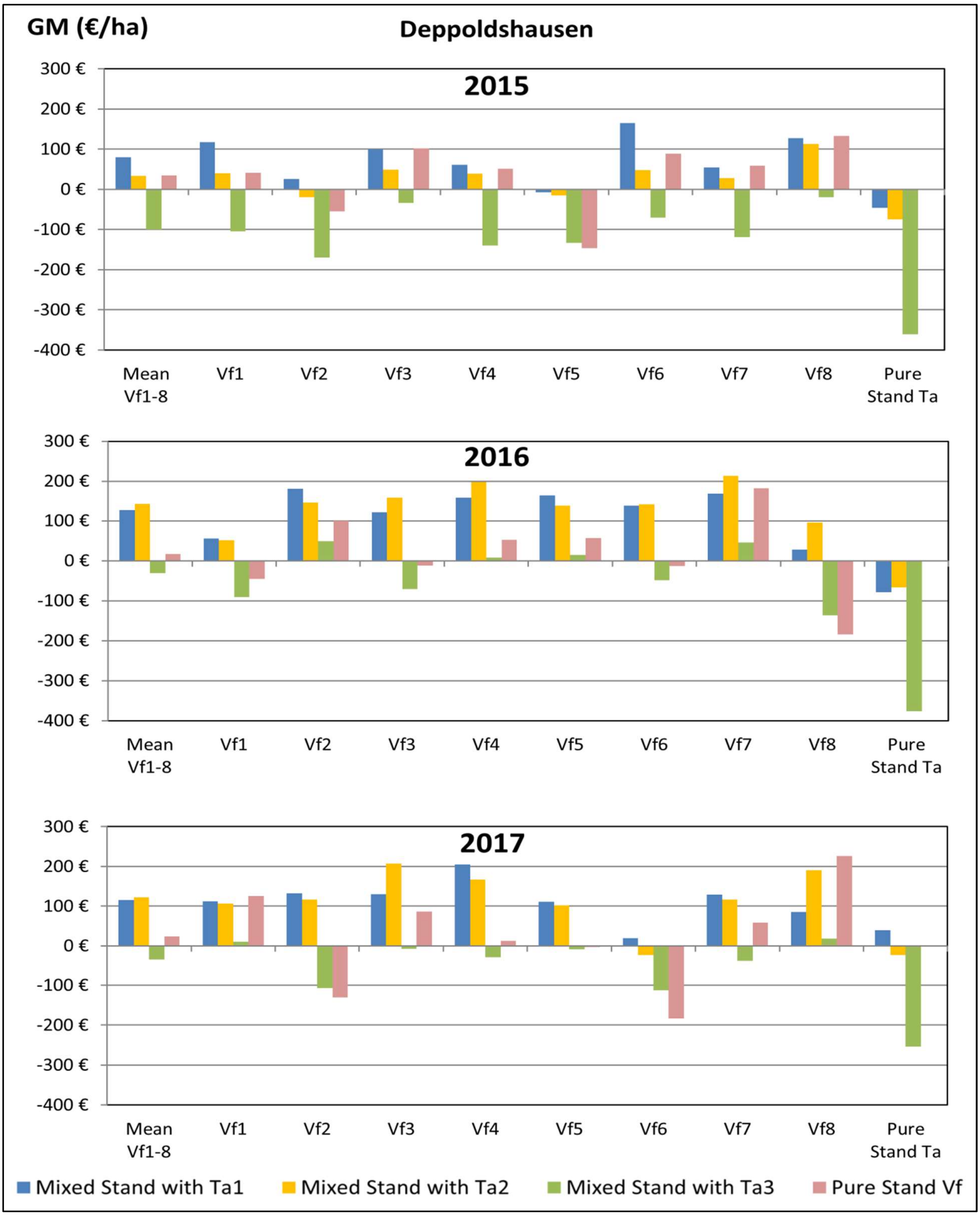


Figure 3: Mean values of the GM (Euro/ha) for the site Deppoldshausen for mixed stands with winter faba bean (*Vicia faba*, Vf) and winter wheat (*Triticum aestivum*, Ta) grouped after faba bean genotypes (Vf1-8) as well as their corresponding pure stands for winter faba bean (Pure Stand Vf, red columns) and winter wheat (Pure Stand Ta, right block) for different years

3.2 Relative Gross Margins of Mixtures to Their Corresponding Pure Stands

3.2.1 Methodical Approach

The calculations presented in the previous section allow a direct comparison of the GM of the mixed stands with the respective GM of the individual pure stands. Thus, one compares the cultivation of the mixed stands with the cultivation of either the wheat pure stand or the faba bean pure stand. In addition to these comparisons with the individual pure stands, it is possible to simultaneously calculate the relative relationship between the mixed stand and their two corresponding pure stands of winter faba bean and winter wheat. Against the background of the assumed positive mixing effect in the mixed stand, which leads to a yield advantage in the mixed stand, this comparison is particularly relevant. Economically, this mixing effect can be evaluated on the basis of the so-called "relative gross margin of mixtures". The relative $relative\ GM_{Mixture}$ relates the GM of cultivating one hectare of the mixed stand to the GM of cultivating half a hectare of each of the two pure stands (cf. equation (1)). Thus, it is assumed that both species are cultivated in pure stands and the question, whether the cultivation of both species in a mixed stand on the same area is economically advantageous, is answered. Following e.g. PELZER et al. (2012), this relative GM of the mixed stand can be calculated as follows:

$$relative\ GM_{Mixture} = \frac{GM_{Mixture\ Vf\ \&\ Ta}}{(0.5 \cdot GM_{Vf} + 0.5 \cdot GM_{Ta})} \qquad (1)$$

The $relative\ GM_{Mixture}$ relates the GM of cultivating one hectare of mixed stand to the GM of cultivating half a hectare of both pure stands. A value greater than 1 implies that the cultivation of the mixed stand is superior to the cultivation of both pure stands in combination on separate areas at the GM level from an economic point of view. In comparison to other parameters used in the literature, such as the relative yield total of the mixed stand (WILSON, 1988), differences in market performance and variable costs are also taken into account here. Figure 4 illustrates this graphically for both sites and all years. The diagonals correspond to a $relative\ GM_{Mixture}$ of 1. Points above the diagonals thus correspond to a $relative\ GM_{Mixture}$ > 1 and imply the economic advantage of the mixed stand at the GM level compared to both pure stands.

