Forage production and soil water balance in oat and common vetch sole crops and intercrops cultivated in the summer-autumn fallow season on the Chinese Loess Plateau

Zikui Wang, Hailiang Jiang, Yuying Shen
State Key Laboratory of Grassland Agro-Ecosystem, Lanzhou University, Lanzhou, 730020, China
College of Pastoral Agricultural Science and Technology, Lanzhou University, Lanzhou, 730020, China

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- Intercropping
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ABSTRACT

Integrating forage crops into traditional wheat and maize cropping systems is a potential alternative for increasing fodder supply while maintaining sustainable grain production on the Loess Plateau of China. This study was conducted to evaluate the biomass and crude protein production as well as the soil water balance and water use efficiency of oat (Avena sativa L.) and common vetch (Vicia sativa L.) intercrops compared to sole crops. Field experiments were conducted during the fallow season after wheat harvesting (mid-July to late October) in 2011 and 2012. Five cropping patterns were tested: sole oat (SO), sole common vetch (SV), and three intercrops of oat to common vetch in rows of two to one (I21), one to one (I11), and one to two (I12). Rainfall in 2011 was abundant, but the early season was very dry. Rainfall in 2012 was less than average but distributed similarly with the long-term pattern. When harvested in late September, I21 showed the greatest aerial biomass and crude protein yield of 3.20 and 0.36 t ha⁻¹, respectively, in 2011, and SO showed the greatest biomass and crude protein yield of 5.70 and 0.51 t ha⁻¹, respectively, in 2012. When harvested one month later, the crude protein content of common vetch maintained a large value, while that in oat was reduced by 21 %–29 %. I21 still showed the greatest biomass and crude protein yield in 2011, and in 2012, SO had the highest biomass yield of 7.74 t ha⁻¹ while SV showed the highest crude protein production of 0.65 t ha⁻¹. The land equivalent ratio was above unity in all intercropping systems in 2011 and below unity in all systems in 2012. The soil water in the 0–120 cm layer in all treatments was fully recharged in 2011, but depleted in 2012, and the depletions in SV and I12 were significantly less than that of the other treatments (P < 0.05) on both harvesting dates. In 2011, water use efficiencies based on biomass and crude protein on both harvesting dates were all greatest in I21, water use efficiencies at the early and late harvestings were greatest in SO and I12, respectively. Therefore, the intercrops with a greater oat proportion had the advantage of maintaining system production when early season water availability was unfavorable, while those with a greater common vetch proportion had the potential of improving forage quality and conserving soil water to maintain the production of the main crop under normal water conditions. Selection of a proper planting pattern should take initial soil water conditions and rainfall availability into consideration.

1. Introduction

China’s dominant agriculture system has been defined as grain farming, however, it cannot satisfy national food security, which emphasizes nutrient security (Li and Lin, 2014). Continued growing demand for livestock products provides a motivation to practice integrating crop-livestock systems. However, the limited availability and quality of livestock feed in traditional grain production districts restrict the ability of resource-poor farmers to increase their livestock production (Liu et al., 2012; Komarek et al., 2015). Livestock production on the Chinese Loess Plateau relies predominantly on pen feeding with wheat (Triticum aestivum L.) and maize (Zea mays L.) residues and lucerne (Medicago sativa L.), and shortages and the low quality of forages particularly during winter and early spring limit local livestock production (Nolan et al., 2008; Komarek et al. 2012). These feed gaps greatly restrict farmers’ income and the subsequent economic development of a regional livestock industry (Hou et al., 2008). Hence, diversifying cropping systems that generate forage is a potential way to
Table 1

<table>
<thead>
<tr>
<th>Soil layer (cm)</th>
<th>Particle size distribution (%)</th>
<th>Field water capacity (%)</th>
<th>Soil available water (mm)</th>
<th>Organic matter content (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–10</td>
<td>15.4</td>
<td>77.0</td>
<td>7.6</td>
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<td>8.5</td>
<td>29.5</td>
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<td>90–120</td>
<td>12.9</td>
<td>80.5</td>
<td>6.6</td>
<td>28.9</td>
</tr>
</tbody>
</table>
2.2. Experimental design

