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Weed suppression and crop yield performance in sole and intercrops of common vetch and spring wheat depending on seed density ratio in organic farming

Unkrautunterdrückung und Ertragsleistung in Reinsaat und Gemengen von Saatwicken mit Sommerweizen in Abhängigkeit vom Saatstärkenverhältnis im ökologischen Landbau

Zusammenfassung

Die Saatwicke (*Vicia sativa* L.) kann durch ihren hohen Rohproteingehalt im Korn eine alternative Körnerleguminose zu Ackerbohnen, Erbsen, Lupinen und Sojabohnen darstellen. Da eine Körnernutzung von Saatwicken unüblich ist, müssen Anbausysteme für diese Nutzung entwickelt werden. Unkrautkonkurrenz stellt im Körnerleguminosenanbau ein zentrales Problem dar, sodass Gemenge-Anbausysteme für die Saatwicke konzipiert werden müssen, die eine gute Unkrautunterdrückung gewährleisten. Vor diesem Hintergrund wurden unterschiedlich zusammengesetzte Gemenge aus Saatwicken mit Sommerweizen und deren Reinsaaten im Jahr 2018 in Norddeutschland untersucht. Ziel war es, diejenigen Saatstärkenverhältnisse zu bestimmen, die die höchste Unkrautunterdrückung und den höchsten Gesamt- sowie Saatwickenertrag erreichen. In einem Feldversuch mit vierfacher Wiederholung wurden zu drei Ernteterminen die Biomasse der Kulturpflanzen sowie zur Vollreife die Kornerträge erfasst. Dabei wurde jeweils auch die Unkrautbiomasse geerntet und deren Stickstoffgehalt analysiert. Die Transmission der photosynthetisch aktiven Strahlung zum Unkrautbestand wurde über den Vegetationsverlauf gemessen. Die Bewertung der Erträge und der Unkrautunterdrückung der Gemenge erfolgte mithilfe verschiedener Indizes. Zudem wurden mögliche Ursachen der Unkrautunterdrückung diskutiert. In den Gemengen mit steigendem Weizenanteil nahm die Unkrautbiomasse ab, wobei diese auch weniger Stickstoff enthielt. Während der Jugendentwicklung transmittierten Gemenge mit höheren Weizenanteilen weniger photosynthetisch aktive Strahlung zum Unkrautbestand, wohingegen diese Gemenge in den späteren Entwicklungsstadien mehr Licht zum Unkraut durchließen. Die Gemenge erzielten höhere Gesamtbiomassen und Gesamtkornerträge als die Reinsaaten. Der mittlere Land-Äquivalenzkoeffizient (LER) aller Gemenge, berechnet anhand der Kornerträge, betrug 1,32. Der Index tatsächlicher Ertragsgewinn oder -verlust (AYL) gab einen mittleren tatsächlichen Ertragsgewinn der Gemenge von 73% im Vergleich zu den Reinsaaten an. Der Konkurrenzquotient (CR) wies den Weizen im Vergleich zur Wicke als konkurrenzstärker aus, sodass der Weizen für den höheren Gesamtertrag der Gemenge verantwortlich war. Es konnte gezeigt werden, dass die Saatwicke in Gemengen mit Sommerweizen erfolgreich angebaut werden kann. Wenn der Wickenanteil im Gemenge nicht zu hoch ist, kann Unkraut durch Gemengeanbau effektiv unterdrückt werden. Bei hohen Wickenanteilen im Gemenge ist die Unkrautunterdrückung nicht ausreichend. Die Konkurrenz um Licht im frühen Entwicklungsstadium und um Stickstoff bestimmt das Unkrautwachstum in Gemengen aus Saatwicke mit Sommerweizen.

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Abstract

Common vetch (*Vicia sativa* L.) can be an alternative grain legume to faba beans, peas, lupins and soy beans due to its high grain protein content. As it is uncommon for grain use, cropping systems need to be developed. Weed infestation is a major problem in grain legume cultivation. Therefore, intercropping systems for common vetch which ensure a low level of weed infestation need to be designed. Thus, weed suppression of common vetch in a replacement series with spring wheat was examined in Northern Germany in the year 2018. It was the aim to define which seed density ratios will achieve the highest weed suppression, total and common vetch yield. Three harvests of crop and weed biomass and a grain harvest at full maturity were carried out in a field experiment with four replications. Weed nitrogen content was examined. Transmission of photosynthetically active radiation to weed canopy level was measured during the season. Yield and weed suppression of intercrops were analysed by different indices, and factors contributing to weed suppression were discussed. With increasing wheat ratio, weed biomass in intercrops decreased and less nitrogen was taken up by weeds. Less photosynthetically active radiation was available to weed canopy level during juvenile development in intercrops with higher wheat ratios, whereas more radiation was available to weeds in these intercrops in later stages. Higher total biomass and grain yield was achieved in intercrops compared to sole crops. The mean land equivalent ratio (LER) of all intercrops calculated from grain yield was 1.32. The index actual yield loss or gain (AYL) specified a mean actual yield gain of intercrops of 73% compared to sole crops. The competitive ratio (CR) revealed that wheat was more competitive compared to vetch. Wheat was responsible for the extra yield of intercrops. It can be concluded that common vetch can be successfully grown in intercrops with spring wheat. Effective weed suppression due to intercropping was possible when the vetch ratio was moderate. With high vetch ratios sufficient weed suppression cannot be achieved. Crop-weed competition for nitrogen and for light in the early growth stages determined weed growth in vetch-wheat intercrops.

Key words: Intercropping, common vetch, weed suppression, indices, organic farming, photosynthetic active radiation, seed density ratio

Introduction

Besides the major aim to increase and stabilize crop yields, agriculture has the objective to design cropping systems with less environmental impacts. To make cropping systems more independent from herbicides weed suppression can be helpful. It is defined as the ability of a crop to reduce weed growth (Hansen et al., 2008). Moreover, cropping systems with legumes are interesting due to self-sufficiency of nitrogen. In addition, intercrops are an interesting management option as they enhance biodiversity in agriculture (Jensen et al., 2015). In the context of climate change the common vetch (*Vicia sativa* L.) could gain in importance, as it has low requirements for soil and climate and has a high adaptability to different site conditions (Jäpel, 1965; Freyer et al., 2005). With a view to Europe's protein demand common vetch could be interesting due to its nutritive values. The grains of common vetches have high crude protein contents of up to 34 % (Jeroch et al., 1993; Böhm, 2015), but also contain anti-nutritive factors (Freyer et al., 2005; Huang et al., 2017). In Europe common vetch is mostly grown as a cover or forage crop (Freyer et al., 2005). However, the cultivation of common vetches as grain legumes can be promising (Francis et al., 1999; Lauk et al., 2007; Böhm, 2013b). Therefore, cropping systems for common vetch with grain use need to be developed. These cropping systems need to achieve sufficient grain yields of common vetch, prevent lodging of vetches to ensure harvest, and ensure a production with a low level of weed infestation as weeds are a major challenge in grain legume cropping (Charles et al., 2007; Zimmer et al., 2015). In organic cereal and grain legume cropping harrowing and hoeing is common. However, mechanical weed control is difficult in vetch cultivation due to its herbaceous growth. Thus, intercropping common vetch with a cereal might be the solution. Intercrops of grain legumes with cereals may have many advantages, namely yield gain, enhanced yield stability, more efficient use of resources, increased nitrogen-fixation rate of legumes, higher protein concentrations in cereals, higher lodging resistance and a reduction of pests, diseases and weeds (Bedoussac et al., 2015). Many experiments have shown extra yield of intercrops compared to sole crops, which is usually expressed by the land equivalent ratio (LER). The LER is the relative land area under sole crops that is needed to produce the same yield as in intercropping (Willey, 1979). Other indices can be helpful to assess the yield benefit of intercrops. Actual yield loss or gain (AYL) is the proportionate yield loss or gain of intercrops compared to the corresponding sole crops (Banik, 1996). The difference to LER is that the seed density ratios are respected (Banik, 1996; Banik et al., 2000). The competitive ratio (CR) calculates the number of times one crop is more competitive than the other (Willey and Rao, 1980). The cumulative relative efficiency index (REIc) is the relative efficiency of the cropping partners assessed over different time periods (Connolly, 1987).