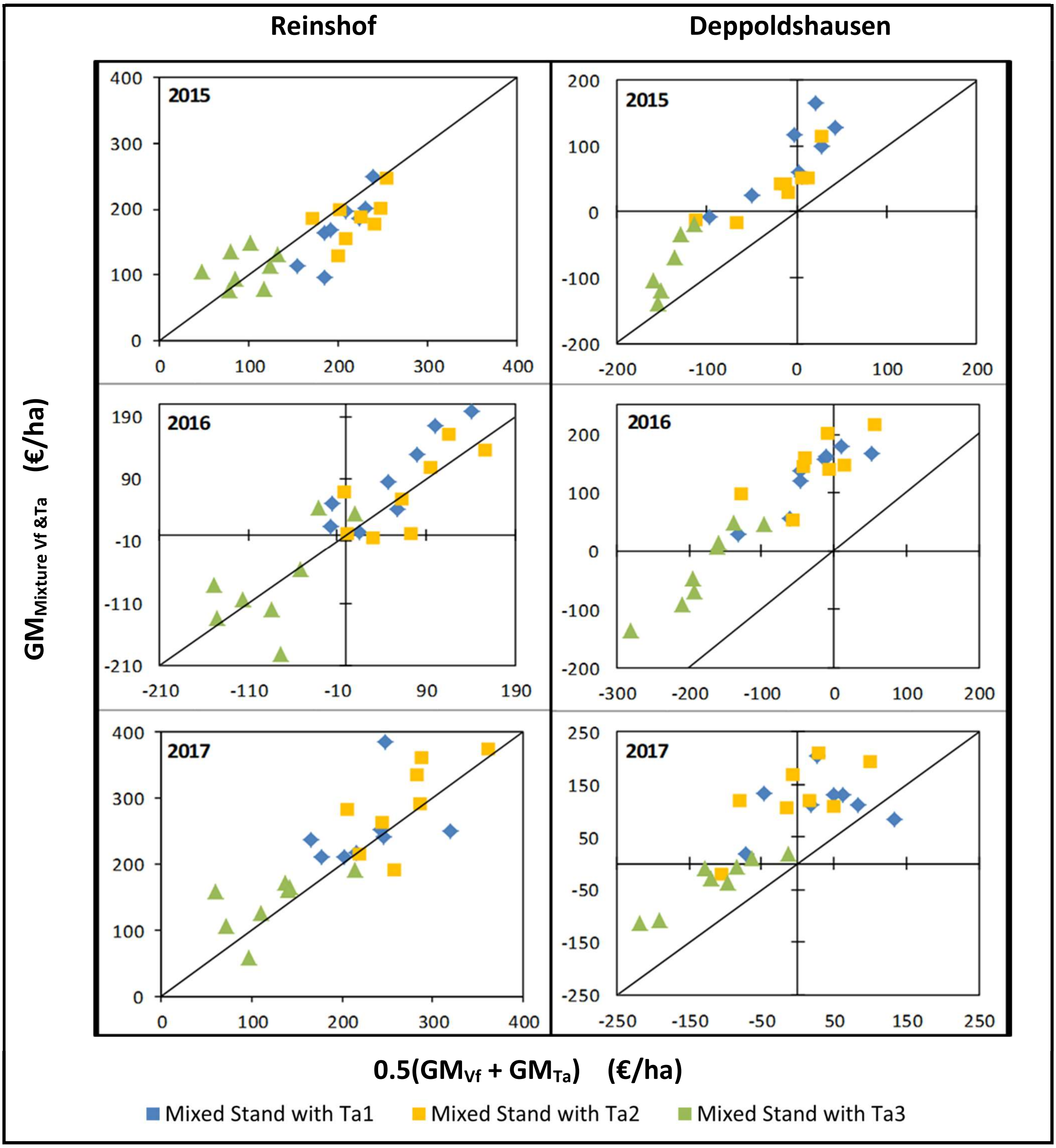


Figure 4: Relative Gross Margins of Mixtures 2015-2017 for Reinshof and Deppoldshausen

3.2.2 Relative Gross Margins of Mixtures for the Reinshof Site

For 2015, the relative $GM_{Mixture}$ for combinations with Ta1 and Ta2 are mostly smaller than 1, i.e. a positive mixing effect cannot be observed at the GM level (Fig. 4). For combinations with the hybrid wheat Ta3, about half of the mixed stands have a relative $GM_{Mixture}$ greater than 1 and are thus superior to the separate cultivation of winter wheat and winter faba bean. In 2016, the overall impression regarding the advantageousness of the mixed stands changes. In particular, mixed stands with Ta1 show here relative $GM_{Mixture}$ greater than 1 for the most part. Compared to the previous year, combinations with Ta2 are also clearly more positive compared to their two corresponding pure stands. For 2017, the advantageousness of the mixed stands in terms of the relative $GM_{Mixture}$ is even more pronounced. Also, all GM are in the positive value range that year. With only a few exceptions, the relative $GM_{Mixture}$ are larger than 1.

A comparison over the years shows a mixed picture for the Reinshof site with regard to the relative $GM_{Mixture}$. A clear advantage, as it can be found on yield level in almost all cases for the mixed stands of winter wheat and winter faba bean (SIEBRECHT-SCHÖLL, 2019), cannot be determined on the GM level. Among other things, this is due to the fact that the GM also takes into account costs that are higher for the mixed stand.

3.2.3 Relative Gross Margins of Mixtures for the Deppoldshausen Site

For the Deppoldshausen site, which has overall poorer site characteristics and soil quality, the relative $GM_{Mixture}$ are except for one all above the diagonal, i.e. the positive mixing effect can also be clearly determined at the GM level in 2015. In 2016, this positive yield effect is even more evident in the relative $GM_{Mixture}$; all relative $GM_{Mixture}$ are here well above the diagonal. For the year 2017, the relative $GM_{Mixture}$ of almost all mixed stand combinations are above 1, but not as pronounced as in the previous year.

Over the years, it can be seen at the Deppoldshausen site that mixed stands with the hybrid wheat Ta3 perform worst in absolute values (Euro/ha) and for the most part even result in negative GM, which is in particular due to the very high seeding density and thus very high seed costs. However, these mixed stands are in all cases superior to their two corresponding pure stands in the relative GM. The positive mixing effect of the mixed stand at this marginal site is overall very clear at the level of the relative GM. The relative economic advantage of the mixed stand is clearly more pronounced here than at the high-yielding site Reinshof. This again indicates that mixed cropping seems to be particularly suitable for areas with poorer site properties, since resource utilization in the mixed stand is favored by the complementary use of the growth factors.

