frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 20 May 2024
DOI 10.3389/fsufs.2024.1385296

OPEN ACCESS

EDITED BY
Bin Yao,
Chinese Academy of Forestry, China

REVIEWED BY
Jingxue Zhao,
Lanzhou University, China
Luo Chongliang,
Chinese Academy of Sciences (CAS), China
Shuzhen Zhang,
Xinjiang Agricultural University, China

*CORRESPONDENCE
Qingping Zhang
✉ zhangqp2008@lzu.edu.cn
Fuhong Miao
✉ miaofh@qau.edu.cn

RECEIVED 12 February 2024
ACCEPTED 17 April 2024
PUBLISHED 20 May 2024

CITATION
Jiao Y, Zhang Q and Miao F (2024) Forage yield, competition, and economic indices of oat and common vetch intercrops in a semi-arid region.
Front. Sustain. Food Syst. 8:1385296.
doi: 10.3389/fsufs.2024.1385296

Forage yield, competition, and economic indices of oat and common vetch intercrops in a semi-arid region

Yu Jiao[1,2], Qingping Zhang[3]* and Fuhong Miao[1,2]*

[1]College of Grassland Science, Qingdao Agricultural University, Qingdao, China, [2]Key Laboratory of National Forestry and Grassland Administration on Grassland Resources and Ecology in the Yellow River Delta, Qingdao, China, [3]College of Agriculture and Forestry, Linyi University, Linyi, China

Intercropping of annual favorable legumes with grains to produce forage is utilized extensively worldwide to improve resource use efficiency. To identify the best intercropping system for a semi-arid region of China, intercrops of oat (*Avena sativa* L.) and common vetch (*Vicia sativa* L.) at five planting proportions and oat and common vetch monocrops were produced over the 2011 and 2012 growing seasons in Xifeng, northwest China. Several indices were used to evaluate yields, competitive interrelationships between the two crops, and economic returns. The oat mono-crop had the highest dry matter yield (6.51 t ha^{-1}), while the oat–common vetch intercrop, with an 80: 20 planting ratio, produced the highest crude protein production (696 kg ha^{-1}). The land equivalent ratio (1.167), relative crowding coefficient (2.445), and actual yield loss (0.750) were more favorable for the oat–common vetch intercrop at a seeding ratio of 20: 80. The oat–common vetch intercrop at a seeding ratio of 20: 80 showed the highest values for monetary advantage index (35.51). Overall, the autumn-sown 20: 80 oat–common vetch intercrop was more productive from resource utilization and economic perspectives.

KEYWORDS

actual yield loss, competitive, intercropping, forage, land equivalent ratio, monetary advantage

1 Introduction

Intercropping of grain and Leguminosae has many advantages over monocultures, such as better use of light, water (Luo et al., 2016; Tamburini et al., 2020; Liu H. et al., 2023), and nutrients, higher yields than those from legume monocultures, increased feed value (Pinto et al., 2022), reduced nitrous oxide emissions from soil (Shen et al., 2018), and better control of the occurrence of pests and weeds (Gronle et al., 2015; Maitra et al., 2021; Koskey et al., 2022). It also increases soil organic matter (Cong et al., 2014). Intercropping is more below-ground competitive and intercropping than monocropping, thus changing the resource playing field (Liu X. et al., 2023). Therefore, intercropping is receiving increasing attention because of its potential to increase agricultural production's sustainability (Andersen et al., 2007; Duchene et al., 2017).

The ratio of each species in a mixed sowing system, and the growth conditions affect the efficiency of intercropping (Caballero and Goicoechea, 1986). For example, oat–pea intercrops fell short of achieving any grain yield advantage in soil with low organic matter content

10.3389/fsufs.2024.1385296

(Neugschwandtner and Kaul, 2014). Interspecific competition is one of the factors that affect the component species to determine their yields in a mixture, compared with those from monocultures (Caballero et al., 1995). Traditionally, the aggressivity index (A) indicated the relative yield of one crop over a companion crop in an intercropping system (McGilchrist, 1965). More recently, the land equivalent ratio (LER) is now the predominant metric used to evaluate competitiveness (Agegnehu et al., 2006; Esmaeili et al., 2011). Compared with the LER, the actual yield loss (AYL) index provides more accurate information regarding the competition among and within the component crops, as well as the behavior of each species in the intercropping system. This is because AYL emphasizes the productivity of each plant, whereas LER merely considers the yield per unit land area (Banik et al., 2000). In addition to dry matter (DM) yield, the efficiency of environmental resource use and economic profitability should also be considered (Ghosh, 2004; Midya et al., 2005; Gitari et al., 2020). None of the competitiveness indices provide insights into the economic advantages of intercropping systems.

The Loess Plateau is a large geographical region (62,000 km^2) in northwestern China (Figure 1). Despite the challenging climate, this region is home to some 80 million people who depend on traditional rain-fed farming techniques and play a vital role in China's food production. Winter wheat (*Triticum aestivum* L.) is the main crop in traditional cropping systems. The harvest takes place in late June or early July, and there is a period of summer fallow from July to September. Hence, the overall effectiveness of utilizing precipitation is frequently diminished due to the significant evaporation of moisture to the exposed soil throughout the idle season (Zixi et al., 1994; Chen et al., 2023). Total effective precipitation (TEP) is typically as low as 82%, whereas planting forage crops followed by winter wheat can increase TEP to 97% and is encouraged (Fengrui et al., 2000).

In addition, crop-livestock systems are essential to dryland agriculture, providing food security and livelihood options for people. Livestock are also a vital source of income for the local farmers and government aims to double small ruminant numbers and expand the area of forage through the "Six Million" project in the Longdong Loess Plateau (Malézieux et al., 2009). With livestock production expanding in this region, a challenge currently faced by farmers is to choose profitable annual forage crops stored by hay or silage to solve the feed deficit during winter and early spring. While the right choice of annual forage crops may depend on unpredictable nature of precipitation in this region and subsequent winter wheat. Intercrop of cereals and legumes is not only increasing water and land use efficiency (Zhu et al., 2022; Raza et al., 2023), enhancing soil carbon and nitrogen (Jensen et al., 2020), enrichment of microbial communities (Lai et al., 2022), but also stimulating subsequent wheat yield under rainfed conditions (Scalise et al., 2015). Therefore, in this study, oat (*Avena sativa* L.), which has a higher dry matter when sown in summer fallow than in spring on the Loess plateau (Zhang Y, et al., 2015), was intercropped with common vetch (*Vicia sativa* L.) at five different seeding ratios. Competition indices were calculated for each of the intercrops, as well as economic and yield indices. These indices have not been used previously to evaluate competition among different seeding ratios or to evaluate economic advantages of oat–common vetch intercrops. We hypothesized that an intercrop of oat and common vetch with high dry matter, crude protein (CP) yield and economic benefit could be used as hay for livestock production during the summer fallow period on the Loess Plateau.