Intercropping can reduce weed infestation (Liebman and Dyck, 1993; Hauggaard-Nielsen et al., 2001; Szumigalski and Van Acker, 2005; Hauggaard-Nielsen et al., 2008; Bilalis et al., 2010; Corre-Hellou et al., 2011; Nelson et al., 2012; Gronle et al., 2015). To evaluate the weed suppression in intercrops indices are helpful for interpretation. According to SZUMIGALSKI and VAN ACKER (2005), relative weed density (RWD) and relative weed biomass (RWB) compare weed density or biomass of the intercrop with all sole crops. Thus, a synergism or antagonism in weed suppression of the cropping partners can be indicated (SZUMIGALSKI and VAN ACKER, 2005). Conversely, weed reduction (WR) compares the weed biomass of the intercrop with that sole crops, which is less competitive against weeds (CARTON, 2017).

The basic mechanisms for weed suppression in intercropping are more effective resource usurping from weeds compared to sole cropping or suppression through allelopathy (LIEBMAN and DYCK, 1993). From studies with pea-barley intercrops it is known that crop-weed competition for nitrogen is important for weed suppression (HAUGGAARD-NIELSEN et al., 2001; POGGIO, 2005; CORRE-HELLOU et al., 2011). CORRE-HELLOU et al. (2011) emphasised that dynamics of nitrogen use in intercrops is interrelated with that of light use, as the capability for absorbing soil nitrogen relates with the leaf area. Field experiments with intercrops of triticale and winter peas revealed that light transmission to weed canopy level is a factor for weed suppression, especially when normal-leafed winter peas were grown (GRONLE et al., 2014).

In this field experiment, weed suppression and crop yield performance of intercrops of common vetch and spring wheat will be investigated in a replacement series. The objective is to determine seed density ratios of vetch and wheat which will achieve the strongest weed suppression. Yield performance and weed suppression are analysed by different indices. Furthermore, it is the aim to indicate factors contributing to weed suppression in an intercrop of common vetch and spring wheat.

Materials and methods

Site and soil

The field experiment was carried out in 2018 at the Thünen Institute of Organic Farming research station in Trenthorst, Northern Germany, which is managed according to European organic standards (EUROPEAN UNION, 2007). Due to the crop rotation of the experimental station and times of breaks in legume cultivation the preceding crop was spring wheat (*Triticum aestivum* L.). A higher disease pressure in wheat was not observed. The soil type was a Stagnic Luvisol according to World Reference Base for Soil Resources (IUSS WORKING GROUP WRB, 2015) with pH of 6.6 and a loam soil texture.

The 30-year (1986–2016) mean annual precipitation at the experimental site is 693 mm with a mean temperature of 9.0 °C. In the long term average the mean temperature from April to August is 14.2 °C and the precipitation rate is 306.5 mm. In the growing period from April to August 2018 the mean temperature (16.6 °C) was 2.4 °C warmer than the 30-year (1986–2016) mean and the experimental site received only half the amount (157.9 mm) of the longterm average precipitation. Weather data were recorded at the nearby weather station Lübeck-Blankensee from the German Meteorological Service.

Experimental design and management practices

The experiment was carried out as a block design with four replicates. The plot size was 2.5 m × 15.0 m. Non-destructive measurements were taken in a length of 10 m of the plot, while destructive measurements were taken in 5 m length of the plot. The first experimental factor was the seed density ratio, which was performed as a replacement series (WILLEY, 1979). Spring wheat and common vetch were grown as sole crops and as three replacement intercrops with 75 % common vetch and 25 % spring wheat, 50 % common vetch and 50 % spring wheat as well as 25 % common vetch and 75 % spring wheat. The seed densities for sole crops were 120 and 400 germinable kernels m^{-2} for common vetch and spring wheat, respectively. For spring wheat, the cultivar Quintus was used. The second factor was the cultivar of vetch. However, in this publication the different vetch cultivars will not be considered, because no differences between vetch cultivars were found for most parameters. Thus, for vetch data means of the five cultivars are presented.

Primary tillage was carried out with a mouldboard plough in autumn 2017. Prior to seeding secondary tillage was performed with a cultivator and followed by a rotary harrow. Crops were sown on 21st April 2018 with a plot seeder (PZT D3–24 Quatro, Agrar Markt Deppe, Germany), which is especially constructed for row intercrops, at a sowing depth of 3.5 cm and with a row distance of 12.5 cm. The intercrops were sown in alternating rows. No mechanical weed control was performed and no fertilizer was applied. Perennial weeds, in particular Canada thistle (*Cirsium arvense* (L.) Scop.) and Coltsfoot (*Tussilago farfara* L.), were removed three times by hand until EC 33 of spring wheat as they occurred in patches and are not spread over all plots unlike annual weeds.

Sampling and analytical methods

To assess growth of sole crops, intercrops and weeds biomass harvests of aboveground biomass were done four times during the growing season. Due to very time-consuming sampling, this was partly done on three consecutive days. The first biomass harvest was done 39, 40 and 41 days after sowing (d.a.s.) during stem elongation stage of both crops. The second biomass harvest was done 65, 66 and 67 d.a.s. during full flowering of wheat and full to end of flowering of common vetch. The third biomass harvest was done 88 d.a.s. during early milk stage of wheat and mid of pod development stage of common vetch. The last biomass harvest was done 101, 102, 103 and 104 d.a.s. during full maturity of both crops. Weeds and crops were harvested from 0.5 m^2 on the first, second and third harvest and on 1.0 m^2 on the last harvest. Crops and weeds were cut at ground level. Weed biomass samples were dried at 60 °C and crop biomass samples were dried at 105 °C to constant weight at the first three harvests and at 40 °C to constant weight at the last biomass harvest. Weed dry matter samples from the first biomass harvest were milled with a ball mill (MM 400 Retsch, Germany) with a frequency of 30 s^{-1} for 90 seconds and weed dry matter samples from the second and third biomass were milled with a sieve of 0.5 mm with a Cyclotec sample mill (Foss Tecator 1093, Denmark). Milled samples were analysed for nitrogen content with a CNS analyzer (Vario MAX Cube Elementar Analysensysteme, Germany). From weed biomass and weed nitrogen content nitrogen accumulation of weeds were calculated. Crop samples from the last biomass harvest were threshed with a threshing machine K35 (Baumann Saatzuchtbedarf, Germany) and cleaned with a seed cleaner Schlingmann (Baumann Saatzuchtbedarf, Germany). After threshing, a subsample of grain was dried to constant weight at 105 °C to calculate the dry matter grain yield.