3.3 Whole-Farm Optimization Model

3.3.1 Functionality and Planning Assumptions for Linear Programming

A whole-farm optimization model can be used to identify the economically optimal production program, taking into account intra-farm interdependencies arising from the competition of different production methods for scarce fixed production factors. However, what is of particular relevance for the mixed cropping cultivation under consideration is the possibility of a sensitivity analysis within the optimization model. In terms of a "what-would-be-if" analysis, stability ranges for the GM for the mixed stand can be identified in the form of a ceteris paribus (c.p.) comparison. This can be used to answer the question of how high the GM of the mixed stand would have to be, in order to be included in the economically optimal production program, all other things being equal. Stability ranges determined in this way also provide information about the area on which the mixed stand with the corresponding GM would be included in the production program. Thus, implications regarding the economic viability of the mixed stand can be derived that go beyond the concretely calculated GM of the mixed stand, and can give indications on the extent of possible financial support options.

In the whole-farm model, the mixed stand is in direct competition with other production methods, taking working hours, crop rotation and greening restrictions (incl. EFA) into account. Using linear programming, the total gross margin can be maximized and the economically optimal production program can be identified. In addition, different scenarios can be considered, which can provide information about farm adjustment reactions, e.g. in case of a politically induced change of planning assumptions. Formally, the linear optimization model can be represented as follows:

$$\max_{x_i} TGM = \max_{x_i}\left(\sum_{i=1}^{I} GM_i \cdot x_i\right) \tag{2}$$

$$s.t. \quad \sum_{i=1}^{I} a_{j;i} \cdot x_i \leq \overline{b_j} \;\; for\, j = 1,2,\ldots,J \tag{3}$$

$$x_i \geq 0 \tag{4}$$

Equation (2) represents the target function. The total gross margin (TGM, in Euro) is the sum of the GM of individual production processes i (for $i = 1,2,\ldots,I$) weighted by their respective cultivation areas x_i (in ha). The maximization is performed under constraints (3), where j (with $j = 1,2,\ldots.,J$) denotes the capacity constraints to be considered. In sum, the products of the capacity demands of the respective production method $a_{j;i}$ and the cultivation area x_i cannot exceed the endowment with the corresponding capacity $\overline{b_j}$. In addition, according to equation (4), the cultivation area of the production methods cannot become negative.

In order to be able to estimate a whole-farm model based on the field experiment data, an example farm was constructed, further planning assumptions made and restrictions formulated. The model was created for the year 2016, as representative yield data from the most recent census of agriculture 2016 could be used. The planning assumptions and capacity restrictions made are described below:

- The constructed example farm cultivates 70 ha of arable land (Lower Saxony average 2016: 68.7 ha), it is a pure arable farm. The farm generates average yields (ML und LSN, 2017) and achieves average market prices (AMI, 2020; KTBL, 2020) (see Table 5).
- The farm is managed on a part-time basis, one worker with 960 working hours (Wh) per year is available (50% position at 160 Wh/month), of which 240 Wh each can be used within 3 months, on the one hand to prevent that all Wh are performed within a short period of time and on the other hand to be able to balance monthly labor peaks.
- Production methods are: Winter wheat, silage maize (biogas), winter rapeseed, winter faba bean, mixed stand of winter faba bean and winter wheat, winter catch crop (mixture of oil radish, mustard, phacelia), fallow land.
- Crop rotation restriction include: a maximum of 66 % wheat, a maximum of 33 % rapeseed, a maximum of 50 % maize and a maximum of 25 % faba bean (KTBL, 2018). It is assumed that the mixed stand is counted with 50 % towards each of the corresponding crop rotation restrictions.
- Greening requirements that arise for a farm with more than 30 ha of arable land and apply to the farm under consideration, are taken into account (BMEL, 2015): at least 3 different main crops must be cultivated. The land share of the first main crop cannot exceed 75 %. First and second main crop cannot exceed a land share of 95 % in total. At least 5 % of the arable land must be used to provide the EFA.
- Silage maize can be produced for a neighboring biogas plant, but there is no delivering obligation. A winter catch crop must be grown before silage maize. By assumption, this is cultivated unfertilized and without chemical crop protection measures (creditable for greening).

The cost calculation for the different production methods is mainly based on the data from the KTBL. An average field size of 5 ha and a farm-to-field distance of 2 km are assumed. Cultivation is mostly applied non-rotational on medium soils. Yields correspond to the average yields for Lower Saxony from 2016, where available (ML und LSN, 2017). Prices for wheat and rapeseed are from AMI (2020); for silage maize from KTBL (2020). For the GM of winter faba bean (Vf7) and the mixed stand (Vf7 and Ta1), the results of the 2016 Reinshof experiment were used. The GM composition of the other production methods is illustrated in Table 5.

Table 5:
GM of Further Production Methods

	Winter wheat	Silage maize (biogas)	Winter rape-seed	Winter catch crops	Fallow land (1 year)
Yield dt/ha	83.3	465	36.80	0	0
Price €/dt	15.52	3.20	36.70	0	0
Revenue €/ha	1,292.82	1,488.00	1,350.38	0	0
Seed €/ha	84.00	242.00	85.80	74.95	34.20
Fertilizer €/ha	267.90	40.70	213.90	0	0
CPP €/ha	163.20	111.08	203.72	0	0
Hail Insurance €/ha	9.70	10.51	29.85	0	0
variable machine costs €/ha	179.14	119.70	171.73	65.08	75.59
Interests €/ha	5.28	6.89	5.23	1.04	0.56
Contractor €/ha		400.00		0	
Variable Costs €/ha	709.22	927.2	710.23	141.07	110.36
Gross Margin €/ha	583.60	560.89	640.14	-141.07	-110.36

Based on the assumptions described above and taking into account the greening regulations valid in 2016, the optimization table shown in Table 6 is derived. In the context of greening, a mixed stand of grain legumes and cereals was not considered in 2016 (BMEL, 2015).