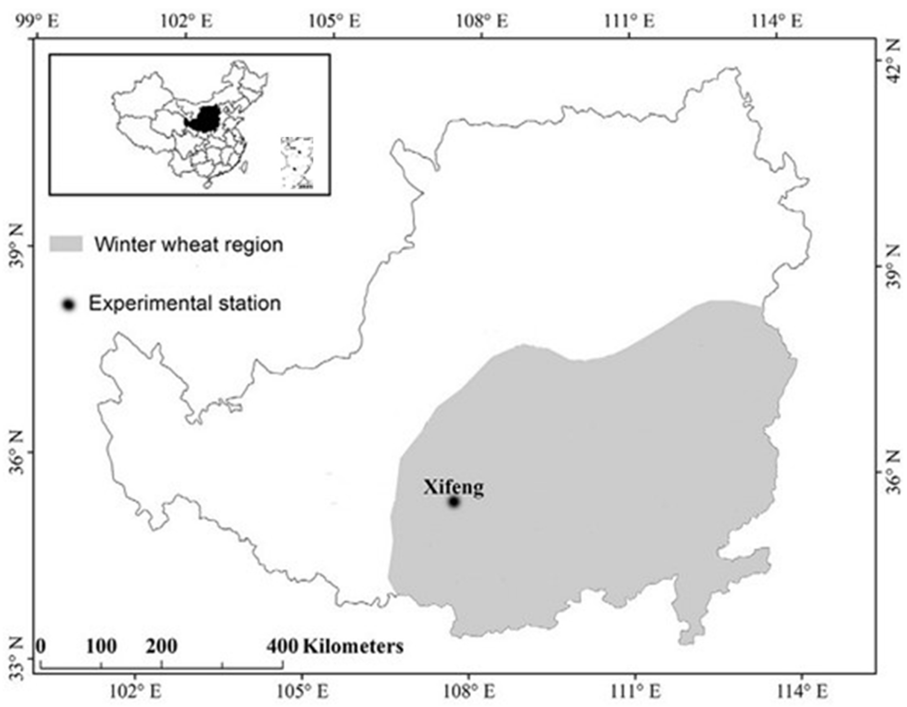

FIGURE 1
Location of experimental station on the Loess Plateau, northwest China.

The objectives of this 2-year study were as follows: (1) to evaluate the forage and protein yields of oat and vetch grown in monocultures and intercrops in a semi-arid region; (2) to examine the effect of competition between oat and common vetch in this intercropping system; and (3) to assess overall productivity, competition, and economic parameters for each of the intercrops and monocrops.

2 Materials and methods

2.1 Site description, experimental design, and measurements

This study was conducted over the 2011 and 2012 growing seasons at the Loess Plateau Research Station of Lanzhou University (35°40′ N, 107°51′ E, elev. 1,298 m) located at Xifeng, Gansu Province, northwest China. The region is characterized as a semi-arid zone, with mean annual precipitation of 548 mm concentrated in July–September. Average annual pan evaporation is 1,504 mm, about three times higher than the precipitation. Average annual mean temperature is 8.3°C, and mean temperatures in the hottest (July) and coldest (January) months are 21.3°C and −5.3°C, respectively. Average annual solar radiation is 5,489 MJ m^{-2}. The mean length of the annual growing season is 255 d. The dominant soil type is sandy loam with an average field water-holding capacity of 0.22 kg·kg^{-1} and a wilting point of 0.07 kg·kg^{-1}. In this area, 0–10 cm soil organic carbon 9.6 g·kg^{-1}, available nitrogen 23.6 mg·kg^{-1}, available phosphorus 6.2 mg·kg^{-1}, total nitrogen 0.7 mg·kg^{-1}. The organic carbon of 10–20 cm soil was 10.2 mg·kg^{-1}, available nitrogen 31.5 mg·kg^{-1} and available phosphorus 7.2 mg·kg^{-1}.

The seeding rate for monocultures of oat (cultivar No. 2 Qingyin) and common vetch (cultivar No. 3 Lanjian) was 165 (about 495 seeds m^{-2}) and 105 kg ha^{-1} (about 200 seeds m^{-2}), respectively. The intercrops were sown in a replacement series using the following oat–common vetch seeding ratios (%): 80: 20, 67: 33, 50: 50, 33: 67 and 20: 80, corresponding to 396-40, 332-66, 248-100, 163-134 and 99-160 seeds m^{-2}, with row spacing of 30 cm. The seeds of both kinds were planted at the same time. The research methodology employed a randomized complete block approach consisting of four separate replications. The dimensions of the land were 4 meters by 6 meters. A 15-hp cultivator was used to prepare the seedbed down to a measurement of 20 cm in depth. Planting was carried out in a single fade using a 4-coulter plot drill and seeds were deposited at a depth of 4 cm. On 7 July 2011 and 12 July 2012, crops were seeded manually. Based on local fertilizer recommendations, nitrogen and phosphorus were applied prior to sowing at rates corresponding to 46 kg N and 100 kg P_2O_5 per hectare, respectively. Weeds were effectively controlled in all plots through human hoeing. The climatic conditions during the 2-year study period are shown in Figure 1.

Plants in a 0.75 m^2 sampling area within every plot were removed manually to ground level on October 25, 2011, and on October 21, 2012, when common vetch was at the pod-filling stages and oat was at the kernel milk stage. Samples were separated into component species and weighed. To assess the dry matter (DM) yield, subsamples (0.5 kg fresh weight) of each species from each plot were dried in a hot air draft oven at a constant temperature of 65°C until they reached a stable weight.

2.2 Crop nitrogen concentration and protein yield

The sub-samples utilized for DM measurements were pulverized using a Wiley mill to achieve a particle size small enough to pass through a 1-mm screen. The Kjeldahl method was employed to ascertain the aggregate nitrogen content in intact plant samples (Black, 1965). The crude protein (CP) is determined by multiplying the amount of nitrogen by an amount of 6.25 (Jones, 1931). Crop protein yield (kg ha^{-1}) for this intercropping system was calculated as follows:

$$\text{Crop protein yield} = \text{N\%oat} \times 6.25 \times \text{DM}_{\text{oat}} + \text{N\%vetch} \times 6.25 \times \text{DM}_{\text{vetch}}.$$

2.3 Competition indices

Multiple concurrence assessments were used to compute the possible advantages of intercropping and the influence of inter-species rivalry in the mixture. The LER was used as the criterion to assess the advantage of a mixed stand containing both oat and common vetch as desired species (Osiru and Willey, 1972). The LER was calculated as follows:

$$LER = LER_{oat} + LER_{vetch}$$

$$LER_{oat} = \frac{Y_{OV}}{Y_O} \qquad LER_{vetch} = \frac{Y_{VO}}{Y_V}.$$

where Y_O and Y_V are the yields of oat and common vetch in a pure stand, and Y_{OV} and Y_{VO} are the DM yields of oat and common vetch in any one mixture.