Every 7 to 12 days, beginning at stem elongation stage (20 d.a.s.), measurements of the photosynthetically active radiation (PAR) above crop canopy and PAR transmitted to weed canopy level were taken to determine the fraction of PAR transmitted to weed canopy level. A SunScan Canopy Analysis System type SS1 and a BF5 Sunshine Sensor (Delta-T Devices Ltd, UK) were used. PAR measurements were taken at weed canopy level and four measurements per plot were taken. Weed canopy level was defined as a dynamic height as weeds grow and PAR was measured on ground level at the first and second measurement, at 5 cm at third and fourth measurement and at 10 height from the fifth measurement onwards.

Calculation of indices describing intercrop systems

Weed and crop biomass as well as crop grain yield were used to calculate relative weed biomass (RWB), weed reduction (WR), land equivalent ratio (LER), competitive ratio (CR), actual yield loss or gain (AYL), and cumulative relative efficiency index (REIc).

RWB (equation 1) was calculated according to Szumigalski and Van Acker (2005). WBI is the weed biomass in the intercrop and WBS_{cv} and WBS_{sw} are the weed biomasses in the sole crops of common vetch and spring wheat, respectively. RWB < 1indicates synergistic weed suppression by the intercrop partners.

$$RWB = \frac{WBI}{\frac{WBS_{cv} + WBS_{sw}}{2}} \quad [1]$$

WR (equation 2) shows the weed suppression of the intercrops compared to the sole crop of common vetch. Relative weed biomass was calculated according to Carton (2017).

$$WR = 100 \times \frac{WBS_{cv} - WBI}{WBS_{cv}} \quad [2]$$

LER (equation 3, 4, and 5) is the relative land area under sole crops that is needed to produce the same yields as in intercropping. The land use efficiency will be greater of an intercrop compared to the corresponding sole crops, if the LER values are > 1 (Willey, 1979). I_{cv} and I_{sw} are the biomasses in the intercrop of vetch and wheat, respectively, and S_{cv} and S_{cw} are the biomasses of the vetch and wheat sole crop, respectively. In case of the final harvest grain yield instead of biomass was used.

$$LER_{cv} = \frac{I_{cv}}{S_{cv}} \quad [3]$$

$$LER_{sw} = \frac{I_{sw}}{S_{sw}} \quad [4]$$

$$LER = LER_{cv} + LER_{sw} \quad [5]$$

CR (equation 6) shows the number of times one crop is more competitive than the other. It is the ratio of the LER of both crops, corrected by the proportion in which the crops were sown as an intercrop (Willey and Rao, 1980). As the values of the two crops are reciprocals of each other, only the CR for common vetch is calculated. P_{cv} and P_{sw} are the seed density ratios of common vetch and spring wheat, respectively.

$$CR_{cv} = \left(\frac{LER_{cv}}{LER_{sw}}\right) \times \left(\frac{P_{sw}}{P_{cv}}\right) \quad [6]$$

AYL (equations 7, 8 and 9) is the proportionate yield loss or gain of intercrops compared to the corresponding sole crop respecting sowing proportions. A positive AYL shows a yield gain whereas as a negative AYL shows yield loss. The value of the AYL shows the relative quantity of yield loss or gain (Banik, 1996; Banik et al., 2000).

$$AYL_{cv} = \left(LER_{cv} \times \frac{100}{P_{cv}}\right) - 1 \quad [7]$$

$$AYL_{sw} = \left(LER_{sw} \times \frac{100}{P_{sw}}\right) - 1 \quad [8]$$

$$AYL = AYL_{cv} + AYL_{sw} \quad [9]$$

REIc (equations 10, 11 and 12) is the relative efficiency of common vetch and spring wheat assessed over the time period. It compares the change in dry matter (K) of both intercrop partners within the time interval (t1 to t2). If both intercrop partners have the same proportional growth in one interval, the ratio of their change (REIc) is equal to 1 (Connolly, 1987). The time interval is given between t1 and t2.

$$K_{cv} = \frac{I_{cvt2}}{I_{cvt1}} \quad [10]$$

$$K_{sw} = \frac{I_{swt2}}{I_{swt1}} \quad [11]$$

$$REIc = \frac{K_{sw}}{K_{cv}} \quad [12]$$

REIc was calculated for three intervals: from sowing to first biomass harvest, from first to second biomass harvest, and from second to third biomass harvest. For the first time interval, the seed weight for the corresponding area was taken as biomass.

Statistical analysis

Statistical analysis was performed with SAS version 9.4 (SAS Institute, 2013). Weed biomass, grain yield, weed nitrogen content and accumulation were analysed by polynomial regression analysis with one quantitative and one qualitative factor in Proc GLM. The quantitative factor, the ratio of vetch in the seeding mixture, was the independent variable. The wheat sole crop had a ratio of 0% vetch and the vetch sole crop had a ratio of 100% vetch. The qualitative factor is the vetch cultivar, which is not examined in this publication. For weed nitrogen content a first-degree polynomial was fitted and for grain yield a second-degree polynomial was used. For weed biomass and for weed nitrogen accumulation a third-degree polynomial was fitted, according to the lack-of-fit test. The regression model for a third-degree polynomial is shown in equation 13. First- and second-degree polynomials are appropriate.

$$y_{ijk} = \mu + b_k + \alpha_{j1} x_i + \alpha_{j2} x^2{}_i + \alpha_{j3} x^3{}_i + e_{ijk} \qquad [13]$$

y_{ijk} is the dependent variable. The subscript i indicates the ratio of vetch, j the vetch cultivar, k the block. μ is the general mean, b is the effect of the block, α of the vetch cultivar and x is seed density ratio of vetch in the crop stand. In the regression model, the wheat sole crop is represented by a crop stand with a ratio of 0% vetch.

PAR transmission to weed canopy level at each date was analysed by analysis of variance in Proc GLM. A nested two factorial model was used. By using a control factor, the treatments were categorized into wheat sole crop and treatments with vetches. Within the treatments with vetches there was a two-factorial structure. The first factor was the ratio of vetch in the intercrop and the second factor was the vetch cultivar which is not examined in this publication. If necessary, data were transformed with logarithm to achieve homogeneity of variances and normal distribution. The model of the analysis of variance is shown in equation 14.

$$y_{ijkm} = \begin{array}{l} \mu + d_k + g_m + g_m \times \alpha_j + g_m \times \beta_i \\ + g_m \times (\alpha \cdot \beta)_{ij} + e_{ijkm} \end{array} \qquad [14]$$

y_{ijkm} is the dependent variable. The subscript i indicates the ratio of vetch, j the vetch cultivar, k the block, and m the control factor level. μ is the general mean, d is the effect of the block, g of the control factor, α of the vetch cultivar and β of the seed density ratio of vetch in the crop stand. Means were compared with a Tukey test at a significance level of α = 0.05.

The indices RWB, WR, LER, CR, AYL, and REIc were calculated for each intercrop plot. The calculations were done according to Oyejola and Mead (1982). The means of each intercrop treatment of RWB, LER, CR and REIc was compared to a value of 1 with a t-test in Proc Ttest. Likewise, the means of each intercrop treatment of AYL and WR were compared to a value of 0. Additionally, an analysis of variance was performed for the different indices in Proc GLM to see the influence of seed density ratio. Subsequently a comparison of means was performed with a Tukey test at a significance level of α = 0.05.