The field experiment was carried out during the fallow season after the harvesting of winter wheat in early July, which was designed and settled by a random complete block method with five treatments and three replications. The treatments for the crop planting pattern including two sole crops (sole oat, SO, and sole common vetch, SV) and three intercrops. Three intercropping systems with oat to common vetch planting ratios of two to one (two rows of oat alternated with one row of common vetch, I21), one to one, (one row of oat alternated with one row of common vetch, I11), and one to two (one row of oat alternated with two rows of common vetch, I12) were designed to test the effects of the proportion of oat on the system production and soil water balance because we hypothesized that a greater oat proportion would contribute to greater system production but more water consumption. Crops were seeded by hand on 11 July 2011 and on 12 July 2012. All crop rows followed a north-south orientation. The individual plot area was 5 × 6 m². The sole oat was planted with a seeding rate of 165 kg ha⁻¹ and an inter-row distance of 30 cm, and the sole common vetch was planted with a seeding rate of 105 kg ha⁻¹ and inter-row distance of also 30 cm. Oat and common vetch intercropping in this study was replacement intercropping (several oat rows were replaced by common vetch rows). The overall proportional density of each crop species was equal in both the sole and intercropping treatments. The distance between adjacent oat and common vetch rows in intercropping was also 30 cm. According to local fertilization recommendations, nitrogen and phosphorous were applied as diammonium phosphate before sowing at rates equivalent to 46 kg ha⁻¹ N and 100 kg ha⁻¹ P₂O₅, respectively. All plots were kept free of weeds by hand hoeing.

2.3. Data collection and calculations

2.3.1. Leaf area index

The leaf area index (LAI) of different systems was measured using an LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, NE, USA), and the measurements were taken monthly from late July to late October in each season. Five measurements of diffuse light transmission through the canopy were taken for each replicate. Light sensors were set to cross the crop rows in sole crop plots and cross the intercropping strips to make sure that measurements in each replicate contained one or more complete intercropping strip (Wang et al., 2015b).

2.3.2. Aerial biomass yield

Forage crops were harvested in late September and late October to evaluate the fallow season production in continuous wheat and winter wheat-maize rotation systems respectively (Fig. 1). For each harvesting, all of the plants in five adjacent 50-cm-long crop rows were cut manually to ground level in sole crop plots, and all of the plants in the 100-cm-long oat and common vetch strip were harvested in intercropping plots. In intercrops, the yield of each crop on a per row basis were calculated based on the sampling area of each crop while the yield on a system basis was calculated based on the sampling area of both crops. Sampled plants were placed in an oven for half an hour at 105 °C to kill the fresh tissues and then dried at 65 °C to constant weight to determine the aerial biomass yield.

2.3.3. Crude protein yield

Subsamples of those used for aerial biomass measurements were prepared and ground with a Wiley mill to pass through a 1-mm screen. The total nitrogen in whole plant samples was determined using the Kjeldahl method (Bremner, 1965). The crude protein content was calculated by multiplying the nitrogen concentration by 6.25 (Horowitz, 1980). The crude protein yield was calculated as follows:

\[ CP_{yield} = DM(t\text{ ha}^{-1}) \times CP(g\text{ g}^{-1}) \]  

(1)

where \( CP_{yield} \) represents crude protein yield (t ha⁻¹) and that for the intercropping system was calculated as the weighted mean of oat and common vetch.

2.3.4. Land equivalent ratio

The land equivalent ratio (LER) was used to compare the yields of intercropping systems relative to the yields of sole crops, which was determined as follows (Rao and Willey, 1980):

\[ LER = \frac{Y_{SO}}{Y_{IO}} + \frac{Y_{IV}}{Y_{SV}} \]  

(2)

where \( Y_{SO} \) and \( Y_{SV} \) are the biomass or CP yield of oat in intercropping and sole crop (t ha⁻¹), respectively, and \( Y_{IV} \) and \( Y_{SV} \) are the biomass or CP yield of common vetch in intercropping and sole crop (t ha⁻¹), respectively. When the LER is greater than 1.0, there is a land use advantage of intercropping. This land use advantage is expressed in terms of the relative land area that would be required as two sole cropping systems to produce yields equivalent to an intercropping system.