The relative crowding coefficient (K) quantifies the degree of dominance of one species over another in a mixture (Lithourgidis et al., 2011), and was calculated as follows:

$$K = K_{oat} \times K_{vetch}$$

$$K_{oat} = \frac{Y_{OV} Z_{VO}}{(Y_O - Y_{OV}) Z_{OV}} \qquad K_{vetch} = \frac{Y_{VO} Z_{OV}}{(Y_V - Y_{VO}) Z_{VO}}$$

Z_{OV} and Z_{VO} represent the proportional proportions of oat and common vetch that are seeded in a mixture. When the multiplication of the two coefficients (K_{oat} and K_{vetch}) exceeds one, it results in a yield advantage. When the value of K is one, there is no advantage in terms of yield. There is a yield disadvantage when K is lower than one.

Aggressivity (A) was calculated as follows:

$$A_{oat} = \left(\frac{Y_{OV}}{Y_O Z_{OV}}\right) - \left(\frac{Y_{VO}}{Y_V Z_{VO}}\right)$$

If the value of A_{oat} is 0, it indicates that both crops have equal competitiveness. If the value of A_{oat} is positive, it indicates that oat is the dominating species. Conversely, if A_{oat} is negative, it suggests that oat is the species being dominated. Aggressivity of common vetch was determined in the same way.

$$A_{vetch} = \left(\frac{Y_{VO}}{Y_V Z_{VO}}\right) - \left(\frac{Y_{OV}}{Y_O Z_{OV}}\right)$$

Partial real yield loss (AYL_{oat} or AYL_{vetch}) represents the relative change in yield, either loss or gain, of each species when planted as intercrops compared to their yield in a monoculture. The AYL was calculated as follows (Banik et al., 2000):

$$AYL_{oat} = \left\{\left[\frac{Y_{OV} / Z_{OV}}{Y_O / Z_O}\right] - 1\right\}$$

$$AYL_{vetch} = \left\{\left[\frac{Y_{VO} / Z_{VO}}{Y_V / Z_V}\right] - 1\right\}$$

$$AYL = AYL_{oat} + AYL_{vetch}$$

2.4 Economic indices

The Monetary Advantage Index (MAI) offers insights into the economic benefits of the combining system. The MAI was calculated as follows:

$$MAI = \left(Y_{OV} P_{oat} + V_{VO} P_{vetch}\right) \times \frac{LER - 1}{LER}$$

A higher MAI score corresponds to a more profitable cropping scheme (Ghosh, 2004). The intercropping advantage (IA) was computed utilizing the subsequent equation (Banik et al., 2000).

$$IA_{oat} = AYL_{oat} \times P_{oat}$$

$$IA_{vetch} = AYL_{vetch} \times P_{vetch}$$

$$IA = IA_{oat} + IA_{vetch}$$

where P is the hay price, average hay procurement price per ton: common vetch = €55, oat = €43 (Lithourgidis et al., 2006).

2.5 Statistical analyses

An integrated analysis of variance (ANOVA) was conducted to independently examine the dry matter (DM), concentration, and yields of CP in both sole crops and intercrops, considering data from many years. Data were analyzed employing the mixed model feature in SPSS version 16.0 (SPSS Inc., Chicago, IL, United States) utilizing an autoregressive covariance structure. Year was a random effect, seeding ratio was a fixed effect. Bartlett's test was used to examine the homogeneity of variances. The competition and economic indices were differentiated using the least significant difference (LSD) test with a significance level of 0.05.

3 Results

3.1 Variations in yearly precipitation

The precipitation patterns observed throughout crop growth (July–October) in both 2011 and 2012 closely resembled the historical average but with some end-of-season variations (Figure 2). Since there were no significant effects between years, minor rainfall and temperature differences had no effect on DM or index measurements.

3.2 Aboveground dry matter

The analysis of variance for above ground dry matter (ABDM) data of oat and common vetch indicated notable variations exist among seed ratios. However, there were no significant effects on yield for either year or year x seed ratio (Table 1).

As expected, the ABDM yield was significantly higher for the oat monoculture than for the common vetch monoculture and the oat–common vetch intercrops ($p < 0.05$). As the ratio of common vetch increased in intercrops, the ABDM yield of oats decreased. For example, the oat ABDM was 6.51 t ha^{-1} in the monoculture but decreased with higher proportions of common vetch in the mixture (2.15 and 2.24 t ha^{-1} in the 33:67 and 20:80 oat–common vetch intercrops, respectively). Common vetch showed an ABDM advantage when sown in a mixture. Common vetch constituted 49 and 55% of the AGDM in the 33:67 and 20:80 oat–common vetch intercrops, respectively (Table 1).

3.3 Crude protein percentage and yield

We determined the CP concentration (%) and protein yield (kg ha^{-1}) for each of the monocrops and intercrops (Table 1). The lowest CP concentration was in the oat monoculture (8.12%), and the highest CP concentration was in the common vetch monoculture (14.88%). However, the common vetch monoculture had the lowest protein yield (496 kg ha^{-1}) because of its low DM yield (3.34 t ha^{-1}). In the intercrops, the CP percentage increased as the ratio of common vetch in the intercrops increased. The maximum protein output was in the 80:20 oat–common vetch intercrop (696 kg ha^{-1}). This was because of the high dry matter yield of the 80:20 oat–common vetch intercrop (6.39 t ha^{-1}).