Table 6:
Optimization Tableau Zero-Solution

	Winter wheat	**Silgae Maize**	**Winter Rapeseed**	**Winter Faba bean (Vf7)**	**Mixed stand (Vf7/Ta1)**	**Winter Catch Crops**	**Fallow Land (1year)**	**Capacity restrictions**
GM (€/ha)	583.60	560.89	640.14	171.99	198.08	-141.07	-110.36	
Cultivation (ha)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Area require.(ha)	1	1	1	1	1	1	1	≤ 70
Total Wh	8.57	8.26	7.46	9.59	12.82	3.75	3.43	≤ 960
Wh Jan.-March	0.87	0.47	1.05	0.85	0.85	1.64	0	≤ 240
Wh April-June	1.21	6.02	0.63	1.38	1.38	0	2.67	≤ 240
Wh July-Sept.	4.05	0.13	5.53	3.12	5.81	2.11	0	≤ 240
Wh Oct.-Dec.	2.44	1.64	0.25	4.24	4.78	0	0.76	≤ 240
Crop rotation								
WW (max. 66%)	0.33	-0.66	-0.66	-0.66	0.165	-0.66	-0.66	≤ 0
Rapeseed (max. 33%)	-0.33	-0.33	0.66	-0.33	-0.33	-0.33	-0.33	≤ 0
Maize (max. 50%)	-0.50	0.50	-0.50	-0.50	-0.50	-0.50	-0.50	≤ 0
Faba bean (max. 25%)	-0.25	-0.25	-0.25	0.75	0.375	-0.25	-0.25	≤ 0
Pre-crop maize	0	1	0	0	0	-1	0	≤ 0
Greening								
WW & Rapeseed (max. 95%)	0.05	-0.95	0.05	-0.95	0.025	-0.95	-0.95	≤ 0
WW & Maize (max. 95%)	0.05	0.05	-0.95	-0.95	0.025	-0.95	-0.95	≤ 0
(…)								
EFA (min. 5% of 70 ha)	0	0	0	-0.7	0	-0.3	-1	≤ -3.5

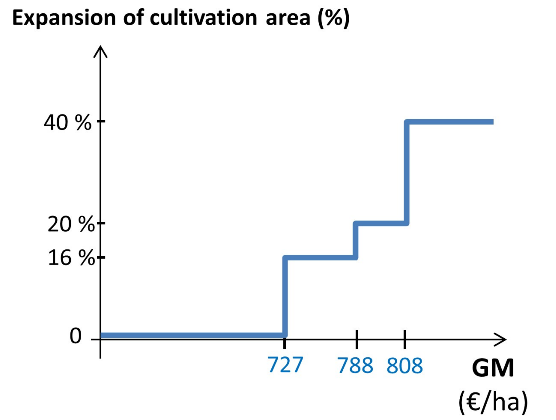
3.3.2 Scenario 1: Model Taking Policy Restrictions Valid in 2016 into Account

The results of linear programming show that in the economically optimized farm, the mixed stand is not included in the production program (Table 7). Most of the area is cultivated with winter wheat, so the crop rotation restriction is fully utilized and has a limiting effect. To meet the greening requirements in force in 2016, 8.2 ha of winter catch crops (weighting factor EFA: 0.3) is cultivated, which is assumed to be a mixture of three species, and about 1 ha of land is set aside as fallow land (weighting factor EFA: 1). The calculated GM of the winter catch crop and the fallow land are negative, but are nevertheless preferred in the economically optimized farm to the cultivation of winter faba bean (weighting factor EFA: 0.7), which would also be suitable for the provision of the EFA.

Table 7:
Economically Optimal Production Program under Political Restrictions of 2016

Cultivation	ha	%
Winter wheat	46.5	66%
Silage maize	8.2	12%
Winter rapeseed	6.0	9%
Winter faba bean	0.0	0%
Mixed stand winter wheat & winter faba bean	0.0	0%
Winter catch crop	8.2	12%
Fallow land	1.0	2%
TGM	34,327 €	

Stability Ranges Mixed Stand



Performing the sensitivity analysis in the form of a ceteris paribus (c.p.) comparison, allows the identification of stability ranges for the GM of the mixed stand. Only with a GM of approx. 727 Euro/ha would the mixed stand, all other things being equal, be included in the production program with a land share of 16 %. At the same time the cultivation of winter wheat in pure stand would be reduced and the cultivation of rapeseed completely removed from the production program. This corresponds to more than a tripling of the current GM (from 198 Euro/ha to 727 Euro/ha). The GM of the mixed stand would thus also have to be decidedly higher than the GM of wheat pure stand (583 Euro/ha vs. 727 Euros/ha), partly because the working hour requirement in the mixed stand is higher. With a further increase to 788 Euro/ha, an expansion of the land share of the mixed stand to a total of 20 % would be economically optimal. Only at a GM of 808 Euro/ha would there be a further considerable expansion of the land under mixed stand cultivation. Consequently, an expansion of the mixed stand cultivation to 40 % of the arable land and a simultaneous reduction of the cultivation of the wheat pure stand to 15 % would only take place when the GM of the mixed stand is approximately quadrupled. One of the reasons for this is that the mixed crop competes directly with the wheat pure stand in the crop rotation and in the greening restrictions. In addition, there are the increased working hours (especially due to separation of the mixed yields) in the time-critical harvesting phase.

3.3.3 Scenario 2: Model Taking the Changed Policy Restrictions for EFA from 2018 into Account

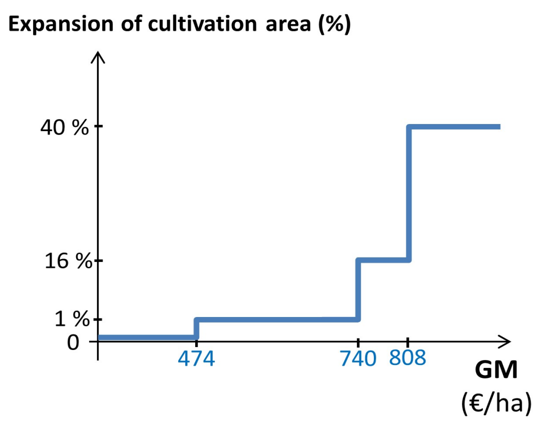
In a second scenario, the changes implemented in 2018 for the provision of the EFA were taken into account. Specifically, this means that mixed cropping with grain legumes and cereals is eligible for EFA with a weighting factor of 1, if the legume predominates in the plant stand and subject to the prohibition of chemical crop protection products (BMEL, 2018). For the model, it is assumed that the considered mixed stand meets the requirements to be counted as EFA.

In this scenario, it can also be seen that the mixed stand is not included in the economically optimal production program. However, the winter faba bean pure stand is included in the production program to provide the EFA because the change in regulations in 2018 changed the weighting factor for legumes (from 0.7 to 1.0; BMEL 2018). For the example farm, it is therefore economically worthwhile to cultivate previously fallow land with winter faba beans after the new regulation. The rest of the production program has not changed much compared to the first scenario; winter wheat is again the most cultivated in terms of land share. The TGM changes by only 5 Euros compared to the previous scenario (Table 8).

