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# Strategies for reducing the fertilizer application rate in the ridge and furrow rainfall harvesting system in semiarid regions

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The ridge and furrow rainwater harvesting (RFRH) system is a promising water-saving planting technique for dryland farming, but we lack a full understanding of the effects of different fertilizer rates (N:P) on plant nutrient uptake and nutrient use efficiency (NuUE) in foxtail millet using this planting method, as well as the available nutrient residues in the soil. We conducted field studies (Loess Plateau, China) comparing RFRH planting (R) and traditional flat planting (T) at four different fertilizer rates to determine suitable fertilizer application rates for R during 2013–2015. Compared with T, R improved the soil moisture and the utilization of rainwater and fertilizer, thereby enhancing the grain yield, water use efficiency (WUE), grain nutrient uptake, and NUE in a dry year, but with no improvements in a rainy year. The grain yield and WUE exhibited parabolic increasing trends as the fertilizer application rate increased over three years, but no significant increase was found when the fertilizer rate exceeded 189:96 kg N:P ha$^{-1}$ under R, which significantly reduced the NuUE and might waste nutrients. Therefore, we recommend R combined with 189:96 kg N:P ha$^{-1}$ as a promising planting strategy for foxtail millet in semiarid areas.

In the semiarid Loess Plateau region of northwest China, dryland farming is the major agricultural type and crop production depends mainly on limited and erratic precipitation[1]. This region is strongly governed by the monsoon climate, where over 60% of the annual rainfall is received between July and September[2]. Most of the rainfall is low intensity (<5 mm) and it cannot be utilized by crops. In addition, occasional thunderstorms in this region cause great water losses and soil erosion[3]. Strong winds in the spring and high temperature radiation in the summer lead to high rates of soil evaporation[3]. Thus, the development of planting methods is an urgent requirement in order to maximize the water use efficiency (WUE) due to the limited water resources in this area.

The ridge and furrow rainwater harvesting (RFRH) system has been used in semiarid agro-ecosystems to solve the problem of water shortages in China since the early 1990s[4]. This planting method comprises alternate parallel ridges and furrows built along the contours of a field, where the ridge is usually mulched with film for rainwater harvesting and the furrow is used for crop planting without mulching[5, 6]. This method can improve the soil water conditions by collecting water from light rain and retaining surface runoff from heavy rain. Plastic mulching prevents the evaporation of water and prolongs the period of moisture availability to provide sufficient water in the critical growth stages by crops, thereby improving crop production and the WUE[7–9]. Ren et al.[10] found that the RFRH system can improve the soil water content in the 0–100 cm layer by 5–12% under rainfall of 230–440 mm, where the maximum increase obtained in the maize yield was 75% compared with the conventional flat planting system. In a semiarid area, Ding et al.[8] showed that the RFRH system could increase the millet yield by 135.3–108.5% as well as improving the WUE by 6.8–10.3 kg ha$^{-1}$ mm$^{-1}$ compared with traditional flat planting. Thus, the RFRH system is one of the most efficient methods for maximizing the utilization of rainfall and improving crop productivity in semiarid regions[11].

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In addition to water, fertilizer (nitrogen and phosphorus) is another key factor that determines the crop yield in dryland farming because of its positive effects on improving the leaf area, dry matter content, and WUE[12–14]. However, excessive fertilizer inputs contribute little to further increases in the crop yield, which might lead to excessive water consumption and a waste of fertilizer. Thus, excessive fertilizer application does not facilitate the sustainable utilization of fertilizer resources and it increases the risk of environmental pollution, such as N and P leaching into groundwater, ammonia volatilization into the atmosphere, and $N_2O$ emissions via microbial denitrification[13, 15–17]. In recent years, strategies have been proposed to reduce fertilizer inputs to an appropriate level that exactly satisfies a crop's needs[18]. Thus, Liu et al.[19] found that a lower application rate ($110\,kg\,N\,ha^{-1}$) for maize on ridges and furrows mulched with plastic-film system obtained 82% of the maximum yield, increased the nitrogen use efficiency (NUE), and mitigated the risk of nitrogen losses from the system. Wang et al.[14] also suggested that a moderate fertilizer application rate ($210\,kg\,N\,ha^{-1}$) in wheat fields could increase the uptake of soil-N and decrease $NO_3$-N leaching under supplemental irrigation. However, Zhong et al.[17] considered that it is not appropriate to reduce the nitrogen application rate because a lack of nitrogen can decrease the soil organic carbon contents, thereby decreasing the long-term soil productivity and reducing crop yields. Therefore, the optimal fertilizer application rate should be determined based on analyses of soil residual nutrients to achieve superior crop yields and use resources efficiently.