3.4 Competition indices

The values for the competition indices K (Table 2) and A (Table 3) indicated that oat was the stronger competitor in the oat–common vetch intercrops. The values of A and K for oat differed significantly among seeding ratios. As evident from the formula for A, the values

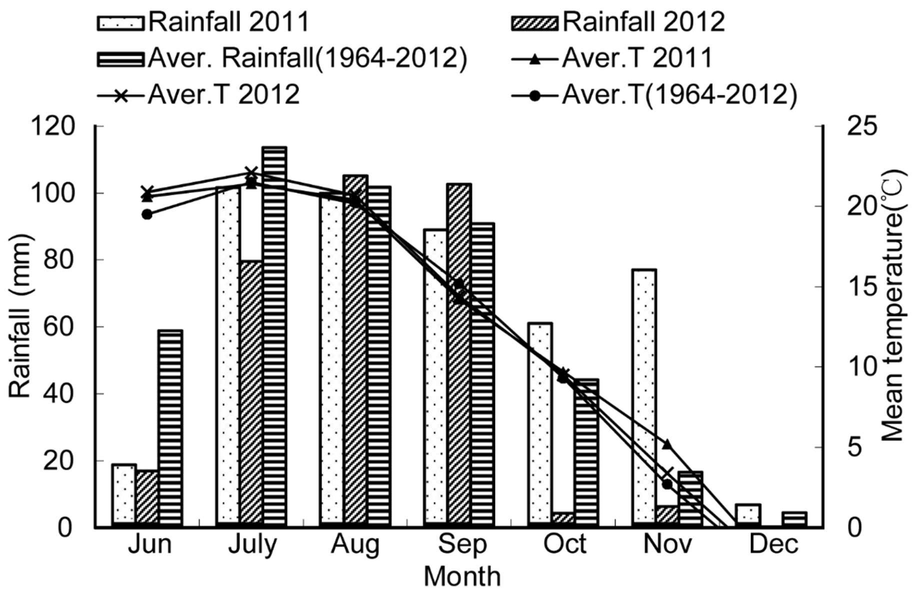

FIGURE 2
Monthly rainfall and mean air temperature (T) during 2011 and 2012 growing seasons at Qingyang Research Station, Gansu, China.

TABLE 1 Forage and protein yield of oat (O) and common vetch (V) monocultures and intercrops at different seeding ratios.

Treatment (seeding ratio)	Above-ground dry matter yield (t ha^{-1})			Crude protein (%)	Protein yield (kg ha^{-1})
	Oat	Vetch	Total		
O:V(100:0)	6.51 (0.82)	0.00	6.51 (0.82)	8.12 (1.28)	528 (5)
O:V(80:20)	5.76 (0.37)	0.62 (0.10)	6.39 (0.40)	10.91 (1.75)	696 (24)
O:V(67:33)	4.81 (0.56)	0.95 (0.17)	5.76 (0.60)	10.12 (2.34)	642 (20)
O:V(50:50)	3.18 (0.31)	1.52 (0.11)	4.70 (0.23)	12.03 (1.65)	565 (21)
O:V(33:67)	2.15 (0.23)	2.14 (0.37)	4.30 (0.51)	13.12 (1.89)	563 (21)
O:V(20:80)	2.24 (0.32)	2.75 (0.33)	4.99 (0.49)	13.81 (2.68)	654 (18)
O:V(0:100)	0.00	3.34 (0.56)	3.34 (0.56)	14.88 (2.87)	496 (18)
$LSD_{0.05}$	0.75	0.94	1.04	1.65	141

Values shown are averaged over two growing seasons (2011 and 2012). Standard errors are shown in parentheses.

for A of oat and common vetch are numerically identical but differ in their sign. In this experiment, A_{oat} was positive (indicating dominance) in the 80:20, 67:33, and 50:50 oat–common vetch intercrops. The highest A_{oat} value was in the 20:80 oat–common vetch intercrop (Table 3). The values of K, which represent crowding, were notably higher for oat than for common vetch and did not show a smooth trend with respect to the range of seed ratios. However, the K_{oat} values were highest when oat was a minor or major mixture component, and lower when oat and common vetch were mixed in similar proportions (Table 2).

3.5 Economic indices

The values for AYL calculated for mixture components varied with seeding rate and were positive for oat and negative for common vetch, indicating a general yield loss for common vetch in intercrops. The LER_{oat} values exhibited a positive correlation with the proportion of oat in intercrops, while the LER_{vetch} values showed a positive correlation with the proportion of common vetch in intercrops. As year effects were not statistically significant, the average LER for the 2011 and 2012 growing seasons was used to calculate MAI. For the mixtures, both AYL and LER showed similar trends to that of K with respect to seeding ratios, with the lowest values for the 50:50 mixtures (Table 3).

The economic indices IA and MAI varied significantly with the seeding rate. Positive IA values were obtained for oat at seeding ratio 80:20 and 67:33 and the highest IA value was for the 80:20 oat–common vetch intercrop. The IA values for common vetch were all negative except that for the 20:80 mixture. This value was smaller than those obtained for oat so that the total IA followed the same pattern as that of IA_{oat}. The highest overall IA (0.254) was for the 80:20 oat–common vetch intercrop. Similar to the trends in yield (Table 1), the MAI showed positive values for the oat–common vetch intercrops with seeding ratios of 80:20, 67:33, and 20:80 (18.54, 5.90, and 35.51, respectively).

TABLE 2 Land equivalent ratio (LER) and relative crowding coefficient (K) for monocrops and oat (O)–common vetch (V) intercrops with different seeding ratios.

Treatment (seeding ratio)	Land equivalent ratio			Relative crowding coefficient		
	LER_{oat}	LER_{vetch}	LER	K_{oat}	K_{vetch}	K
O:V(80:20)	0.885 (0.060)	0.186 (0.020)	1.070 (0.056)	1.920 (0.178)	0.912 (0.060)	1.751 (0.152)
O:V(67:33)	0.739 (0.040)	0.284 (0.017)	1.023 (0.042)	1.394 (0.615)	0.807 (0.082)	1.125 (0.537)
O:V(50:50)	0.488 (0.057)	0.455 (0.022)	0.944 (0.055)	0.955 (0.238)	0.835 (0.073)	0.798 (0.215)
O:V(33:67)	0.330 (0.046)	0.641 (0.091)	0.971 (0.130)	1.001 (0.161)	0.878 (0.232)	0.879 (0.386)
O:V(20:80)	0.344 (0.066)	0.823 (0.052)	1.167 (0.093)	2.098 (0.939)	1.165 (0.183)	2.445 (0.812)
$LSD_{0.05}$	0.13	0.15	0.20	0.45	0.22	0.86

Values shown are averages from two growing seasons (2011 and 2012). Standard errors are shown in parentheses.

TABLE 3 Aggressivity (A) and actual yield loss (AYL) for oat (O)–common vetch (V) intercrops at different seeding ratios.

Treatment (seeding ratio)	Aggressivity		Actual yield loss		
	A_{oat}	A_{vetch}	AYL_{oat}	AYL_{vetch}	AYL
O:V(80:20)	0.671 (0.050)	−0.671 (0.050)	0.106 (0.015)	−0.072 (0.019)	0.034 (0.010)
O:V(67:33)	0.401 (0.087)	−0.401 (0.087)	0.103 (0.060)	−0.138 (0.051)	−0.035 (0.004)
O:V(50:50)	0.017 (0.003)	−0.017 (0.003)	−0.023 (0.014)	−0.090 (0.043)	−0.113 (0.096)
O:V(33:67)	−0.320 (0.049)	0.320 (0.049)	0.001 (0.001)	−0.044 (0.014)	−0.043 (0.026)
O:V(20:80)	−0.590 (0.041)	0.590 (0.041)	0.720 (0.329)	0.029 (0.015)	0.750 (0.034)
$LSD_{0.05}$	0.32	0.32	0.41	0.03	0.49

Values shown are averages from two growing seasons (2011 and 2012). Standard errors are shown in parentheses.