2.3.5. Soil water content

The soil water content was measured at sowing and each harvesting to a depth of 120 cm in six layers: 0–10, 10–20, 20–30, 30–60, 60–90, 90–120 cm. The soil samples were taken at central plot in sole crop plots. The soil oil water content in intercropping plot was supposed to...
be the average of soil water content in oat strip and common vetch strip as the two component crops consume water differently (Yin et al., 2015; Ling et al., 2017), and samples were taken at the center of both crop strips. Samples were oven-dried at 105 °C for 8 h to determine the gravimetric soil water content and volumetric water content calculated using soil bulk density. Water use (WU) over the crop growing season was calculated using the water balance equation:

\[
WU = P - \Delta S - R + CR - DP
\]

(3)

where \( P \) is effective precipitation (mm), which is calculated using the USDA Natural Resources Conservation Service methods (SCS, 1972); \( \Delta S \) is the decrease in soil water stored in the 0–120 cm layer from beginning to end of season (mm); \( R \) is the runoff (mm), which was neglected because the experimental site has a flat topography; \( CR \) is the capillary rise of water into the evaluated soil layer, which was also neglected since the underground water at the site is below 50 m; and \( DP \) is soil water percolation through the bottom of evaluated soil cores, and it was also neglected in our calculation since we assumed that rainfall water was rarely infiltrated to the depth of 120 cm in a short term.

Surface evaporation of bare soil was estimated with Ritchie’s evaporation model (Ritchie, 1972), which assumes that soil evaporation takes place in two stages represented by two parameters: \( U \) and \( CONA \). \( U \) represents the amount of cumulative evaporation when the surface soil water supply is greater than the atmospheric demand; and \( CONA \) is an empirical coefficient which depends greatly on soil hydraulic properties. Potential evaporation in stage 1 was estimated with the combination equation (Penman, 1963), and the cumulative evaporation \( U \) was estimated as 10 mm following the recommended values by FAO56 (Allen et al., 1998). The relationship between cumulative soil evaporation (Es) in the second stage and \( CONA \) was formulated as follows:

\[
Es = CONA \times t^{1/2}
\]

(4)

where \( t \) is the time (day) that the second stage lasts. \( CONA \) for the onsite soil was parametrized by Yang et al. (2018), and the value was 4.6 mm day\(^{-0.5}\).

2.3.6. Water use and water use efficiency

The WUE (kg ha\(^{-1}\) mm\(^{-1}\)) was calculated for the biomass (WUE\(_{AB}\)) and crude protein yield (WUE\(_{CP}\)):

\[
WUE_{AB} = A_{B \text{yield}}/WU
\]

(5)

\[
WUE_{CP} = C_{P \text{yield}}/WU
\]

(6)

where \( A_{B \text{yield}} \) and \( C_{P \text{yield}} \) represent the aerial biomass yield and crude protein yield, respectively.

2.4. Statistical analysis

Statistical analyses were conducted for each experimental year using an ANOVA in GenStat Release 17.0 (Lawes Agricultural Trust, Roth Amsted Experimental Station, Oxford, UK). Differences between the biomass, crude protein and WUEs among the various cropping systems grown within each season were compared using Tukey’s LSD at \( P = 0.05 \).

3. Results

3.1. Weather conditions

Fig. 2 presents the monthly rainfall distribution, solar radiation, and maximum and minimum air temperatures in 2011 and 2012 compared with the long-term values (1981–2018). The ten-day rainfall distribution was also presented. Annual rainfall was 614.5 mm in 2011, which was 16.4 % more than the historical average, and was 493.6 mm in 2012, which was 6.5 % less than the historical average. The total rainfall during the summer-autumn fallow period (July–October) was 444.6 mm in 2011, which was 31.3 % more than the historical average, and was only 313.4 mm in 2012, 7.5 % less than the history average. Air temperature and radiation reached their greatest values in June and July, respectively, and showed decreasing tendencies through the fallow season. Rainfall, air temperature and radiation in July and August were similar in the two years. In September and October, it rained a lot in 2011 and the maximum air temperature and solar radiation were much lower than those in 2012.

3.2. Dynamics of leaf area index

The LAI development pattern in different treatments was fitted with data collected on four dates in the growing season using the Gaussian equation and is shown in Fig. 3. The determination coefficients of the fitted curves were all greater than 0.93 except for MO in 2011. The canopy of sole oat showed the greatest development rate while that of sole common vetch showed the lowest rate. In 2011, the canopy development in all of the treatments was restricted by poor water availability during the early season in 2011, the maximum LAI of sole oat was less than 2.0 m\(^2\) m\(^{-2}\) and that of sole common vetch was approximately 1.0 m\(^2\) m\(^{-2}\). Intercrops had lower LAI increasing rates in the mid-season but greater increasing rates in the late-season compared with sole oat, and LAI in all of the intercropping plots were far greater than that in sole common vetch. Large amounts of rainfall occurred in late June and early July in 2012 (Fig. 2) and soil water condition was favourable for crop establishment and growth; therefore, canopy in all systems developed more quickly compared to 2011. Maximum LAI of sole oat reached nearly 3.0 m\(^2\) m\(^{-2}\) and that in sole common vetch was approximately 1.8 m\(^2\) m\(^{-2}\). The maximum LAI in I12 was around the average of the sole crops, while that in I21 and I11 showed a similar canopy development pattern with sole oat and attained far greater maximum LAI.