Furthermore, it has been hypothesized that the soil moisture and fertilizer contents will have synergistic effects on crop growth, and thus if both the water and fertilizer are managed appropriately, their synergistic interaction can increase the crop yield, WUE, and NUE[20–22]. Guo et al.[23] also reported that the optimal N fertilization rates in dry, normal, and wet years were 45, 135, and $180\,kg\,ha^{-1}$, respectively, in a rain-fed winter wheat cropping system on the Loess Plateau, China. Wang et al. found that the RFRH system was beneficial for harmonizing the relationship between soil water and nutrients, and for stimulating nutrient uptake by crops to obtain a high yield[24]. In semi-humid regions, Li et al. highly recommended RFRH practices combined with an N rate of $75\,kg\,ha^{-1}$ as a promising strategy to increase the wheat yield and WUE, which could increase the N fertilizer productivity and N uptake efficiency[9]. Thus, it is necessary to optimize the fertilizer input rate under the RFRH system to obtain further increases in the yield and WUE during dryland farming.

It should be noted that most previous studies of RFRH planting systems did not consider land loss problems. However, sacrificing a portion of the land area to provide water for crop growth is the essence of rainwater harvesting farming, which has been applied in some arid and semiarid regions[25]. In our study, the RFRH system had ridges and furrows with widths of 60 cm, which is suitable for most crops and it facilitates mechanized operations, as well as obtaining better yield increases[8, 26], although it loses some of the land area. Our research group have performed many studies using this RFRH system since the dryland farming project started in China in 1995, where previous studies focused mainly on water regulation[27], appropriate precipitation[10], and cover materials[5]. In the present study, we determined suitable fertilizer application rates for use in this RFRH system. Therefore, we conducted a field fertilizer trial in a dryland agricultural system to elucidate the effects of fertilizer on foxtail millet under the RFRH system, which we compared with the traditional flat planting pattern. The main objectives of this study were as follows: (1) to clarify the effects of the RFRH system on nitrogen and phosphorus uptake by foxtail millet under different fertilizer rates (F0: no fertilizer, F1: N:P at $93:48\,kg\,ha^{-1}$, F2: N:P at $186:96\,kg\,ha^{-1}$, and F3: N:P at $279:144\,kg\,ha^{-1}$); (2) to compare the soil nutrient residue levels ($NO_3$-N and available P) under the RFRH system and traditional flat planting with different fertilizer rates; and (3) to identify a highly efficient and sustainable fertilization strategy for use in foxtail millet production with the RFRH system during dryland farming in the semiarid area of China.