4 Discussion

4.1 Aboveground dry matter

Intercropping is becoming more popular in sustainable agricultural methods, because of its potential to increase the efficiency of resource use. In previous studies on intercropping systems, it has been reported that oat dominated pea (*Pisum sativum* L.) (Neugschwandtner and Kaul, 2016), at 66:33 common vetch–barley (*Hordeum vulgare* L.) intercropping (Osman and Nersoyan, 1986), 55:45 common vetch–oat intercrop (Dhima et al., 2007) and 75:25 oat–faba bean (*Vicia faba* L.) intercropping (Dhima et al., 2014) had higher yield than their respective monocrops. These findings suggested that the maximum DM yields depend both on the species and on the seeding ratio. However, Another study found that the seeding ratios had no impact on the dry matter yields in combinations of pea and cereals, such as wheat or oat (Carr et al., 1998).

In this study, the contribution of common vetch to DM yield decreased with higher proportions of common vetch in the intercrops. This may have been because of competition between oat and common vetch in the intercrops, given that all the competition indices pointed out that oat was the prevailing species in the mixture. One possible explanation is that the tillering capacity of oat made it more competitive than common vetch (Lithourgidis et al., 2011). Another possible explanation is that oats grow faster initially and have a higher plant height than the intercropping common vetch. Putting the intercropped common vetch a disadvantage in terms of light (Feng et al., 2015).

The mechanisms that explain over-yielding intercropping are generally attributed to specific mutual complementarity (Dong et al., 2018) and beneficial interactions among species (facilitation) in resource use (Stomph et al., 2020). Cong et al. (2014) showed that facilitation of P, Fe, Mn and Zn acquisition is a potentially important cause of overyielding in annual intercropping systems. Cereal/legume intercropping improves phosphorus acquisition (Hinsinger et al., 2011).

4.2 Crude protein

The concentration of CP is a crucial nutritional key qualities of forage crops and is commonly utilised to assess forage systems, particularly intercropping systems (Yolcu et al., 2009). The CP concentration was shown to increase in intercrops due to the legume contribution (Bedoussac et al., 2014). In the Mediterranean environment, pure common vetch or higher proportions of common vetch intercropped with oat showed higher CP yields (Lithourgidis et al., 2006), because of the low proportion of protein in the ABDM of oat (Lithourgidis et al., 2011). However, Li et al. (2006) found no notable disparities in nitrogen intake between intercropping systems that combine legumes and cereals, and the traditional practice of growing these crops separately. The study found that the common vetch monocrop had the highest CP concentration at 14.88%. Another study found that CP yields were greatest with a 3:1 ratio of oats to common vetch, increasing 21.3 and 6.1% over oats alone and wild peas alone, respectively (Qu et al., 2022). However, in this semi-arid region under summer-sowing conditions, the highest CP yield (696 kg ha^{-1}) was in the oat–common vetch intercrop with an 80:20 seeding ratio. This was because of the high DM yield of this intercrop.

4.3 Competition indices

The LER is an indicator of the effectiveness of environmental resource use in intercropping compared to monocropping (Willey and Rao, 1980). Intercropping benefits species' development and productivity when the LER is greater than one; Intercropping has a negative effect on the growth and yield of crops grown in mixtures when the LER is less than one (Reddy and Chetty, 1984; Ofori and Stern, 1987). Dhima et al. (2007) reported LER values ranging from 1.05 to 1.09 in a mix of common vetch with wheat, triticale (×Triticosecale Witt mark), barley, and oat at common vetch–cereal ratios of 55:45 and 65:35. LER for maize and cowpea (*Vigna unguiculata* L., Walp) intercropping exceeded 1 (1.91 and 1.53) and found that the intercrops were more stable than monocrops (Dimande et al., 2024). In another study, the land productivity of intercrops was 12–32% higher than those of monocrops (Chapagain and Riseman, 2014; Xu et al., 2021). In the present study, the oat–common vetch intercrop at a seeding ratio of 20:80 showed the highest LER value (1.17); This suggests that to attain the same yield as an intercrop, a solo cropping system would need to occupy an area that is 17% greater (Midya et al., 2005). Nassab et al. (2011) reported that a 67:33 mixture of maize and sunflower (*Helianthus annuus* L.) showed a higher LER value than those of other mixtures and monocrops. Wang et al. (2021) found that in oat and common vetch intercropping, LER was highest when oats were sown at a rate of 50%, which was 11–57% higher than other sowing rates. In the present study, the LER value for the 50:50 oat–common vetch intercrop was lower than one, suggesting strong competition between the two crops in this mixture.

In the intercrop mixtures, the K_{oat} values were higher than the K_{vetch} values, which indicates that oat was more competitively effective than vetch under these conditions. However, Dhima et al. (2007) report that *K* was higher for common vetch than for cereals in the mixture of vetch with wheat or triticale (65:35 common vetch–cereal). The *K* values exhibited a comparable pattern to the LER values in this investigation. In all mixtures, the *K* value was greater than one, indicating that there was a yield advantage of intercropping (Willey and Rao, 1980; Banik et al., 2000; Ghosh, 2004). The *K* value was above two in the 67:33 and 20:80 oat–common vetch mixtures, indicating a substantial yield increase from intercropping.

The A values indicated which species was dominant in the intercrops. Common vetch was the dominant species (as indicated by positive A_{vetch} values) only when it was the main component in the mixture (67% or 80%) (Table 3). Similar results have been reported previously for common vetch–wheat and common vetch–triticale mixtures (65:35) (Dhima et al., 2007). The study showed that the difference in aggression to competition ratios between oats and common wild pea was not significant under the mixed cropping system (Zhu et al., 2022). In the present study, oat was dominant in the oat–common vetch intercrops with seeding ratios of 80:20, 67:33, and 50:50. Cereals like maize, sorghum (*Sorghum bicolor* L) Moench, and pearl millet (*Pennisetum americanum* L) were also reported to be dominant in groundnut–cereal intercropping systems (Ghosh, 2004).