Results

Weed biomass

19 annual weed species were found in the field experiment. The three most dominant weed species were *Atriplex patula*, *Chenopodium album* and *Stellaria media*. Polynomial regression showed that weed biomass increased with increasing ratio of vetch in the intercrop at all four harvest dates (Fig. 1). Weed biomass increased from first to second and from second to third harvest date, whereas weed biomasses of the third and fourth harvest dates scarcely differed. A slight increase in weed biomass was determined for a vetch ratio between 0 and 40 to 60% in the intercrop. The inflection points showed that the slope of the regression curve started to increase at a vetch ratio of 32%, 29%, 6%, and 29% for the first, second, third, and fourth harvest, respectively. However, visual assessment revealed that weed biomass at first and second harvest date started to rise steeply from a vetch ratio in the intercrop with more than 60%, and at the third and fourth harvest already from approximately 40% onwards. The coefficients of determination (R^2) for the regression of weed biomass against seed density ratio decreased from first to fourth harvest date (Fig. 1).

Two out of three RWB values were significantly lower than 1 at the first, second, and third harvest date, whereas at the fourth harvest date no RWB value differed significantly from 1 (Table 1). At all harvest dates, RWB was significantly lower in intercrops with a vetch ratio of 25 and 50% than in those with 75% vetch. Except for intercrops with a vetch ratio of 75% at the last harvest date all WR values are significantly different from 0%. At the first three harvest dates, WR was significantly higher in intercrops with 25% and 50% vetch than in those with 75% vetch (Table 1). Intercrops with 25% vetch achieved a significantly higher weed reduction than those with 75% vetch at fourth harvest, while WR in intercrops with 50% vetches was intermediate.

PAR transmission to weed canopy level

PAR transmission to weed canopy level at different seed density ratios of the intercrops decreased in the first half of the growing period, while in the second half of the growing period it levelled off (Fig. 2). At all nine measurement dates significant differences of PAR transmission between different seed density ratios were detected. Until 42 d.a.s. PAR transmission increased in the order from wheat sole crop, 25% vetch and 75% wheat, 50% vetch and 50% wheat, 75% vetch and 25% wheat to vetch sole crop. 42 d.a.s. the order reversed, and afterwards lowest transmission was determined in vetch sole crop and highest in wheat sole crop.

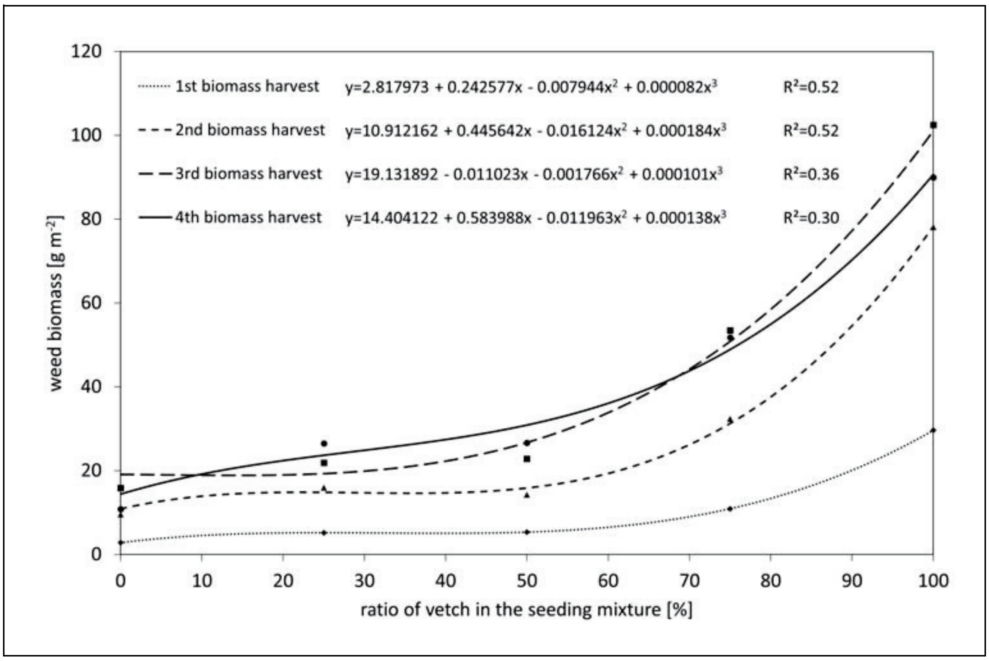

Fig. 1. Weed biomass [g dry matter m^{-2}] as a function of ratio of common vetch in the seeding mixture in a replacement series of spring wheat and common vetch at different biomass harvests. Symbols show the means of the measured values.

Table 1. Relative weed biomass (RWB) and weed reduction (WR) of intercrops of common vetch and spring wheat depending on ratio of vetch in the seeding mixture at different sampling dates.

	ratio of vetch [%]	Relative weed biomass (RWB)	Weed reduction (WR) [%]
1st biomass harvest	25	0.32 b *	82.4 a *
	50	0.36 b *	80.2 a *
	75	0.75 a	58.3 b *
2nd biomass harvest	25	0.37 b *	78.7 a *
	50	0.35 b *	79.7 a *
	75	0.81 a	54.0 b *
3rd biomass harvest	25	0.40 b *	76.2 a *
	50	0.42 b *	74.6 a *
	75	1.05 a	36.5 b *
4th biomass harvest	25	0.67 b	59.0 a *
	50	0.72 b	55.3 ab *
	75	1.45 a	9.8 b

* indicates that RWB value is significantly different from 1 and WR is significantly different from 0% (α = 0.05). Means followed by the same letter are not significantly different within one harvest date (α = 0.05).

Regression analysis for the PAR data of the second measurement date 32 d.a.s. against the seed density ratio showed that PAR available to weeds increased with increasing ratio of vetch in the intercrop during juvenile development (Fig. 3).

Nitrogen in intercrop-weed interaction

Regression analysis revealed increasing weed nitrogen content with increasing ratio of vetch in the intercrop for all three harvest dates (Fig. 4). Weed nitrogen content decreased from first to third biomass harvest. The slope of the regression function increased from first to third harvest.

Weed nitrogen accumulation increased with increasing ratio of vetch in the intercrop according to polynomial regression (Fig. 5). Weed nitrogen accumulation increased from first to second harvest. However, weed nitrogen accumulation from second and third harvest scarcely differed. The coefficient of determination (R^2) for regression of weed nitrogen accumulation against seed density ratio was lower at third harvest than at first and second harvest (Fig. 5).