Table 7:
Economically Optimal Production Program under Political Restrictions of 2018

Cultivation	ha	%
Winter wheat	46.5	66%
Silage maize	8.6	12%
Winter rapeseed	5.3	8%
Winter faba bean	0.9	1%
Mixed stand winter wheat & winter faba bean	0.0	0%
Winter catch crop	8.6	12%
Fallow land	0.0	0%
TGM	34,332 €	

Stability Ranges Mixed Stand



The sensitivity analysis shows that the mixed stand would be included c.p. at a GM of 474 Euro/ha with a land share of about 1 % (0.8 ha). The mixed stand would then replace the winter faba bean pure stand with respect to the provision of the EFA, but the majority of this restriction would still be fulfilled via the cultivation of the winter catch crop. It becomes clear that the mixed stand with the current GM is not attractive enough from an economic point of view for cultivation on a conventional farm, even if it is creditable for the EFA. Even a hypothetical increase of the weighting factor to 2.1 would c.p. lead to a cultivation of only 0.4 ha of the mixed stand on the example farm at the constant GM (198 Euro/ha).

An increase of the land share to 16% in this scenario would only occur from a GM of 740 Euro/ha for the mixed stand, which would also result in a reduction of the wheat pure stand and a removal of rapeseed cultivation from the production program. A quadrupling of the initial GM to 808 Euro/ha would increase the land share of the mixed stand to 40 % and further reduce the cultivation of wheat in the pure stand. In particular, the competition in the crop rotation restrictions with the wheat pure stand is also a limiting factor for the cultivation of the mixed stand. However, with regard to the crop rotation effects of the mixed stand, there are so far no clear conclusions in the agronomic literature either. For the constraints of crop diversification, there are clear definitions according to which a mixed stand is considered to be counted as two crops species, if the share of the individual crop covers more than 25 % of the land. The crops are then weighted by their respective area coverage (BMEL, 2015). It is assumed that the 50 % to 50 % seeding rate of the IMPAC³ experiments meets this definition. In the example farm, however, it is not the greening requirements that have a restrictive effect, but the crop rotation restrictions, according to which the proportion of wheat should not exceed 66 % in the crop rotation. Mathematically, this restriction can easily be divided according to the seeding ratio and taken into account in the programming. However, it is not clear whether this division is optimal from a practical and crop management point of view. There is also the question of whether the crop rotation restriction should be based on the faba bean, which in our example should not exceed a share of 25 %. In concrete terms, this raises the question of the time intervals at which a mixed stand can or should be grown on the same land from an agronomic point of view.

Overall, it can be seen that the mixed stand in the form carried out in the field experiment is not yet competitive enough to be integrated into the economically optimized example farm. Even an assumed crediting within the framework of the EFA does not allow the inclusion in the economically optimal production program. While the concrete numerical values are only valid for the example farm considered, the fundamental issue will be similar in many German farms. However, it must be noted that the positive pre-crop effects of the mixed stand were not considered in the GM calculation. These can have a positive effect on the relative competitiveness of the mixed stand, but not to an extent that would decisively influence the profitability in the example farm and lead to the required tripling of the GM.

4 Discussion

In the crop science literature, one of the main advantages mentioned of mixed stands is the increased total yield compared to the corresponding pure stands. These results are also confirmed for the field experiments considered here (SIEBRECHT-SCHÖLL, 2019). However, it is evident at the GM level of these production methods that this yield advantage does not carry through to the same extent at the economic level. Comparing the GM of the mixed stand with the individual pure stands, it can be seen that at the high-yielding Reinshof site, the (unfertilized) wheat pure stands yields the highest overall GM in two out of three years, and this despite the by assumption lower price of fodder wheat in the pure stand. In contrast, at the marginal site Deppoldshausen, the mixed stands results in the highest GM overall in two out of three years. This impression is also continued in the relative $GM_{Mixture}$. For the Deppoldshausen site, the clear advantage of the mixed stand is seen in all years, while the results for Reinshof are mixed. Problematic from a practical agricultural point of view is that these comparisons and relative references are made to the likewise extensively produced (unfertilized) pure stand yields. However, with regard to wheat pure stand yields this benchmark is only of very limited relevance from a practical point of view, because wheat in conventional agriculture is generally not produced extensively and with the use of nitrogen fertilizers, which leads to substantially higher yields than those in the experiments. The yield level of the experiments is in principle more suitable as a benchmark for organically produced wheat. However, organic fertilization is also used in many cases in organic farming. In addition, there is the application of herbicides in the pre-emergence stage in the field experiment, which makes the assumption of prices for organically produced crops unsuitable. The use of herbicides must also be viewed critically with regard to the assumed recognition of the mixed stand as an EFA, due to the pesticide ban that has been in place since 2018 (BMEL, 2018).

A conflict of objectives on the economic level can be seen based on our results with regard to hybrid wheat. With respect to yields, the mixed stands with hybrid wheat deliver very high total yields across all years (SIEBRECHT-SCHÖLL, 2019), but at the GM level, these combinations consistently perform worst, especially due to the higher seed costs. However, against the background of the sowing density applied in pure stand for hybrid wheat (320 seeds/m²), which is decidedly too high from a practical point of view, the calculated GM can lead to incorrect conclusions. The variety used, Hybery, is described as one of the most productive wheat varieties, at a seed density of 160 seeds/m² (ZIPPERT et al., 2013). If the hybrid wheat was to perform as positively in the mixed stand at half the seed density, the relative competitiveness of this mixed stand would improve drastically as the largest cost factor of the seed would be halved.

One of the objectives of the IMPAC³ project was to identify traits that lead to the yield advantage in the mixed stand, in order to be able to select varieties for cultivation in mixed stands. On the economic level, it is clear that there is a parallel need for research on cultivation under practical conditions for making mixed cropping with main crops as a cultivation method applicable in practice. Although extensive cultivation methods, as in the present experiment, are becoming increasingly important, it must be questioned to what extent they can be implemented on a large scale. If one compares, for example, conventionally produced wheat yields with the total yields of the mixed stand, it becomes obvious that the yield level in conventional agriculture is significantly higher. Against the background of the absolute scarcity of land, which will continue to increase in the future, the question arises to what extent losses in land productivity in return for more extensive production are sustainable in the long term. Similar concerns have already been raised with respect to organically produced crops, particularly in the context of global food security (OECD/FAO, 2020). With regard to the cultivation of mixed stands, it will therefore be essential to strive for yield increases, which will only be possible through continuous research in all disciplines of the agricultural sector.