3.3. Aerial biomass production

Fig. 4A–C show the aerial biomass yield of oat and common vetch in different systems on a per row basis and the total system yield when the crops were harvested in late September. The aerial biomass production of oat on a per row basis was higher in all of the intercrops in 2011, however, no yield advantage of intercropping was found in 2012. The greatest aerial biomass yield was found in I11 in both seasons with values of 4.69 and 6.54 t ha\(^{-1}\) in 2011 and 2012 respectively. For common vetch, forage production was restrained by intercropping. The greatest yield was found in SV in both seasons with values of 1.40 and 3.18 t ha\(^{-1}\) in 2011 and 2012 respectively. It can be seen that water limitation in the early season of 2011 had more adverse effects on the development growth of common vetch compared to oat, average biomass production of common vetch in 2012 was almost twice of that in 2011. I21 showed the greatest total biomass production in 2011 with the values of 3.20 t ha\(^{-1}\), and SO showed the greatest value of 5.70 t ha\(^{-1}\) in 2012.

Fig. 4 D–F show the aerial biomass yield when the crops were harvested in late October. When harvested one month later, the averaged differences between 2011 and 2012 were enlarged compared to that of the early harvesting. Biomass production of oat on a per row basis was greater in intercrops, although the differences among treatments were not significant in both seasons. Common vetch in intercrops still showed less production compared with that in the sole crop. The total biomass production in intercropping systems decreased as the proportion of oat in intercropping decreased. I21 still produced the most aerial biomass yield of 3.97 t ha\(^{-1}\) in 2011, and SO produced greatest yield of 7.74 t ha\(^{-1}\) in 2012. The land equivalent ratio based on forage yield was the greatest in I21 with the value of 1.12; in 2012, the
LER of all treatments were still below 1.0 (Table 2), variance among treatments were also insignificant (P = 0.11 in 2011 and P = 0.12 in 2012). Similar to early harvesting, oat showed an intercropping advantage while common vetch showed an intercropping disadvantage in all of the cases in both years as indicated by their partial LER values.

The land equivalent ratio based on biomass (LERb) and crude protein (LERc) yield are listed in Table 2. Values of LERb at early harvesting exceeded 1.0 in all intercrops in 2011, I21 achieved the greatest value of 1.27, the differences among treatments was not significant (P = 0.35); in 2012, LER in all of the intercropping systems were below 1.0, I12 showed the greatest value of 0.87, differences among treatments was also not significant (P = 0.25). Oat showed an intercropping advantage in both years as its partial LER (LERb_o) exceeded its planting proportion (0.67, 0.5 and 0.33 in I21, I11 and I12, respectively) excepted I21 in 2012. Common vetch showed an intercropping disadvantage as its partial LER (LERb_v) was lower than the planting proportions of 0.33, 0.5 and 0.67 in I21, I11 and I12, respectively.

Fig. 2. Distribution of monthly rainfall, solar radiation and maximum and minimum air temperatures (Tmax and Tmin) in 2011 and 2012 (A) and ten-day rainfall as compared to the long-term averaged value (1981–2018) (B).

Fig. 3. Fitted LAI dynamics (lines) and measured values (points) in oat and common vetch sole crops and intercrops in the summer-autumn fallow season of 2011 and 2012, phonology of oat at each sampling was also presented. LAI values were measured on four dates during the growing season and were fitted with Logistic equation. SO and SV represent sole oat and sole common vetch respectively; I21, I11 and I12 represent intercrops with oat to common vetch ratios of two to one, one to one and one to two respectively.
3.4. Crude protein yield

When harvested in late September, there was no significant difference in the crude protein content of oat among the different systems, and the value averaging 11.6 % and 9.2 % in 2011 and 2012, respectively, and that of common vetch was also not significantly affected by planting patterns, with the value averaging 15.9 % and 16.0 % in 2011 and 2012, respectively. The crude protein content of forage was the greatest in SV, and intercropping with a greater vetch proportion tended to have greater crude protein content (Fig. 5A). The system crude protein production was greatest in I21 with a value of 0.36 t ha⁻¹ in 2011. SO obtained the greatest value of 0.51 t ha⁻¹ in 2012 but it was not significantly greater than that of other systems (Fig. 5B). Oat showed an apparent intercropping advantage in all of the treatments in 2011 and in I11 in 2012, while intercropped vetch showed a disadvantage in crude protein production compared with sole vetch, and the values of LERc were above 1.20 in all intercrops in 2011 and ranged from 0.74-0.93 in 2012 (Table 2).