## Results

**Soil water content (SWC) profile and soil water storage (SWS).** The changes in the SWC profiles in the 0–200 cm soil layers under the two planting patterns are shown in Fig. 1. The differences in the rainfall amounts and distributions during 2013–2015 led to dynamic variations in the SWC profiles. In 2013, the total rainfall was 537 mm and heavy rainfall (189 mm) occurred during 82–89 days after sowing (DAS), which led to deep rainwater infiltration exceeding 200 cm under both planting patterns (Fig. 1a and b), while the SWC remained at values above 15% throughout the whole growing season. Due to insufficient rainfall, the SWC tended to decrease in the 2014 and 2015 growing seasons, and the lowest SWC in the top soil layer was close to the wilting coefficient (8%) at the filling stage, where fluctuations in the soil moisture occurred mainly in the 0–120 cm soil depth. In 2014, 157 mm of rainfall fell during 134–154 DAS (Fig. 1), which led to soil water infiltration to depths of 140 and 120 cm under RFRH planting (R) and traditional flat planting (T) at harvesting (Fig. 1c and d), respectively. In 2015, no deep rainwater infiltration occurred (Fig. 1e and f).

The SWS levels in the 0–120 and 120–200 cm soil depths during the foxtail millet growing season are shown in Table 1. The planting pattern and fertilizer rates mainly affected the SWS in the 0–120 cm soil depth in all three years, whereas the SWS in the 120–200 cm depth was significantly affected by planting pattern at jointing in 2013 and harvesting in 2014, while it was also significantly affected by the fertilizer rate at the filling and harvesting stages in 2014. R improved the average SWS in the 0–120 cm depth by 11–25 mm, 6–12 mm, and 13–30 mm compared with T in the 2013, 2014, and 2015 growing seasons, respectively. At heading (95 DAS) in 2013 and harvesting (154 DAS) in 2014, R significantly increased the average SWS in the 120–200 cm soil depth by 12 mm ($P < 0.05$) and 10 mm ($P < 0.05$), respectively, compared with T. There were only small differences in the SWS among fertilizer rates at the seedling stage, and the SWS in the 0–120 cm soil depth tended to decrease as the fertilizer rate increased, but with R planting, no significant decrease was found when the fertilizer rate exceeded F2 in all three years. In 2014, the SWS in the 120–200 cm soil depth had a similar trend among fertilizer rates at the filling (108 DAS) and harvesting (154 DAS) stages.
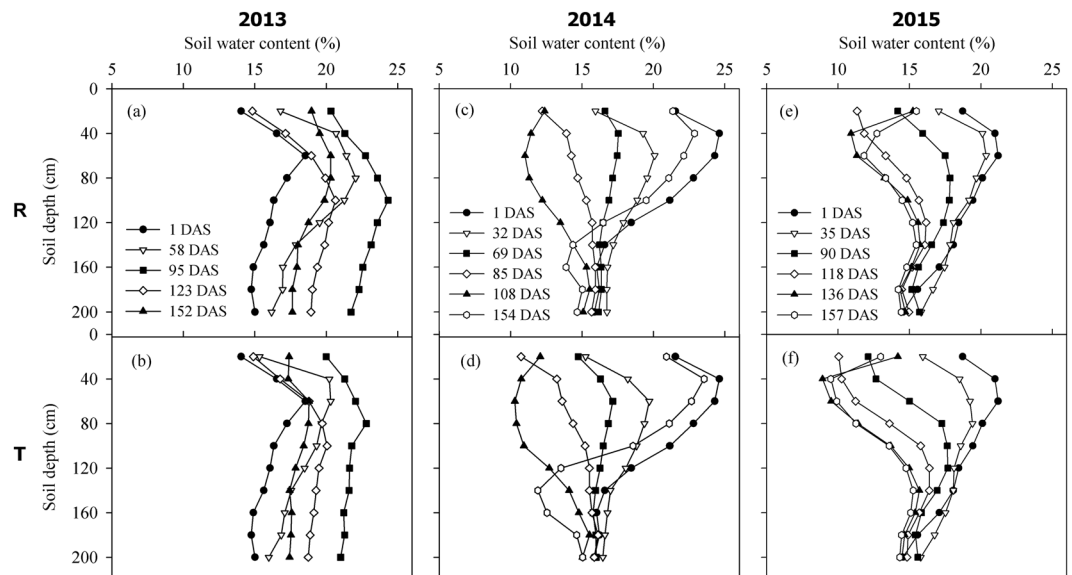
**Figure 1.** Dynamic variations in the soil water content (%) profile in the 0–200 cm soil layers with days after sowing (DAS) under two planting patterns regardless of the fertilizer rate in the 2013–2015 growing seasons for foxtail millet. Note: R = ridge and furrow rainfall harvesting planting; T = traditional flat planting.