The whole-farm model shows that the mixed stand of winter wheat and winter faba bean is not competitive enough to be integrated into the economically optimized example farm. Even the assumed crediting under the 2018 EFA regulations cannot considerably influence this result. The seeding rate in the experiment was 50 % of the seeding rate of both pure stands. The seeding rate of 50 % to 50 % used in the experiments, corresponds to a seeding density of 20 seeds/m² winter faba bean and 160 seeds/m² winter wheat, assuming the same germination capacity. This would result in a total plant population of 180 plants/m². If the proportion of the plant population is calculated on the basis of the individual plants, the proportion of legumes is only 11.11 % (20 of 180 plants/m²), while that of wheat is 88.88 % (160 of 180 plants/m²). This example shows that the terms "seeding rate/seeding ratio" and "seeding density/plant stand" cannot be used synonymously in connection with the cultivation of mixed stands, which makes communication between the different actors difficult. This peculiarity arises in mixed cropping cultivation from the different requirements of the crop species. Formulations such as "The requirement is that the proportion of legumes in the plant stand predominates" (translated from BMEL, 2018) are therefore not necessarily open to unambiguous interpretation. For the considered experiments, the "seeding rate" 50 % legumes to 50 % cereals corresponding to the usual seeding rate in pure stand, results in a "plant stand" of 11 % legume plants and 88 % cereal plants. In grain yield, the legume share (dt/ha) in the considered experiment is in most cases far above 50 % (cf. Fig. 1, SIEBRECHT-SCHÖLL, 2019), which is also partially due to the markedly higher TSW. Biomass yields may again differ from grain yields, although based on the morphology of winter faba bean, biomass per plant is in many cases higher than that of wheat. In addition, the proportions of legumes and cereals in the total yield (grain and biomass) will always vary depending on the environmental conditions in a given year, which can help stabilize the total yield in the mixed stand. The stabilization of the total yield is one of the assumed advantages of the cultivation of mixed stands in terms of risk reduction through crop diversification. However, this can result in a case where cereals outweigh legumes in biomass and grain yield, even if a seeding rate where more than 50 % of the proportion of the legume seeding rate was used. In view of political restrictions on the cultivation of mixed stands, greater attention should therefore be paid to the wording, as this could otherwise lead to ambiguities. In order to avoid uncertainties regarding the fulfillment of restrictions from the farmers' point of view, it would be recommendable to link them to the sowing and not to the resulting plant population. As referring the actual plant population can be problematic due to the fluctuating proportions of the species, which cannot be clearly predicted depending on the annual environmental conditions. However, it should be noted that both from a biodiversity and yield point of view, mixed stands with higher proportions of legumes in the seeding rate should be aimed for (HOF und SCHMIDTKE, 2006).

In the whole-farm model it also becomes clear that factors beyond the GM are relevant for the practical implementation. One of these factors is the increased working time in the mixed stand during the time-critical harvesting phase due to the separation of the mixed yield. According to the assumption, the separation of the mixed yield was done through wind sifting by the farmer. In practice, the question arises whether additional investments in machinery by the farmer would be required to ensure clean separation of the mixed yield. Marketing of the mixed yield is in principle possible, but is cited as one of the major obstacles from the perspective of German farmers (BONKE und MUSSHOFF, 2020). Furthermore, the separation of the mixed yield is a process step in the value chain, which is not needed for pure stands and thus represents an additional cost factor. At this point, the technological lock-in around the dominant crops also becomes apparent again (MEYNARD et al., 2018). For livestock farms, the use of mixed yields as fodder can be an opportunity to save separation costs and additional work time entirely, which can result in improving the relative competitiveness of the mixed stand.

However, in our constructed arable farm, the crop rotation restriction and increased work hours are responsible for the fact that the mixed stand would have to be much higher in the GM than the wheat pure stand in order to be included in the economically optimal production program. Thus, from a practical point of view, the relevant comparison is with the profitability of the species in the mixed stand that is dominantly used in agriculture. Against the background that cereals are produced on more than 6 Mio. ha in Germany, whereas grain legumes are produced on only about 0.2 Mio. ha. (DESTATIS, 2020), the line of thought in terms of promoting biodiversity should also be towards shifting from pure cereal stands to mixed stands with cereals in order to reduce the share of cereals in crop rotations. If, on the other hand, production were to be shifted from pure legume stands to mixed stands with legumes, the question arises as to whether this would ultimately actually lead to an increase in biodiversity within German agricultural production. For the example farm, the results further show that the inclusion of the mixed stand under the assumption of the higher GM in the sensitivity analysis leads to rapeseed being eliminated from the production program. Hence, the overall number of different crop types within the crop rotation would remain stable.

With respect to other ecosystem services associated with mixed cropping, it should be emphasized that these have not been included in the economic assessment carried out at the monetary level. On the one hand, this is due to insufficient data and on the other hand due to the fact that many ecosystem services can only to a limited extent be monetarily evaluated at the farm level. The symbiotic nitrogen fixation of the legume is an example of a benefit of mixed cropping that can contribute to reducing fertilizer costs and potentially negative environmental impacts equally. In this regard, the mixed stand of legumes and cereals is also advantageous over the legume pure stand because nitrogen leaching in the mixed stand is decreased and nitrogen use efficiency is increased (JENSEN et al., 2020; HAUGGAARD-NIELSEN et al., 2003; SENBAYRAM et al., 2015). However, the reported stability ranges for the GM of the mixed stand in the optimized model show that even accounting for the cost of saved fertilizer in the subsequent crop would still not be sufficient to lead to its inclusion into the economically optimized production program.
This raises the question which options are available to improve the profitability to make cultivation attractive for German farmers. The provision of ecosystem services in mixed stands is a substantial ecological advantage over conventional pure stands, making this form of cultivation interesting for a more sustainable production. However, the associated ecosystem services, such as increasing biodiversity within arable land, are currently not explicitly valued in the market in monetary form. The implementation of policy restrictions could help to further establish mixed cropping in German agriculture. However, the results of BONKE und MUSSHOFF (2020) suggest that increasing political pressure may also have a negative influence on the intention to cultivate mixed stands. Voluntary support measures seem to be the preferable option here. The eco-schemes proposed as part of the CAP reform could be one way to encourage mixed cropping adoption in practice. In addition, there is the possibility of improving the market performance of the mixed stand by utilizing consumers higher willingness to pay for sustainably produced food (e.g. BAHRS et al., 2020). For example, LEMKEN et al. (2017a) show that German consumers are willing to pay more for foods with legume content, which have been produced in a more environmentally friendly way. However, analogous to the animal welfare label, which is now established in Germany, this would require a differentiation of products based on the production process and a corresponding certification. Furthermore, there is the possibility that farmers would also be willing to forego part of their profits in favor of a more ecologically beneficial production, as altruistic entrepreneurial goals can also be pursued by farmers (e.g. CHOUINARD et al., 2008).