When harvested in late October, the crude protein content of oat was largely reduced compared with early harvesting in both years while that of common vetch maintained a great value. The crude protein content of oat presented an average of 8.5 % and 7.3 % and that of common vetch presented an average of 17.5 % and 16.8 % in 2011 and 2012, respectively. The crude protein content of forage was still the greatest in SV, and the differences between SV and other systems were enlarged compared with that of early harvesting (Fig. 5C). The system crude protein production was still the greatest in I21 in 2011, with a value of 0.36 t ha⁻¹, and in SV in 2012, with the value of 0.65 t ha⁻¹ (Fig. 5D). Values of LERc at late harvesting ranged from 0.96 to 1.18 and 0.84-0.98 in 2011 and 2012, respectively (Table 2). Oat still contributed more to the system LERc in all of the cases.

3.5. Soil water content

Fig. 6 shows the soil water storage in the 0–120 cm soil layer at planting and the two harvesting dates in the two seasons. Only 42.2 mm rainfall occurred in the 40 days before seeding in 2011 (Fig. 1C); soil water storage was largely depleted by the previous wheat; and the soil water content at planting was close to the wilting point. Large amounts of rainfall occurred in the middle and late growing season, far exceeded the crop water use; therefore, soil water content at all layers were fully recharged, the soil water storage at both harvesting dates approximated

![Fig. 4. Aerial biomass yield of oat and common vetch on row basis and the system biomass yield in different treatments at early and late harvesting (EH and LH) in the growing season of 2011 and 2012. Values presented are the means with standard deviation bar. Different letters indicate significant differences between treatments (P < 0.05). SO and SV represent sole oat and common vetch respectively; I21, I11 and I12 represent intercrops with oat to common vetch ratios of two to one, one to one, and one to two respectively.

Table 2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Early harvesting</th>
<th>Late harvesting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LERb_o</td>
<td>LERb_v</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I21</td>
<td>1.27</td>
<td>0.17</td>
</tr>
<tr>
<td>I11</td>
<td>1.17</td>
<td>0.30</td>
</tr>
<tr>
<td>I12</td>
<td>1.21</td>
<td>0.64</td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I21</td>
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<td>0.23</td>
</tr>
<tr>
<td>I11</td>
<td>0.77</td>
<td>0.19</td>
</tr>
<tr>
<td>I12</td>
<td>0.87</td>
<td>0.52</td>
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</table>
to field capacity. The rainfall distribution in 2012 was more even, although the total rainfall from planting to last harvesting was only 259.3 mm, which could not meet crop water use; therefore, the soil water content maintained low values at both harvesting dates. No significant differences were found among intercrops and between I12 and SV at early harvesting, and the soil water storage in I12 and SV were significantly greater than other treatments. The soil water storage at the late harvesting showed a similar tendency with the early harvesting while the difference between SV and other treatments increased.

Fig. 7 shows the water content distribution in the 0−120 cm soil profile at different sampling dates in 2012. The soil water content in the 0−30 cm layer was approximately 20 % at the planting date, which was favorable for seed germination and early growth, and that in the under layers was approximately 18 %, whereas no significant difference in soil water was found among treatments in each layer. The soil water content was reduced from planting to the first harvesting, and the lowest reduction was found in SV, although the difference among treatments was still not significant in all of the layers. Only 47.5 mm rainfall occurred during the 36 days between the two harvesting dates, and the soil water was largely depleted in this period. At the last harvesting, the soil water content in SV was significantly greater than that in SO in all of the soil layers except for 10−20 cm layer. The soil water in intercrops was not significantly different from both SO and SV in the 0−60 cm layer; soil water in SV and I12 was significantly greater in the 60−90 cm layer; no significant difference was found among SV, I12 and I11, and among SO and intercrops.
3.6 Water use and water use efficiency