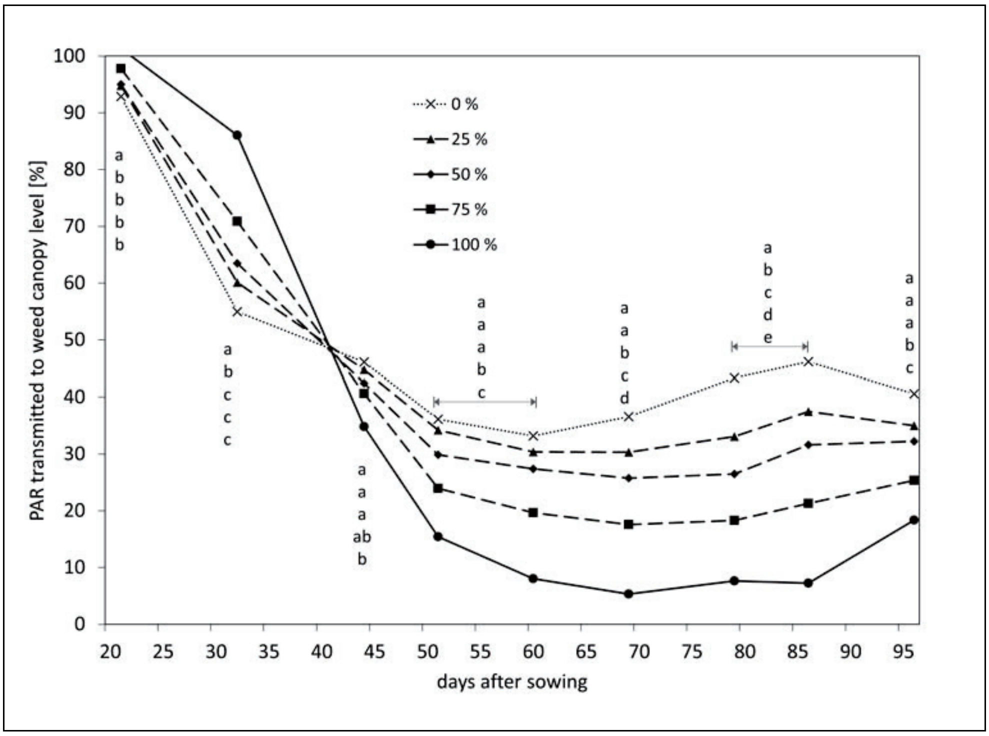

Fig. 2. Photosynthetically active radiation (PAR) transmitted to weed canopy level [%] in a replacement series of spring wheat and common vetch during vegetation. Line type refers to ratio of vetch in the seeding mixture. Means followed by the same letter are not significantly different within one date (α = 0.05).

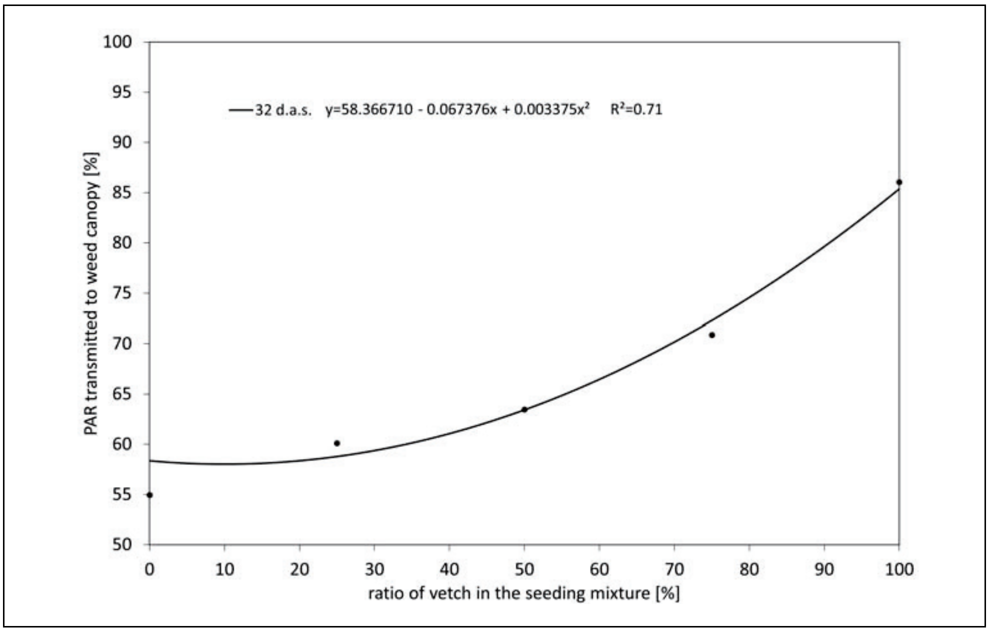

Fig. 3. Photosynthetically active radiation (PAR) transmitted to weed canopy level [%] 32 days after sowing (d.a.s.) as a function of ratio of vetch in the seeding mixture in a replacement series of spring wheat and common vetch. Symbols show the means of the measured values.

Crop biomass

Indices in Table 2 are calculated on the basis of crop biomass. All LER values were significantly different from and higher than 1 (Table 2). Highest LER of 1.33 was reached in an intercrop with 75% vetch at the third biomass harvest. The ratio of vetch in the intercrop had no influence on the LER at all three harvests. For the competitive ratio (CR) of common vetch all values were significantly lower than 1 (Table 2). At first and second harvest a higher ratio of vetch in the intercrop led to a lower competitive ratio of the vetch. At the third harvest no differences in the competitive ratio were detected. All AYL-wheat values were significantly higher than 0 (Table 2). Data from all three harvests showed that actual yield gain of wheat increased with increasing ratio of vetch in the intercrop. All AYL values of vetch were negative, just six of nine values were significantly lower than 0 (Table 2). At the first harvest a lower ratio of vetch in the intercrop resulted in a lower actual yield loss of vetch biomass. At the second harvest the actual yield loss of vetches did not differ between the intercrops with different ratios of vetch. However, at the third harvest date a higher ratio of vetch resulted in a lower actual yield loss of vetch biomass. For all intercrops the AYL values were positive

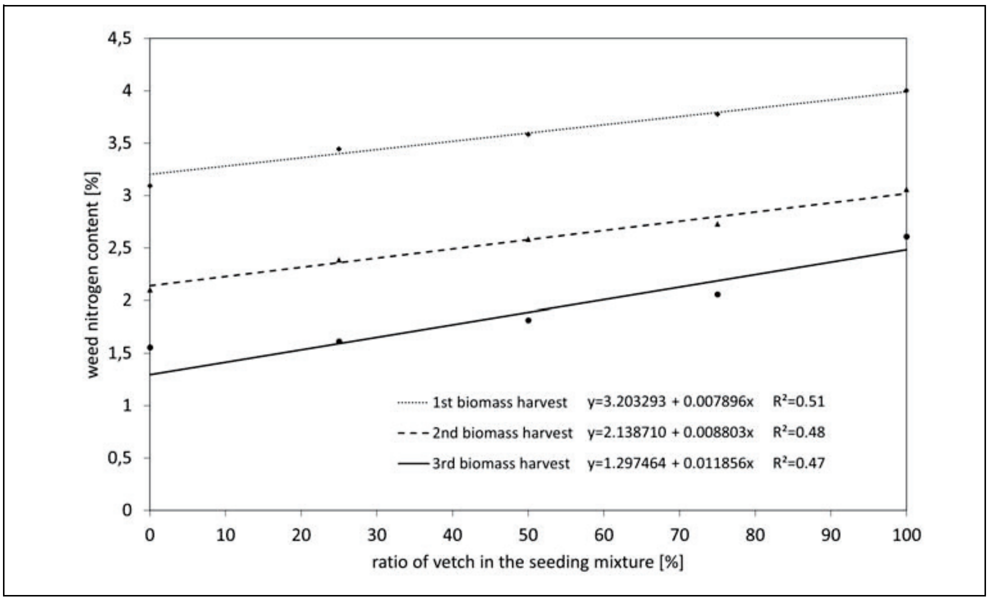

Fig. 4. Nitrogen content [%] of weeds as a function of ratio of common vetch in the seeding mixture in a replacement series of spring wheat and common vetch at different biomass harvests. Symbols show the means of the measured values.