AYL offers more accurate data on both inter-and intraspecific rivalry among part crops and the actions of the various species in intercropping systems, in comparison to other competition indices (Banik et al., 2000). Positive AYL values signify a benefit, whereas negative AYL values signify a drawback in intercrops when the primary goal is to compare production on a per-plant basis (Zhang Q, et al., 2015). Dhima et al. (2007) reported negative AYL values for common vetch–triticale (65:35), common vetch–barley (65:35) and common vetch–oat (55:45) intercrops. Neugschwandtner and Kaul (2014) reported that 75:25, 50:50, and 25:75 oat–pea intercrops did not show yield advantages when grown in fertile soil. Takim (2012) studied maize–cowpea intercrops (67:33, 50:50, and 33:67) and reported negative AYL values for intercropped cowpea ranging from −0.257 to −0.813, indicating a yield loss of 25.7–81.3%, compared with that of a cowpea monocrop. In the present study, the AYL values for common vetch were negative and ranged from −0.044 to −0.138, indicating a yield loss of 4.4–13.8% in intercrops. Although the partial AYL of oat was positive except in the 50:50 oat–common vetch intercrop, the AYL was negative except in the 20:80 and 80:20 oat-common vetch intercrop, and this was insufficient to offset the decrease in crop productivity caused by the presence of common vetch in the mixture.

4.4 Economic indices

Dhima et al. (2007) reported a maximum MAI value of 13.47 for a 20:80 oat–common vetch mixture, while the maximum yield advantage was obtained for a 45:55 oat–common vetch mixture. In the present study, the most advantageous mixtures were the 20:80 oat–common vetch intercrop, followed by the 67:33 oat–common vetch intercrop (IA values of 0.254 and 0.99, respectively; Table 4). Lithourgidis et al. (2011) reported that a 20:80 cereal–pea intercrop

TABLE 4 Intercropping advantage (IA) and monetary advantage index (MAI) for oat–common vetch intercrops at different seeding ratios.

Treatment (seeding ratio)	Intercropping advantage			*MAI*
	IA_{oat}	IA_{vetch}	*IA*	
O:V(80:20)	0.294 (0.033)	−0.040 (0.005)	0.254 (0.010)	18.54 (2.66)
O:V(67:33)	0.176 (0.085)	−0.077 (0.027)	0.099 (0.001)	5.90 (1.02)
O:V(50:50)	0.007 (0.005)	−0.050 (0.024)	−0.043 (0.014)	−13.18 (2.24)
O:V(33:67)	−0.141 (0.062)	−0.025 (0.016)	−0.165 (0.005)	−6,28 (0.15)
O:V(20:80)	−0.259 (0.145)	0.016 (0.003)	−0.242 (0.042)	35.51 (2.44)
$LSD_{0.05}$	0.18	0.17	0.15	7.63

Values shown are averages from two growing seasons (2011 and 2012). Standard errors are shown in parentheses.
Average hay procurement price per ton: common vetch = €55, oat = €43.

provided the maximum economic profit, consistent with our results. In line with our findings, Ghosh (2004) observed that greater LER and K values were linked to notable economic advantages, as indicated by larger MAI values.

The outcomes of our study indicate that the practice of planting oat and common vetch together at various seeding ratios has an impact on the dry matter yield of each species, the degree of rivalry between the two species, and ultimately the economic viability of the intercropping system. By planting oats and common vetpea in different proportions, the method of increasing the yield of annual forage crops is realized to solve the problem of local feed shortage in winter and early spring. In future studies, we can explore the mixed sowing mechanism of annual forage crops and understand the principle of mixed sowing to increase yield, so as to select more mixed crops and clarify the breeding direction of future mixed crops.

On the Loess Plateau, oat–common vetch at a seeding ratio of 20:80 is the optimal intercrop in terms of balancing the nutritive value, competition between species, and economic returns. The results of this study illustrate how yield, competition, resource use, and economic indices can be used to compare different intercrops and identify which systems have the best overall value.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YJ: Writing – original draft, Writing – review & editing. QZ: Conceptualization, Data curation, Writing – original draft. FM: Writing – original draft, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was funded by the Natural Science Foundation of China (31802133, 40121004), the China Agriculture Research System (CARS-34), the Natural Science Foundation of Shandong Province (ZR2020QC189), the Shandong Forage Research System (SDAIT-23-01), and the "Youth Innovation Team Plan" of Universities in Shandong Province (2022KJ166).

Acknowledgments

First, I would like to express my sincere thanks to the financial support of various institutions. Secondly, I would like to thank Yibo Wang and Meixuan Li for their contributions in this research and writing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Agegnehu, G., Ghizaw, A., and Sinebo, W. (2006). Yield performance and land-use efficiency of barley and faba bean mixed cropping in Ethiopian highlands. *Eur. J. Agron.* 25, 202–207. doi: 10.1016/j.eja.2006.05.002

Andersen, M. K., Hauggaard-Nielsen, H., Weiner, J., and Jensen, E. S. (2007). Competitive dynamics in two- and three-component intercrops. *J. Appl. Ecol.* 44, 545–551. doi: 10.1111/j.1365-2664.2007.01289.x

Banik, P., Sasmal, T., Ghosal, P. K., and Bagchi, D. K. (2000). Evaluation of mustard (Brassica compestris Var. Toria) and legume intercropping under 1: 1 and 2: 1 row-replacement series systems. *J. Agron. Crop Sci.* 185, 9–14. doi: 10.1046/j.1439-037X.2000.00388.x

Bedoussac, L., Journet, É.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Prieur, L., et al. (2014). "Eco-functional intensification by cereal-grain legume intercropping in organic farming systems for increased yields, reduced weeds and improved grain protein concentration" in *Organic farming, prototype for sustainable agricultures*. eds. S. Bellon and S. Penvern (Dordrecht: Springer), 47–63.

Black, C. A. (1965). Method of soil analysis part 2. *Chem. Microbiol. Proper.* 9, 1387–1388,

Caballero, R., and Goicoechea, E. L.. (1986). Utilization of winter cereals as companion crops for common vetch and hairy vetch. Proceedings of the 11th General Meeting of the European Grass Fed.