5 Conclusion

Overall, the results indicate that the cultivation of winter faba bean and winter wheat in a mixed cropping system is currently not economically competitive in conventional German agriculture in the implemented form. However, the results show that mixed stands with main crops may be more suitable for sites with more marginal site characteristics. Here, the advantageousness established in the yields also shows up very clearly at the level of the gross margin. However, the results of the sensitivity analysis of the whole-farm optimization model show that the gross margins of the mixed stand would even have to rise far above the gross margin of the currently produced pure cereal stand in order to be integrated into the economically optimized example farm. This is then due to the fact that the mixed stand competes internally with other production methods for scarce production factors. In order to achieve an implementation of mixed cropping with main crops in Germany, it will therefore be essential to improve the relative competitiveness of mixed stands. On the one hand, this points to a need for further research in the disciplines of plant cultivation and breeding and also applies to practical issues, such as the crop rotation effects of mixed stands with main crops. On the other hand, it will also be relevant to address and involve other actors in the value chain besides farmers. Some of the challenges that arise from a practical point of view for the cultivation of mixed cropping with main crops are caused by the technological lock-in. Only if the technical requirements for cultivation are created and the sales opportunities improved, will the cultivation of mixed cropping with main crops be feasible on a large scale in Germany.

Summary

The profitability of mixed cropping with winter faba bean and winter wheat

One possibility to increase the biodiversity in German agriculture is mixed cropping. The simultaneous cultivation of legumes and non-legumes can inter alia help to save synthetic nitrogen fertilizers. However, this form of cultivation is currently not widespread in Germany and the availability of information is low from a practical point of view. In particular, only very limited information about the economic efficiency of different mixed cropping combinations is available. Against this background, this paper evaluates the profitability of mixed stands using the example of winter faba bean and winter wheat based on the results of a field trial. The results indicate that mixed cropping with winter faba bean and winter wheat in the implemented form is currently not economically competitive in conventional German agriculture. However, mixed cropping in the present form seems to be suitable especially for

sites with poorer site characteristics. The results of the sensitivity analysis of a whole-farm optimization model show that the gross margins of the mixed stands would even have to surpass that of the dominantly produced cereals in pure stand.

Acknowledgement

This research was funded by the German Federal Ministry of Education and Research (FKZ 031A351A) within the framework of the IMPAC³ project. IMPAC³ is a project of the Centre of Biodiversity and Sustainable Land Use at the University of Goettingen. We thank the project partner Norddeutsche Pflanzenzucht (NPZ).

Very special thanks go to Regina Martsch and Tina Tietz, who managed the field experiments. We thank Marius Michels for valuable comments on the manuscript.

References

1. AMI (2020): Marktdaten: Preise für Getreide, Ölsaaten, Hülsenfrüchte 2015-2017. Agrarmarkt Informations-Gesellschaft mbH. In: https://www.ami-informiert.de/ami-onlinedienste/serviceportal-forschung-lehre/.
2. ANDREWS, D. J. und A. H. KASSAM (1976): The importance of multiple cropping in increasing world food supplies.
3. BAHRS, E., J. DAUBER, P. H. FEINDT, U. HAMM, J. ISSELSTEIN, G. BACKES, H. BRANDT, E.-M. ENGELS, J. ENGELS, A. GRANER, M. HERDEGEN, S. SCHRÖDER, E. THOLEN, S. WAGNER, F. WÄTZOLD, H. WEDEKIND, H. WOLF, V. WOLTERS (WISSENSCHAFTLICHER BEIRAT FÜR BIODIVERITÄT UND GENETISCHE RESSOURCEN) (2020): 10 Empfehlungen für mehr Biodiversität im Ackerbau. Stellungnahme zum Diskussionspapier des BMEL zur „Ackerbaustrategie 2035". In: Berichte über Landwirtschaft - Zeitschrift für Agrarpolitik und Landwirtschaft Sonderheft 231: 1–23.
4. BEDOUSSAC, L., E.-P. JOURNET, H. HAUGGAARD-NIELSEN, C. NAUDIN, G. CORRE-HELLOU, E. S. JENSEN, L. PRIEUR und E. JUSTES (2015): Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. In: Agronomy for Sustainable Development 35 (3): 911–935.
5. BMEL (2015): Umsetzung der EU-Agrarreform in Deutschland - Ausgabe 2015. https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/UmsetzungGAPinDeutschland2015.html
6. BMEL (2018): Änderungen bei den Direktzahlungen ab dem Antragsjahr 2018. https://www.bmel.de/SharedDocs/Downloads/EU/AendDirektzahlungen2018.pdf?__blob=publicationFile.

7. BONKE, V. und O. MUSSHOFF (2020): Understanding German farmer's intention to adopt mixed cropping using the theory of planned behavior. In: Agronomy for Sustainable Development 40 (6): 1–14.

8. CHEN, G., X. KONG, Y. GAN, R. ZHANG, F. FENG, A. YU, C. ZHAO, S. WAN und Q. CHAI (2018): Enhancing the systems productivity and water use efficiency through coordinated soil water sharing and compensation in strip-intercropping. In: Scientific Reports 8: 1–11.

9. CHOUINARD, H. H., T. PATERSON, P. R. WANDSCHNEIDER und A. M. OHLER (2008): Will Farmers Trade Profits for Stewardship? Heterogeneous Motivations for Farm Practice Selection. In: Land Economics 84 (1): 66–82.

10. DESTATIS (2020): Land- und Forstwirtschaft, Fischerei. Landwirtschaftliche Bodennutzung, Anbau auf dem Ackerland (Vorbericht). Statistisches Bundesamt. In: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Publikationen/Bodennutzung/anbau-ackerland-vorbericht-2030312208004.html.

11. GABA, S., F. LESCOURRET, S. BOUDSOCQ, J. ENJALBERT, P. HINSINGER, E.-P. JOURNET und ET AL. (2015): Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. In: Agronomy for Sustainable Development 35 (2): 607–623.

12. HAUGGAARD-NIELSEN, H., P. AMBUS und E. S. JENSEN (2003): The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. In: Nutrient Cycling in Agroecosystems 65 (3): 289–300.

13. HAUGGAARD-NIELSEN, H., B. JØRNSGAARD, J. KINANE und E. S. JENSEN (2008): Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. In: Renewable Agriculture and Food Systems 23 (1): 3–12.

14. HOF, C. und R. RAUBER (2003): Anbau von Gemengen im ökologischen Landbau: 55 S. In: https://biokulturorg.files.wordpress.com/2017/11/anbau-von-gemengen-im-c3b6kologischen-landbau.pdf.