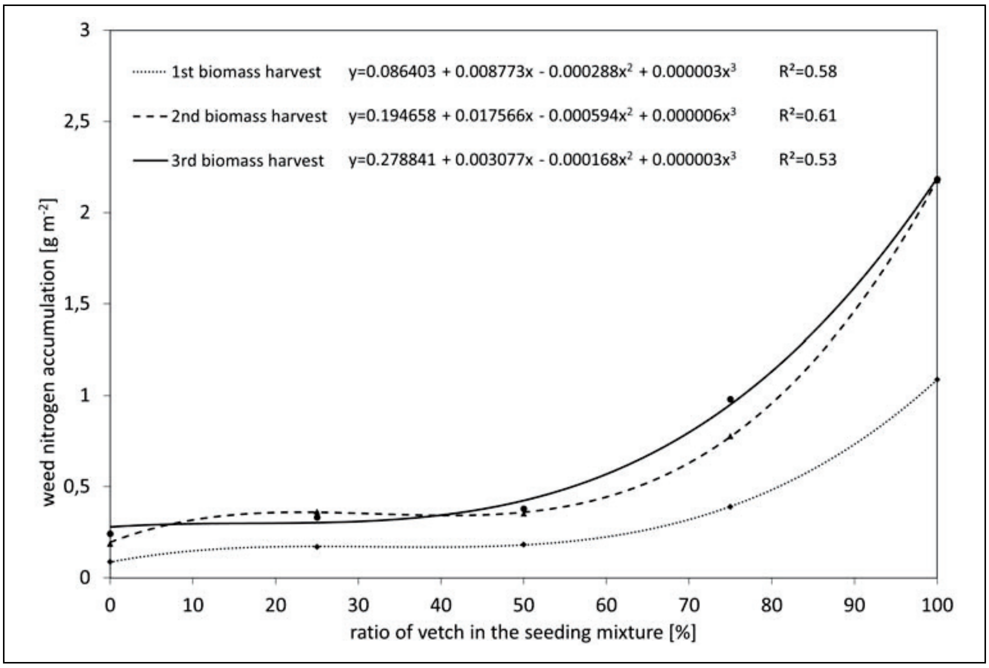

Fig. 5. Nitrogen accumulation [g m^{-2}] in weed biomass as a function of ratio of common vetch in the seeding mixture in a replacement series of spring wheat and common vetch at different biomass harvests. Symbols show the means of the measured values.

(Table 2). AYL values, which were significantly higher than 0, were found in intercrops with 50 or 75% of vetches. The actual yield gain of intercrops increased with an increasing vetch ratio.

For two intercrops in the first interval REIc values were significantly different from 1 (Table 3). In the first interval (T0-T1) vetches in intercrops with a vetch ratio of 25% grew at a higher rate, while wheat grew at higher rate in intercrops with a ratio of 75% of vetch. In the second interval (T1-T2) vetches in intercrops with a vetch ratio of 50% and 75% grew at a higher rate, whereas wheat grew at higher rate in intercrops with a ratio of 25% of vetch. At the third interval (T2-T3) vetches in intercrops with a vetch ratio of 75% grew at a higher rate, while wheat grew at higher rate in intercrops with a ratio of 25% of vetch.

Grain yield

Regression analysis showed that vetch grain yield increased with increasing vetch ratio, whereas wheat grain yield decreased with increasing ratio of vetch in the intercrop (Fig. 6).

Total grain yield varied between 227 to 354 g m^{-2}. Maximum total grain yield was achieved in intercrops. The curve progression for total grain yield of both vetch and wheat was an optimum curve. 43% of vetch in the seeding mixture achieved the maximum total grain yield. However, the total grain yield between the three different intercrops did not differ. The proportion of vetch grain of the total yield increased with increasing ratio of vetch in the seeding mixture. Moreover, Fig. 6 shows the comparison of actual grain yield of intercrop components and total intercrop with the expected grain yield. Expected

Table 2. Land equivalent ratio (LER), competitive ratio (CR) of common vetch, actual yield loss or gain of wheat (AYL-wheat), actual yield loss or gain of vetches (AYL-vetch), actual yield loss or gain (AYL) in intercrops of common vetch and spring wheat depending on ratio of vetch in the seeding mixture at different biomass harvest dates.

	ratio of vetch [%]	LER	CR	AYL-wheat	AYL-vetch	AYL
1st biomass harvest	25	1.09 a *	0.75 a *	0.17 c *	−0.12 a	0.05 b
	50	1.17 a *	0.49 b *	0.58 b *	−0.24 ab *	0.34 b *
	75	1.09 a *	0.30 c *	1.32 a *	−0.32 b *	1.00 a *
2nd biomass harvest	25	1.20 a *	0.59 a *	0.34 c *	−0.23 a *	0.11 b
	50	1.15 a *	0.50 a *	0.56 b *	−0.26 a *	0.31 b *
	75	1.18 a *	0.32 b *	1.46 a *	−0.24 a *	1.22 a *
3rd biomass harvest	25	1.23 a *	0.54 a *	0.39 c *	−0.27 b *	0.12 c
	50	1.31 a *	0.52 a *	0.75 b *	−0.13 ab	0.63 b *
	75	1.33 a *	0.44 a *	1.36 a *	−0.01 a	1.35 a *

* indicates that value is significantly different from 1 for LER and CR and significantly different from 0 for AYL ($\alpha = 0.05$). Means followed by the same letter are not significantly different within one harvest date ($\alpha = 0.05$).

grain yield was calculated across the replacement series by a linear curve progression. For total grain yield and wheat grain yield the curves for actual grain yield ran clearly above the curve for expected grain yield. For vetch grain yield the curve of actual grain yield ran slightly below the curve for expected grain yield.

Indices in Table 4 were calculated on the basis of grain yield. All different intercrop ratios achieved a LER which was significantly above 1 (Table 4). The seed density ratio of the intercrops had no effect on LER. For the competitive ratio of common vetch, all intercrops achieved a CR which was significantly below 1 (Table 4). The seed density ratio of the intercrops did not influence the CR. Actual yield gain for wheat was significantly higher than 0 for all intercrops (Table 4). The AYL of wheat increased with increasing ratio of vetch in the intercrop. In intercrops with a vetch ratio of 25% and 50% significant actual yield loss of vetches was found (Table 4). The actual yield loss of vetch was stronger with low ratios of vetch. The AYL was significantly different from 0 in all intercrops (Table 4). Actual yield gain increased with increasing ratio of vetch.

Table 3. Cumulative relative efficiency index (REIc) in intercrops of common vetch and spring wheat depending on ratio of vetch in the seeding mixture for different time intervals.

	ratio of vetch [%]	REIc
T0-T1	25	0.75 b *
	50	1.07 b
	75	1.80 a *
T1-T2	25	1.21 a
	50	0.92 b
	75	0.89 b
T2-T3	25	1.34 a
	50	1.18 ab
	75	0.84 b

T0-T1 was from sowing to first harvest, T1-T2 from first to second, and T2-T3 from second to third biomass harvest.
* indicates that value is significantly different from 1 ($\alpha = 0.05$). Means followed by the same letter are not significantly different within one time interval ($\alpha = 0.05$).