Table 3 presents the water use and WUE of different cropping systems in both seasons. In 2011, water use was not significantly different among cropping systems on both harvesting dates. WUE based on dry biomass was the greatest in I21 on both dates, and that in the SV was the lowest. WUE based on crude protein was the greatest in I21 on the early harvesting date and was not significantly different among treatments on the late date. The overall water use and WUE in 2012 were all far greater than that in 2011. The water use in SO was the most in 2012 and was not significantly different to those values in intercrops, while treatments with a greater oat proportion tended to show greater WUE for biomass, while treatments with a greater common vetch proportion tended to show greater WUE for crude protein. It should be noted that the WUE for biomass in SV was not significantly lower than those values in intercrops while the WUE for crude protein in SV was significantly greater on both harvesting dates.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Early harvesting</th>
<th>Water use</th>
<th>WUE_{DM}</th>
<th>WUE_{CP}</th>
<th>Late harvesting</th>
<th>Water use</th>
<th>WUE_{DM}</th>
<th>WUE_{CP}</th>
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<td></td>
<td></td>
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<tr>
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<td>2.01 ab</td>
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<td>11.9 bc</td>
<td>1.49 a</td>
<td>283.4 ab</td>
<td>18.7 ab</td>
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<td>1.37 a</td>
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<td>13.7</td>
<td>3.5</td>
<td>0.34</td>
<td>15.70</td>
<td>4.70</td>
<td>0.32</td>
<td></td>
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4. Discussion

4.1 Biomass and crude protein production

This study found that a substantial amount of forage could be produced during the summer-autumn fallow season on the Chinese Loess Plateau, and this production would be very helpful in relieving forage shortages during winter and early spring. The light and temperature conditions are favorable for forage production during the summer-autumn fallow season (Li et al., 2000; Zhang et al., 2019). When fertilizer is fully applied, water availability is the main limiting factor to crop production, and it has a large in season and inter-annual variation. Across the two experimental years more rainfall occurred in 2011 (421.1 mm), although total forage production was less than that in 2012 (259.3 mm) in all treatments because of the variety of the rainfall distribution pattern. Rainfall in June and early July in 2011 was far less than the long-term average, which adversely affected the emergence and early growth of oat and common vetch sowed in mid-July. In 2012, rainfall distribution was more even and the initial soil water content was optimal for crop development in early and middle season, however, limited rainfall in the late season restricted soil water recharge and might adversely affect the next crop production. Previous studies on wheat, maize and pea planted in northwest China also demonstrated that water limitation during early growth could severely restrict crop growth; however, interspecific interactions could be effectively trig-gered in intercrops and a relatively stable yield could be attained when water was limited (Mao et al., 2012; Wang et al., 2015). Both sole oat and common vetch planted in fallow season of 2011 and 2012 in this study had far more biomass yield (average value at early harvesting in two years) than those planted in spring of 2009 and 2010 on our experiment site (Zhang et al., 2018), which might due to that soil water condition in spring and early summer was not as good as that in summer-autumn fallow season under the monsoonal climate.

Oat showed greater biomass production in both years, while common vetch growth was more susceptible to soil water availability and showed a greater production variability. For forage quality, the crude protein content of oat reduced significantly in the late growth. Oat was at the early flowering stage at early harvesting, reproductive growth began after then, and most of the photosynthesis product were transferred to the ear part and lignin proportion in the leaf and stem.
were increased; therefore, the overall protein content decreased. Similar results were also reported by previous studies (Ji et al., 2000; Lithourgidis et al., 2006; Sadeghpour et al., 2014; Zhang et al., 2018). Therefore, the early harvesting of oat ensured the optimized forage quality but would miss the optimal biomass yield. When oat was harvested late, the low crude protein content was not sufficient to target high livestock growth rates, which suggested that it should be combined with another forage source of high protein content when used as forage. The system protein content and yield in intercropping was affected by both biomass yield and protein content of both components. The high protein content in common vetch and high yield in oat are the two main factors which contribute to the higher protein yield. When water was limited in the early season (2011), intercropping facilitated the early growth of oat; therefore, intercropping with a greater oat proportion (I21) obtained the greatest biomass and protein production. When rainfall was evenly distributed and the initial soil water condition was favorable (2012), oat showed superior advantage in biomass production; therefore, sole oat had the greatest protein yield on the early harvesting. However, oat showed less increase in protein in the later growth as compared to common vetch which maintained a high protein content, so intercrops with a greater common vetch proportion obtained the best protein yield among the treatments at later harvesting. Lithourgidis et al. (2006) and Dhima et al. (2007) also found that oat and vetch intercropping was a reliable planting pattern in maintaining high forage yield and improving forage quality. Therefore, in forage production, cereal and legume intercropping is an efficient way to improve both forage quantity and forage quality, the optimal combination ratio of cereal and legume also depends on the rainfall amount and distribution and initial soil water conditions in semi-arid environments.