15. HOF, C. und K. SCHMIDTKE (2006): Erzeugung von Weizen hoher Backqualität durch Gemengeanbau mit Winterackerbohne und Wintererbse im ökologischen Landbau. Abschlussbericht. Dresden, Göttingen. In: https://orgprints.org/15171/1/15171-03OE050-htw_dresden-schmidtke-2006-backqualitaet_weizen.pdf.

16. JENSEN, E. S., G. CARLSSON und H. HAUGGAARD-NIELSEN (2020): Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. In: Agronomy for Sustainable Development 40 (1): 1–9.

17. KTBL (Hrsg.) (2018): Faustzahlen für die Landwirtschaft. YARA, Darmstadt.

18. KTBL (2020): Leistungs-Kostenrechnung Pflanzenbau. In: https://daten.ktbl.de/dslkrpflanze/postHv.html.

19. LEMKEN, D., M. KNIGGE, S. MEYERDING und A. SPILLER (2017a): The Value of Environmental and Health Claims on New Legume Products: A Non-Hypothetical Online Auction. In: Sustainability 9 (8): 1340.

20. LEMKEN, D., A. SPILLER und M. von MEYER-HÖFER (2017b): The Case of Legume-Cereal Crop Mixtures in Modern Agriculture and the Transtheoretical Model of Gradual Adoption. In: Ecological Economics 137: 20–28.

21. MALÉZIEUX, E., Y. CROZAT, C. DUPRAZ, M. LAURANS, D. MAKOWSKI, H. OZIER-LAFONTAINE, B. RAPIDEL, S. de TOURDONNET und M. VALANTIN-MORISON: Mixing Plant Species in Cropping Systems: Concepts, Tools and Models: A Review. In: : Lichtfouse Hg 2009: 329–353.

22. MAMINE, F. und M.'H. FARÈS (2020): Barriers and Levers to Developing Wheat–Pea Intercropping in Europe: A Review. In: Sustainability 12 (17): 6962.

23. MARTIN-GUAY, M.-O., A. PAQUETTE, J. DUPRAS und D. RIVEST (2018): The new Green Revolution: Sustainable intensification of agriculture by intercropping. In: The Science of the total environment 615: 767–772.

24. MEYNARD, J.-M., F. CHARRIER, M.'H. FARES, M. LE BAIL, M.-B. MAGRINI, A. CHARLIER und A. MESSÉAN (2018): Socio-technical lock-in hinders crop diversification in France. In: Agronomy for Sustainable Development 38 (5): 116.

25. ML NIEDERSACHSEN (2020): AL 1 - ANBAU VIELFÄLTIGER KULTUREN IM ACKERBAU HTTPS://WWW.ML.NIEDERSACHSEN.DE/STARTSEITE/THEMEN/LANDWIRTSCHAFT/AGRARFORDERUNG/AGRARUMWELTMASSNAHMEN_AUM/AUM_DETAILS_ZU_DEN_MASSNAHMEN/AL1_ANBAU_VIELFALTIGER_KULTUREN/AL-1---ANBAU-VIELFAELTIGER-KULTUREN-IM-ACKERBAU-122327.HTML

26. ML und LSN (2017): Die niedersächsische Landwirtschaft in Zahlen 2017. Niedersächsisches Ministerium für Ernährung, Landwirtschaft und Verbraucherschutz.

27. OECD/FAO (2020): OECD-FAO Agricultural Outlook 2020-2029. FAO, R./O. P.

28. PELZER, E., M. BAZOT, D. MAKOWSKI, G. CORRE-HELLOU, C. NAUDIN und ET AL. (2012): Pea–wheat intercrops in low-input conditions combine high economic performances and low environmental impacts. In: European Journal of Agronomy 40: 39–53.

29. POSTMA, J. A. und J. P. LYNCH (2012): Complementarity in root architecture for nutrient uptake in ancient maize/bean and maize/bean/squash polycultures. In: Annals of Botany 110 (2): 521–534.

30. RAIFFEISEN WAREN GMBH (2019): Saatgutpreise Winterweizen und Winterackerbohne. personal Communication, E-Mail.

31. ROSA-SCHLEICH, J., J. LOOS, O. MUßHOFF und T. TSCHARNTKE (2019): Ecological-economic trade-offs of Diversified Farming Systems – A review. In: Ecological Economics 160: 251–263.

32. ROTH, F. und W. LINK (2010): Selektion auf Frosttoleranz von Winterackerbohnen (Vicia faba L.): Methodenoptimierung und Ergebnisse Selection on freezing-tolerance of faba bean (Vicia faba L.): Improvement of methods and results. In: Tagungsband der 60. Jahrestagung der Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs 24.-26. November 2009, Raumberg-Gumpenstein: 31–37.

33. SENBAYRAM, M., C. WENTHE, A. LINGNER, J. ISSELSTEIN, H. STEINMANN, C. KAYA und S. KÖBKE (2015): Legume-based mixed intercropping systems may lower agricultural born N 2 O emissions. In: Energy, Sustainability and Society 6 (1): 1–9.

34. SIEBRECHT-SCHÖLL, D. (2019): Züchterische Analyse von acht Winterackerbohnengenotypen für den Gemengeanbau mit Winterweizen. Dissertation. Georg-August-Universität, Göttingen.

35. STEIN, S. und H.-H. STEINMANN (2018): Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems – A case study from Central Europe. In: European Journal of Agronomy 92: 30–40.

36. WEZEL, A., M. CASAGRANDE, F. CELETTE, J.-F. VIAN, A. FERRER und J. PEIGNÉ (2014): Agroecological practices for sustainable agriculture. A review. In: Agronomy for Sustainable Development 34 (1): 1–20.

37. WILSON, J. B. (1988): Shoot Competition and Root Competition. In: The Journal of Applied Ecology 25 (1): 279.

38. ZIPPERT, B., F. WEHNER, S. JUNGERT und S. BÖSE (2013): Sortenwahl Winterweizen II. Sortenwahl - eine Typfrage. In: praxisnah - Fachinformationen für die Landwirtschaft (3): 4–6.

Author addresses:

M. Sc. Vanessa Bonke,

Prof. Dr. Oliver Mußhoff

Department für Agrarökonomie und Rurale Entwicklung

Arbeitsbereich Landwirtschaftliche Betriebslehre

Georg-August-Universität Göttingen

Platz der Göttinger Sieben 5

37073 Göttingen

M. Sc. Vanessa Bonke,

Dr. Daniel Siebrecht-Schöll

Zentrum für Biodiversität und nachhaltige Landnutzung (CBL)

Georg-August-Universität Göttingen

Büsgenweg 1

37077 Göttingen

E-Mail: vanessa.bonke@agr.uni-goettingen.de