Discussion

Weed biomass influenced by seed density ratio

The seed density ratio of the intercrops had major influence on weed biomass (Fig. 1). The coefficients of determination (R^2) for the regression of weed biomass against seed density ratio decreased from first to fourth harvest date (Fig. 1). Thus, weed suppression can be explained better by the composition of the intercrop in the beginning of the growing period. Lowest weed biomass was found in the wheat sole crop. With increasing ratio of vetch in the seeding mixture weed biomass increased and in vetch sole crops highest biomass was found. Many other studies investigating cereal-legume intercrops were conducted with spring pea and barley. They all showed similar results; weed biomass was lower in barley sole and pea-barley intercrops compared to pea sole crops (Mohler and Liebman, 1987; Hauggaard-Nielsen et al., 2001; Poggio, 2005; Hauggaard-Nielsen et al., 2006; Corre-Hellou et al., 2011). For vetch intercropping, Böhm (2014) determined in a replacement series of common vetch and oat that weed biomass was highest in vetch sole crops and declined with increasing proportions of oat. Also intercropping winter peas with winter

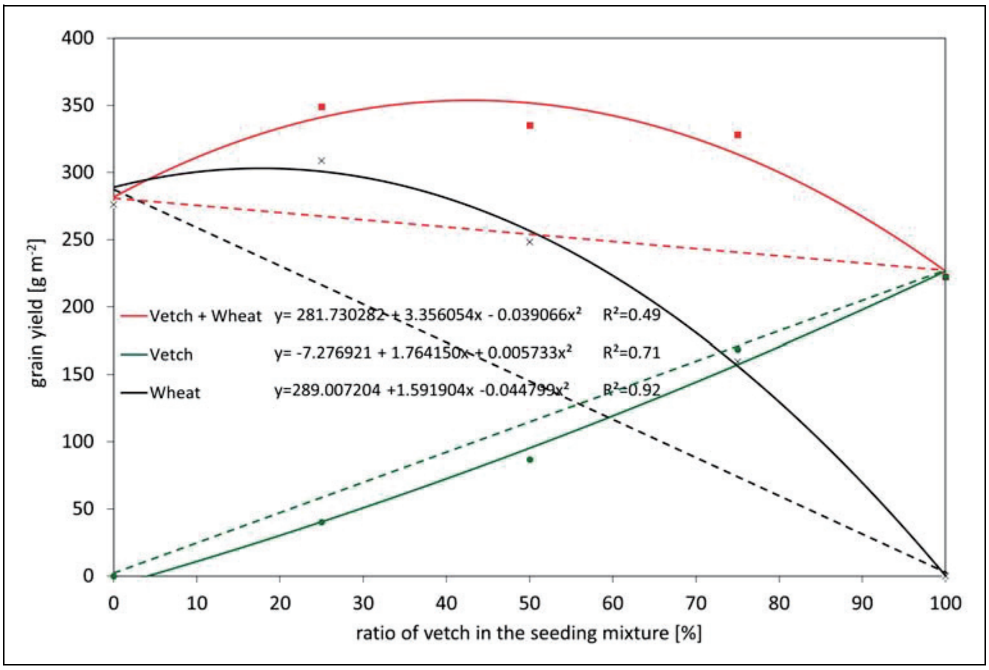

Fig. 6. Grain yield [g dry matter m^{-2}] as a function of ratio of vetch in the seeding mixture in a replacement series of spring wheat and common vetch. Line type refers to expected and actual yield (*solid lines* actual grain yield, *dashed lines* expected yield). Symbols show the means of the measured values.

Table 4. Land equivalent ratio (LER), competitive ratio of common vetch (CR), actual yield loss or gain of wheat (AYL-wheat), actual yield loss or gain of vetches (AYL-vetch), actual yield loss or gain (AYL) in intercrops of common vetch and spring wheat depending on ratio of vetch in the seeding mixture for grain yield.

ratio of vetch [%]	LER	CR	AYL-wheat	AYL-vetch	AYL
25	1.31 a *	0.54 a *	0.49 c *	−0.25 b *	0.24 c *
50	1.30 a *	0.46 a *	0.80 b *	−0.20 ab *	0.59 b *
75	1.36 a *	0.49 a *	1.31 a *	0.04 a	1.35 a *

* indicates that value is significantly different from 1 for LER and CR and significantly different from 0 for AYL (α = 0.05). Means followed by the same letter are not significantly different (α = 0.05).

triticale reduced weed biomass compared to winter pea sole crop (Gronle et al., 2014). However, this effect was considerably stronger for semi-leafless winter peas than for normal-leafed cultivars because normal-leafed cultivars have a good weed suppressive ability anyhow (Gronle et al., 2014).

The enhanced weed suppression in intercrops can also be seen from the indices RWB and WR (Table 1). Both synergistic weed suppression (RWB < 1) and WR decreased during the growing period. This shows that weed suppression in intercrops is especially effective in early growth stages where crops are very sensitive to weed pressure. The higher synergistic weed suppression in intercrops with a vetch ratio of 25% and 50% reflects the results of the weed biomass, which was much higher in intercrops with 75% vetches. Except third harvest date, WR followed the same trend that weed reduction was stronger in intercrops with fewer vetches. Although RWB and WR are calculated differently, both indices basically show the same trend.

Factors contributing to weed suppression

In cereal-legume intercrops fewer resources, which can be light, water, and nutrients (Liebman and Dyck, 1993), are available for weeds, resulting in a suppressed growth of weeds (Bedoussac et al., 2015). The resources used more efficiently in vetch-wheat intercrops than in vetch sole crops, resulting in higher crop biomass and thus higher weed suppressive ability, need to be identified.

Photosynthetically active radiation (PAR). Differences in PAR transmission to weed canopy level between seed density ratios were enormous (Fig. 2). In the period from 20 to 40 d.a.s. more light was transmitted to weed canopy level in crop stands with higher ratios of vetch, whereas in the period after 40 d.a.s. more light was transmitted to the weed canopy level in crop stands with higher ratios of wheat. The reason might be the slower juvenile development of common vetch in comparison to spring wheat in the beginning and by high biomass production and lodging of the vetch in later growth period. Thus, it can be concluded that PAR transmission to weed canopy level in the period from 20 to 40 d.a.s. is of decisive importance for the establishment of weeds in the different crop stands. The regression analysis for the PAR data of the second measurement date against the seed density ratio (Fig. 3) revealed a similar curve progression like that of weed biomass against seed density ratio (Fig. 1). It needs to be considered that the PAR data are one-year results.

In sole and intercrops of pea and oat, GRONLE et al. (2015) determined that the factor light competition between crops and weeds is not responsible for weed suppression. This result was primarily revealed in a pot experiment where shoot and root interference could be controlled. However, GRONLE et al. (2015) showed that in one experimental year highest PAR transmission to weeds was found in pea sole crop and lowest in oat sole crop at the beginning of crop growth. In another field trial the same researcher team showed that in intercrops with triticale and winter peas PAR transmission to weed canopy level is a factor for weed suppression (GRONLE et al., 2014). This was especially the case for normal-leafed winter peas which are comparable to vetch due to their high leaf and biomass production (GRONLE et al., 2014).

Moreover, the availability of PAR in the later stage might be important for late-season weed infestation. However, this effect could not be clearly seen as no late-season weed infestation was found in the year of the field experiment, probably due to summer drought. CORRE-HELLOU et al. (2011) discussed that peas are sensitive to weed infestation during juvenile development, but that they have a high competitive ability for light in later growth stages. Similar to the results for vetch sole and intercrops in the present study, GRONLE et al. (2014) detected that PAR transmission to weed canopy level was very low in sole and intercrops of normal-leafed pea in the later growth period.