Caballero, R., Goicoechea, E. L., and Hernaiz, P. J. (1995). Forage yields and quality of common vetch and oat sown at varying seeding ratios and seeding rates of vetch. *Field Crop Res.* 41, 135–140. doi: 10.1016/0378-4290(94)00114-R

Carr, P. M., Martin, G. B., Caton, J. S., and Poland, W. W. (1998). Forage and nitrogen yield of barley—pea and oat—pea intercrops. *Agron. J.* 90, 79–84. doi: 10.2134/agronj1998.00021962009000010015x

Chapagain, T., and Riseman, A. (2014). Barley–pea intercropping: effects on land productivity, carbon and nitrogen transformations. *Field Crop Res.* 166, 18–25. doi: 10.1016/j.fcr.2014.06.014

Chen, J., Chen, Y., Wang, K., Wang, G., Junhua, W., and Zhang, Y. (2023). Differences in soil water storage, consumption, and use efficiency of typical vegetation types and their responses to precipitation in the loess plateau, China. *Sci. Total Environ.* 869:161710. doi: 10.1016/j.scitotenv.2023.161710

Cong, W.-F., Hoffland, E., Li, L., Six, J., Sun, J.-H., Bao, X.-G., et al. (2014). Intercropping enhances soil carbon and nitrogen. *Glob. Chang. Biol.* 21, 1715–1726. doi: 10.1111/gcb.12738

Dhima, K. V., Lithourgidis, A. S., Vasilakoglou, I. B., and Dordas, C. A. (2007). Competition indices of common vetch and cereal intercrops in two seeding ratio. *Field Crop Res.* 100, 249–256. doi: 10.1016/j.fcr.2006.07.008

Dhima, K. V., Vasilakoglou, I. B., Xh Keco, R., Dima, A. K., Paschalidis, K. A., and Gatsis, T. D. (2014). Forage yield and competition indices of faba bean intercropped with oat. *Grass Forage Sci.* 69, 376–383. doi: 10.1111/gfs.12084

Dimande, P., Arrobas, M., and Rodrigues, M. Â. (2024). Intercropped maize and cowpea increased the land equivalent ratio and enhanced crop access to more nitrogen and phosphorus compared to cultivation as sole crops. *Sustain. For.* 16:1440. doi: 10.3390/su16041440

Dong, N., Tang, M.-M., Zhang, W.-P., Xing-Guo Bao, Y., Wang, P. C., and Li, L. (2018). Temporal differentiation of crop growth as one of the drivers of intercropping yield advantage. *Sci. Rep.* 8:3110. doi: 10.1038/s41598-018-21414-w

Duchene, O., Vian, J.-F., and Celette, F. (2017). Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review. *Agric. Ecosyst. Environ.* 240, 148–161. doi: 10.1016/j.agee.2017.02.019

Esmaeili, A., Sadeghpour, A., Hosseini, S. M. B., Jahanzad, E., Chaichi, M. R., and Hashemi, P. M. (2011). Evaluation of seed yield and competition indices for intercropped barley (*Hordeum vulgare*) and annual medic (*Medicago scutellata*). *Int. J. Plant Prod.* 5, 395–404,

Feng, X. M., Yang, Y., Ren, C. Z., Yue Gao, H., and Zeng, Z. H. (2015). Effects of legumes intercropping with oat on photosynthesis characteristics of and grain yield. *Acta Agron. Sin.* 41, 1426–1434. doi: 10.3724/SP.J.1006.2015.01426

Fengrui, L., Songling, Z., and Geballe, G. T. (2000). Water use patterns and agronomic performance for some cropping systems with and without fallow crops in a semi-arid environment of Northwest China. *Agric. Ecosyst. Environ.* 79, 129–142. doi: 10.1016/S0167-8809(99)00149-8

Ghosh, P. K. (2004). Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. *Field Crop Res.* 88, 227–237. doi: 10.1016/j.fcr.2004.01.015

Gitari, H. I., Nyawade, S. O., Kamau, S., Karanja, N. N., Gachene, C. K. K., Raza, M. A., et al. (2020). Revisiting intercropping indices with respect to potato-legume intercropping systems. *Field Crop Res.* 258:107957. doi: 10.1016/j.fcr.2020.107957

Gronle, A., Lux, G., Böhm, H., Schmidtke, K., Wild, M., Demmel, M., et al. (2015). Effect of ploughing depth and mechanical soil loading on soil physical properties, weed infestation, yield performance and grain quality in sole and intercrops of pea and oat in organic farming. *Soil Tillage Res.* 148, 59–73. doi: 10.1016/j.still.2014.12.004

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., et al. (2011). P for two, sharing a scarce resource: soil phosphorus acquisition in the rhizosphere of intercropped species. *Plant Physiol.* 156, 1078–1086. doi: 10.1104/pp.111.175331

Jensen, E. S., Carlsson, G., and Hauggaard-Nielsen, H. (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. *Agron. Sustain. Dev.* 40:5. doi: 10.1007/s13593-020-0607-x

Jones, D. B. (1931). *Factors for converting percentages of nitrogen in foods and feeds into percentages of proteins, vol. 183.* Washington, DC: US Department of Agriculture.

Koskey, G., Leoni, F., Carlesi, S., Avio, L., and Bàrberi, P. (2022). Exploiting plant functional diversity in durum wheat–lentil relay intercropping to stabilize crop yields under contrasting climatic conditions. *Agronomy* 12, 210–224. doi: 10.3390/agronomy12010210

Lai, H., Gao, F., Hao, S., Zheng, P., Li, Y., and Yao, H. (2022). Nitrogen distribution and soil microbial community characteristics in a legume–cereal intercropping system: a review. *Agronomy* 12:1900. doi: 10.3390/agronomy12081900

Li, L., Sun, J., Zhang, F., Guo, T., Bao, X., Smith, F. A., et al. (2006). Root distribution and interactions between intercropped species. *Oecologia* 147, 280–290.

Lithourgidis, A. S., Vasilakoglou, I. B., Dhima, K. V., Dordas, C. A., and Yiakoulaki, M. D. (2006). Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. *Field Crop Res.* 99, 106–113. doi: 10.1016/j.fcr.2006.03.008

Lithourgidis, A. S., Vlachostergios, D. N., Dordas, C. A., and Damalas, C. A. (2011). Dry matter yield, nitrogen content, and competition in pea–cereal intercropping systems. *Eur. J. Agron.* 34, 287–294. doi: 10.1016/j.eja.2011.02.007

Liu, X., Jiao, Y., Zhao, X., Yu, X., Zhang, Q., Li, S., et al. (2023). Root architecture of forage species varies with intercropping combinations. *Agronomy* 13, 2223–2234. doi: 10.3390/agronomy13092223

Liu, H., Struik, P. C., Zhang, Y., Jing, J., and Stomph, T.-J. (2023). Forage quality in cereal/legume intercropping: a meta-analysis. *Field Crop Res.* 304:109174. doi: 10.1016/j.fcr.2023.109174

Luo, S., Lingling, Y., Liu, Y., Zhang, Y., Yang, W., Li, Z., et al. (2016). Effects of reduced nitrogen input on productivity and N 2 O emissions in a sugarcane/soybean intercropping system. *Eur. J. Agron.* 81, 78–85. doi: 10.1016/j.eja.2016.09.002

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., et al. (2021). Intercropping—a low input agricultural strategy for food and environmental security. *Agronomy* 11, 343–370. doi: 10.3390/agronomy11020343