Most growers in China own very small plots of land, and the main reason for them to practice intercropping is to increase land productivity (Feike et al., 2012). We found that land use efficiency, measured as LER, was above unity in all oat and common vetch intercropping treatments in 2011 but below unity in all treatments in 2012, indicating that the yield advantage of intercropping was more significant under sub-optimal precipitation. Greater productivity of intercropped systems relative to sole crops often result from interspecific interactions in water use under water limited conditions (Keating and Carberry, 1993; Wang et al., 2015a). Studies showed that intercropping could shape crop rooting patterns to exploit soil water when water was in limited supply (Li et al., 2006; Ma et al., 2018; Ojeda et al., 2018c). Oat developed more quickly and was the dominant species in the intercropped treatment; therefore, the yield advantage of intercropped oat was primarily contributed to the interspecific facilitation on water use. The soil water content at planting and early growth was very low in 2011 and the partial land equivalent ratio of intercropped oat \((LER_{oa})\) was much higher than those in 2012, indicating that oat is more competitive than vetch for water uptake in drier soils and the facilitation of intercropped oat by common vetch was enhanced. Although values of \(LER_{oa}\) in 2012 were much lower, they were also greater than the planting proportion of oat (except for the I21 at early harvesting), especially at late harvesting, indicating the yield advantage in intercropping. Low water availability at late season again increased the \(LER_{oh}\). Common vetch was a weaker competitor in intercropping, which was suppressed by oat throughout the whole season, as indicated by the low values of \(LER_{oh}\) in both years. The suppression was more severe when water limitation occurred in the early growing season (2011). When nitrogen was non-limited, legumes were usually adversely affected by water and light competition in cereal and legume intercrops (Adiku et al., 2001; Mao et al., 2012); thus, the disadvantage of intercropped common vetch in this study might be due to the unfavorable light and water conditions induced by oat. It should be noted that the advantage for oat was mainly affected by water availability and not largely affected by the planting ratio, while for common vetch, the disadvantage was more apparent when its proportion in intercrops was low.

### 4.2. Soil water balance and water use efficiency

Rainfall during the fallow period is vital to replenish the depleted soil water and conserve water to maintain a possible stable production of the next crop in arid and semi-arid areas. The amount of rainfall during the fallow period was far greater than the corresponding long-term value in 2011, the soil water was well recharged and the recharge was not differently affected by coping pattern. The greatest amount in water use was found in MV at both harvesting dates (Table 2), which was due to MV presenting the lowest soil coverage and greatest soil evaporation. Bare soil evaporation from planting to early and late harvesting was estimated as 143.5 and 182.7, mm respectively; therefore, considerable water could be saved by converting soil evaporation to plant transpiration after cultivating forage crops. Many previous studies about the long-term fallow period (14–21 months) on the Central High Plain (Haas and Willis, 1962; Black et al., 1974; Farahani et al., 1998; Nielsen and Vigil, 2010, 2017) and short-term fallow period (2–9 months) on the Loess Plateau (Gao and Zhang, 1992; Zhu et al., 1994; Li et al., 2000) also identified low rainfall storage efficiency due to significant soil evaporation and suggested improving crop intensity to increase the rainfall use efficiency and economic return.

In comparison, rainfall in the fallow season was less than normal in 2012, and the soil water in all layers was depleted by forage crops. Bare soil evaporation from planting to early and late harvesting were estimated to be 118.5 and 153.4 mm, respectively, which was only about half of the synchronous cover crop water use; therefore, soil water would be recharged rather than depleted under fallow conditions. The deep layer depletion might not be replenished by snow and rainfall water through November to April of next year and might cause failure of next crop. Therefore, sole common vetch or intercrops with a greater proportion of common vetch should be applied when the fallow season rainfall is limited. Li et al. (2000) also showed that fallow crops such as common vetch and soybean (from early July to late September) had little effect on soil water storage since their growth depended mainly on in season precipitation.