Nitrogen. POGGIO (2005) determined less PAR at weed canopy level in barley sole and pea-barley intercrops compared to pea sole crops and simultaneously less accumulated nitrogen in weed biomass in barley sole and pea-barley intercrops compared to pea sole crops. Thus, higher PAR interception resulted from a greater leaf area caused by more available nitrogen (POGGIO, 2005). Similar results, which showed an interrelation of nitrogen and light use in intercrops, were found in experiments by CORRE-HELLOU et al. (2006) and CORRE-HELLOU et al. (2011), as leaf area relates with the capability for absorbing soil nitrogen. The lower availability of nitrogen to weeds in intercrops and wheat sole crops can be assumed as a further reason for weed suppression. The weed nitrogen content and accumulation decreased with increasing ratio of wheat in the intercrop (Fig. 4). As cereals are more efficient in nitrogen uptake (JENSEN, 1996) and vetches as legumes are self-sufficient in terms of nitrogen, more nitrogen is available for weeds when the ratio of wheat in the crop mixture is reduced. This result is confirmed by many other studies reporting higher weed suppression in cereal sole and cereal-legume intercrops compared to legume sole crops (HAUGGAARD-NIELSEN et al., 2001; POGGIO, 2005; CORRE-HELLOU et al., 2011; GRONLE et al., 2015).

Crop biomass and grain yield influenced by seed density ratio

Vetch biomass and vetch grain yield increased with increasing ratio of vetch in the intercrop, whereas wheat biomass and wheat grain yield decreased with increasing ratio of vetch in the intercrop (Fig. 6). Declining grain or dry matter forage yield as a consequence of a decreasing seed density ratio of vetch in a replacement series of vetch and oat or triticale was also revealed by BÖHM (2013a), EROL et al. (2009) and KOKTEN et al. (2009). Total grain yield has an optimum curve progression which showed an extra yield of the intercrops (Fig. 6). Likewise, in other replacement series of vetches with oat (EROL et al., 2009; BÖHM, 2013a) or triticale (KOKTEN et al., 2009) highest total grain or forage yield was achieved in intercrops. Regression curves of total grain yield varied between 227 to 354 g m^{-2}, whereas single values reached up to 500 g m^{-2}. The total grain yield between the three different intercrops was comparable, but the proportion of vetch grain of the total yield increased with increasing ratio of vetch in the seeding mixture. However, the grain yield data are only one-year results.

Comparison of different indices evaluating productivity of intercrops. The LER increased from first biomass harvest to grain harvest (Tables 2 and 4). Thus, the extra yield in intercrops is built up over time. LER was not affected by the seed density ratio, neither for the biomass nor for the grain yield data. In a replacement series of pea and barley of HAUGGAARD-NIELSEN et al. (2006), seed density ratio also did not affect LER in the first half of the growing season. However, at their last harvest, the LER tended to decline with increasing ratio of peas in the intercrop. The same trend as shown by LER is presented by AYL (Table 2 and 4). AYL increased over time to a value of 0.73 averaged across grain yield of all intercrops, which indicates a yield gain of 73% in intercrops compared to sole crops. Unlike LER, actual yield gain of intercrops increased with an increasing vetch ratio. Thus, AYL is more sensitive to different sowing proportions as they were considered when computing the index. Also BANIK (1996) and BANIK et al. (2000) emphasised that AYL gives more precise information than LER. When intercrops are investigated in a replacement series, it is therefore more useful to quantify the extra yield of intercrops by AYL instead of LER. All values of AYL for wheat were positive (Tables 2 and 4), which showed that there was a yield gain of wheat in intercrops compared to sole crops. Actual yield gain of wheat increased with increasing ratio of vetch in the intercrop. Thus, wheat is more productive with less wheat in the mixture due to reduced intraspecific competition of wheat plants. AYL for vetch showed that common vetches in intercrops with spring wheat tended to have actual yield loss instead of actual yield gain in intercropping (Tables 2 and 4). However, the actual yield loss of vetch biomass was not significant in all intercrops. At first harvest, actual yield loss of vetch biomass was lower in intercrops with a lower ratio of vetch, whereas at third harvest date and for the grain yield data a higher ratio of vetch resulted in a lower actual yield loss of vetch biomass. Thus, intraspecific competition of vetches might be lower than interspecific competition with wheat. The CR values for both biomass and grain yield showed that vetch was always less competitive compared to wheat (Tables 2 and 4). In an 50:50 intercrop of common vetch and spring wheat, Šarunaite et al. (2010) also determined spring wheat as the dominant component in the intercrop, whereas other studies did not clearly show that vetch is less competitive than the cereal (Dhima et al., 2007; Erol et al., 2009).

Results of REIc showed that the intercrop partner with a lower proportion grew at a higher rate at the beginning. This can be explained due to reduced intraspecific com-petition. At the later stage, the intercrop partner with the lower proportion grew at a lower rate, because this partner might be already suppressed. Hauggaard-Nielsen et al. (2006) calculated REIc for two intercrops of pea and barley and reported that barley grew at higher rate in the first growth phase, whereas peas grew at higher rate in the last growth phase in both intercrops with high and low proportions of pea.

Comparison of actual and expected yield. The regression curve of grain yield against seed density ratio revealed that intercrops achieved higher total yield and the indices quantify this yield gain. The comparison of actual grain yield with the expected grain yield (Fig. 6) visualised these results and pointed out spring wheat as the major source for extra yield. It should be noted, that this is the result of a one-year study and could have been caused by the dry weather conditions. Yield benefits of intercrops are caused by more efficient acquisition and use of resources (Hauggaard-Nielsen et al., 2008; Jensen et al., 2015), for instance due to nitrogen fixation grain legumes and cereals can use complementary nitrogen pools in intercropping (Jensen, 1996; Bedoussac et al., 2015). Thus, the legume will rely on fixation of atmospheric nitrogen and the cereal acquires more mineral nitrogen than the legume (Jensen, 1996). Due to improved nitrogen nutrition of intercropped cereals, their leaf area per cereal plant is greater. Thus, intercropped cereals have a higher competitive ability for light than of sole cropped cereals, resulting in a higher relative yield of cereals in intercrops (Corre-Hellou et al., 2006).

Conclusion

This one-year field experiment revealed that weeds can be successfully suppressed in intercrops of common vetch and spring wheat. The core result was that the higher the proportion of wheat in the intercrop, the stronger weeds were suppressed. In fields with low or medium weed infestation, intercropping of wheat and vetch is sufficient for weed management whereas in heavily infested field, additional pre-emergent weed harrowing as well as a false seedbed preparation is recommended.

Maximum total yield was achieved in intercrops and not in sole crops. The optimal ratio differs for maximum yield, high proportions of vetch in grain yield and highest weed suppression. Weed infestation was low in intercrops with a ratio of less than 60% vetch. High total grain yield was achieved with all three intercrops. Higher vetch proportions in grain yield were found in intercrops with higher ratio of vetch in the seeding mixture. Thus, intercropping common vetch with cereals in ratios between 30 and 60% vetch in the mixture seem to be possible. This emphasises the advantages of replacement series compared to field trials with just one intercropping treatment, as replacement series give the possibility to calculate optima for different criteria.

Weed nitrogen content and accumulation increased with higher vetch ratios in the intercrop. In the first 40 days less light reached the weed canopy level in intercrops with higher ratios of wheat compared to intercrops with high vetch ratios. Thus, crop-weed competition for nitrogen and for light in the early growth stages was determined as the major factors contributing to weed suppression in vetch-wheat intercrops.

The mean land equivalent ratio (LER) for grain yield was 1.32. The index actual yield loss or gain (AYL) was predominantly positive. The mean AYL for grain yield indicated a yield gain of 73% compared to the sole crops. AYL was more precise than LER, as it took the different seed density ratios into account. Thus, it is better suited for field experiments with replacement series.

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