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., et al. (2009). Mixing plant species in cropping systems: concepts, tools and models: a review. *Agron. Sustain. Dev.*, 29, 43–62. doi: 10.1007/978-90-481-2666-8_22

McGilchrist, C. A. (1965). Analysis of competition experiments. *Biometrics* 21, 975–985. doi: 10.2307/2528258

Midya, A., Bhattacharjee, K., Ghose, S. S., and Banik, P. (2005). Deferred seeding of blackgram (*Phaseolus mungo* L.) in rice (*Oryza sativa* L.) field on yield advantages and smothering of weeds. *J. Agron. Crop Sci.* 191, 195–201. doi: 10.1111/j.1439-037X.2005.00157.x

Nassab, A. D., Mohammadi, T. A., and Kaul, H.-P. (2011). Competition and yield in intercrops of maize and sunflower for biogas. *Ind. Crop. Prod.* 34, 1203–1211. doi: 10.1016/j.indcrop.2011.04.015

Neugschwandtner, R. W., and Kaul, H.-P. (2014). Sowing ratio and N fertilization affect yield and yield components of oat and pea in intercrops. *Field Crop Res.* 155, 159–163. doi: 10.1016/j.fcr.2013.09.010

Neugschwandtner, R. W., and Kaul, H.-P. (2016). Concentrations and uptake of macronutrients by oat and pea in intercrops in response to N fertilization and sowing ratio. *Arch. Agron. Soil Sci.* 62, 1236–1249. doi: 10.1080/03650340.2016.1147648

Ofori, F., and Stern, W. R. (1987). Cereal–legume intercropping systems. *Adv. Agron.* 41, 41–90. doi: 10.1016/S0065-2113(08)60802-0

Osiru, D. S. O., and Willey, R. W. (1972). Studies on mixtures of dwarf sorghum and beans (*Phaseolus vulgaris*) with particular reference to plant population. *J. Agric. Sci.* 79, 531–540. doi: 10.1017/S0021859600025910

Osman, A. E., and Nersoyan, N. J. E. A. (1986). Effect of the proportion of species on the yield and quality of forage mixtures, and on the yield of barley in the following year. *Exp. Agric.* 22, 345–351. doi: 10.1017/S0014479700014599

Pinto, P., Cartoni-Casamitjana, S., Cureton, C., Stevens, A. W., Stoltenberg, D. E., Zimbric, J., et al. (2022). Intercropping legumes and intermediate wheatgrass increases forage yield, nutritive value, and profitability without reducing grain yields. *Front. Sustainable Food Syst.* 6, 13–29. doi: 10.3389/fsufs.2022.977841

Qu, J., Li, L., Bai, J., Chen, G., Zhang, Y., and Chang, Q. (2022). Influence of different proportion intercropping on oat and common vetch yields and nutritional composition at different growth stages. *Agronomy* 12:1908. doi: 10.3390/agronomy12081908

Raza, M. A., Zhiqi, W., Yasin, H. S., Gul, H., Qin, R., Rehman, S. U., et al. (2023). Effect of crop combination on yield performance, nutrient uptake, and land use advantage of cereal/legume intercropping systems. *Field Crop Res.* 304:109144. doi: 10.1016/j.fcr.2023.109144

Reddy, M. N., and Chetty, C. R. (1984). Staple land equivalent ratio for assessing yield advantage from intercropping. *Exp. Agric.* 20, 171–177. doi: 10.1017/S0014479700003288

Scalise, A., Tortorella, D., Pristeri, A., Petrovičová, B., Gelsomino, A., Lindström, K., et al. (2015). Legume–barley intercropping stimulates soil N supply and crop yield in the succeeding durum wheat in a rotation under rainfed conditions. *Soil Biol. Biochem.* 89, 150–161. doi: 10.1016/j.soilbio.2015.07.003

Shen, Y., Sui, P., Huang, J., Wang, D., Whalen, J. K., and Chen, Y. (2018). Greenhouse gas emissions from soil under maize–soybean intercrop in the North China plain. *Nutr. Cycl. Agroecosyst.* 110, 451–465. doi: 10.1007/s10705-018-9908-8

Stomph, T. J., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., et al. (2020). Designing intercrops for high yield, yield stability and efficient use of resources: are there principles? *Adv. Agron.* 160, 1–50. doi: 10.1016/bs.agron.2019.10.002

Takim, F. O. (2012). Advantages of maize-cowpea intercropping over sole cropping through competition indices. *J. Agric. Biodivers. Res.* 1, 53–59.

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Van der Heijden, M. G. A., Liebman, M., et al. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci Adv.* 6:eaba1715. doi: 10.1126/sciadv.aba1715

Wang, S., Chen, G., Yang, Y., Zeng, Z., Yuegao, H., and Zang, H. (2021). Sowing ratio determines forage yields and economic benefits of oat and common vetch intercropping. *Agron. J.* 113, 2607–2617. doi: 10.1002/agj2.20647

Willey, R. W., and Rao, M. R. (1980). A competitive ratio for quantifying competition between intercrops. *Exp. Agric.* 16, 117–125. doi: 10.1017/S0014479700010802

Xu, R., Zhao, H., Liu, G., You, Y., Ma, L., Liu, N., et al. (2021). Effects of nitrogen and maize plant density on forage yield and nitrogen uptake in an alfalfa–silage maize relay intercropping system in the North China plain. *Field Crop Res.* 263:108068. doi: 10.1016/j.fcr.2021.108068

Yolcu, H., Polat, M., and Aksakal, V. (2009). Morphologic, yield and quality parameters of some annual forages as sole crops and intercropping mixtures in dry conditions for livestock. *J. Food Agric. Environ.* 7, 594–599,

Zhang, Y., Liu, J., Zhang, J., Liu, H., Liu, S., Zhai, L., et al. (2015). Row ratios of intercropping maize and soybean can affect agronomic efficiency of the system and subsequent wheat. *PLoS One* 10:e0129245. doi: 10.1371/journal.pone.0129245

Zhang, Q., Tian, L., Liu, Y., Jiang, H., and Shen, Y. (2015). Yield and water use efficiency of annual forage crops on the loess plateau. *Arid Zone Studies* 32:7,

Zhu, S.-G., Cheng, Z.-G., Yin, H.-H., Zhou, R., Yang, Y.-M., Wang, J., et al. (2022). Transition in plant–plant facilitation in response to soil water and phosphorus availability in a legume-cereal intercropping system. *BMC Plant Biol.* 22:311. doi: 10.1186/s12870-022-03706-6

Zixi, Z., Stewart, B. A., and Xiangjun, F. (1994). Double cropping wheat and corn in a sub-humid region of China. *Field Crop Res.* 36, 175–183. doi: 10.1016/0378-4290(94)90109-0