We found a significant seasonal effect on WUE for all different systems. The variation was also reported in other studies examining the WUE of crops in semi-arid environments (Gheysari et al., 2015; Zhang et al., 2018), which was commonly caused by seasonal growing conditions such as the timing of rainfall as well as crop management. In this study, the fallow season in 2011 had drier sowing conditions, which hindered the canopy and root system development of the crops, in addition, huge amount of rainfall occurred in the middle and late season may not have been efficiently utilized by the crops and hence caused a lower WUE in that season. Although less rainfall occurred in 2012, the timing of rainfall more closely matched the water demand of crops resulting in higher crop WUE. SO and SV had the greatest and lowest biomass WUE, respectively. Other studies also reported that C3 cereals had a greater water use than C3 legumes on the semi-arid Loess Plateau (Li et al., 2000; Zhang et al., 2017, 2018). Once the WUE was calculated to account for forage quality value the differences among systems were less evident, and the crude protein WUE in SO and SV ranged within 1.42–2.16 and 1.37-2.41 kg ha\(^{-1}\) mm\(^{-1}\), respectively. It should be noted that WUE of intercropping was not significantly lower than that of SO in 2011 and that of I21 was the greatest, indicating the advantage of intercropping under unfavorable water condition (Wang et al., 2015a; Ma et al., 2018). In the normal season of 2012, the WUE of crude protein in SO was not significantly lower than that in SV at early harvesting due to its greater biomass production, therefore, it should be the optimal planting pattern for early harvesting. However, the WUE\(_{cp}\) in SO was significantly lower at late harvesting. I21 maintained a comparable WUE\(_{cp}\) with SV and comparable WUE\(_{ab}\) with MO, and it also depleted less soil water compared with MO and other intercrops;
therefore, it should be the optimal pattern for late harvesting in terms of efficient water use.

4.3. Implications for summer-autumn fallow management

The agricultural systems characterized by simple structure, high input and low efficiency have caused many environmental problems in the Loess Plateau area (Hou et al., 2014; Wang et al., 2019). Scholars have always suggested developing crop-livestock farm system to enhance the system sustainability (Ren et al., 2005; Brown et al., 2009; Liu et al., 2012; Li and Lin, 2014), and livestock development strategies are now being promoted by the local government as a means of improving rural livelihoods. However, lack of available suitable forage resources is a significant constraint to increase livestock production and economics, especially during winter and early spring when only poor quality grain crops are available (Komarek et al., 2012). Whole-farm model has demonstrated that using annual forage crops in rotations with staple grain crops can provide opportunities to maintain household food security whilst enhancing potential livestock production, however, sacrificing these staple crops to grow forages can be detrimental for household food security and economics. Therefore, shorter season crops, such as oats, vetch and pea were suggested to be added into currently fallow periods in cropping rotations (Komarek et al., 2015; Zhang et al., 2018). Sole crops and intercropping systems tested in this study could enable forages to be produced in the summer-autumn fallow season of existing grain cropping systems. We suggest that in the season with poor initial soil water condition or abundant rainfall, sole oat and intercrops with greater oat proportion could be used, whereas in the season with good initial soil water condition with normal rainfall distribution, intercrops with greater common vetch proportion should be applied to improve forage production and save water. More experiments and modeling works should be conducted to investigate the effects of fallow crops on system water balance and production on a long-term scale and under different rainfall conditions.

5. Conclusions

This study has found that there are significant prospects to planting shorter season crops during the summer-autumn fallow to enhance livestock production systems in the Loess Plateau region. The results showed that a substantial amount of forage could be produced in the fallow season of continuous winter wheat and winter wheat-maize rotation systems. The yield of both oat and common vetch were reduced due to the water deficiency in the early season in 2011, and the intercropping systems showed yield advantage under this condition, with I21 showing the greatest aerial biomass and crude protein yield and WUE on both harvesting dates. Under favorable growing conditions in 2012, SO showed the greatest aerial biomass yield and WUE for biomass at both harvesting. Moreover, although its crude protein yield and WUE for crude protein were relatively low at late harvesting, I21 maintained superior WUEs. The intercrops with a greater oat proportion has the advantage of maintaining systems production under unfavorable water conditions, while that with a greater common vetch proportion had the potential to improve the forage quality and conserve soil water to maintain the production of the main crop. Selection of planting patterns should take the initial soil water conditions into consideration. I21 was suggested for use if summer drought occurred and the initial soil water condition was poor, and SO and I22 were suggested in the fallow seasons of continuous winter wheat and winter wheat-maize rotation in favorable initial water conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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