**Accumulation of nutrients (nitrogen and phosphorus).**    Table 2 shows the amounts of nitrogen (N) and phosphorus (P) accumulated by straw, grain, and the total plant for foxtail millet after harvesting in 2013–2015. The application of fertilizer significantly affected the accumulation of N and P in all three experimental years, where the accumulation of N and P tended to increase with the fertilizer rate, but the relative gains declined. The planting pattern significantly affected the N and P accumulated by straw (SNA and SPA), and the N and P accumulated by grain (GNA and GPA) in 2014 and 2015, but there were no significant differences in the N and P accumulated by the total plant (TNA and TPA) in 2013–2015. Significant interaction effects between the planting pattern and fertilizer rate were also found in 2014 and 2015.

The TNA ranged between 55.0–166.0 kg ha$^{-1}$, 98.5–176.4 kg ha$^{-1}$, and 55.3–150.2 kg ha$^{-1}$ in 2013, 2014, and 2015, respectively. As the fertilizer rate increased, the SNA increased significantly, with a parabolic growth trend, but for GNA, there was no significant increase when the fertilizer rate exceeded F2 regardless of the planting pattern in all three years. In 2014 and 2015, the TNA under R did not differ significantly between F2 and F3, where R maintained a higher GNA and a lower SNA compared with T under the same fertilizer rate. In addition, compared with T/F1, the GNA increased significantly under R/F1 ($P < 0.05$) by 18.6% and 29.7% in 2014 and 2015, respectively. By contrast, the SNA decreased significantly under R/F2 and R/F3 ($P < 0.05$) by 13.5% and 16.8% in 2014, and by 13.8% and 16.1% in 2015, respectively, compared with T/F2 and T/F3. The TPA ranged between 14.3–43.3 kg ha$^{-1}$, 12.0–22.3 kg ha$^{-1}$, and 8.9–19.9 kg ha$^{-1}$ in 2013, 2014, and 2015, respectively. The TPA exhibited a similar trend to TNA. In 2014 and 2015, the GPA under R/F1 increased by 26.2% and 30.2%, respectively, compared with T/F1, and the SPA decreased significantly under R/F2 and R/F3 by 18.6% and 15.6% in 2014, and by 20.4% and 23.4% in 2015, respectively, compared with T/F2 and T/F3.

**Translocation of pre-anthesis total plant nutrients (nitrogen and phosphorus).**    The N and P accumulation rates at anthesis, as well as the translocation amounts and ratios, and contributions to the grain in 2014 and 2015 are presented in Table 3. These results show that the amounts were higher in 2014 than 2015, and at anthesis, the N and P accumulation rates were affected significantly by fertilizer application in both years, where R planting improved the amounts of N and P uptake at the same fertilizer level in 2015. In both experimental years, the N and P translocation amounts and ratios were affected significantly by the fertilizer rate and planting pattern, where R planting significantly improved the translocation amount and ratio compared with T. The translocation amount tended to increase with the fertilizer rate, but there was no significant difference between F2 and F3. By contrast, the translocation ratio tended to decrease and the highest translocation ratio was obtained under R/F1. The N contribution (Nc) of the pre-anthesis total N relative to the grain N ranged from 0.70 to 0.86 g g$^{-1}$ and the P contribution (Pc) ranged from 0.47 to 0.58 g g$^{-1}$ in 2014. In 2015, Nc and Pc ranged from 0.49 to 0.70 g g$^{-1}$ and from 0.21 to 0.39 g g$^{-1}$, respectively (Table 4). In both years, the fertilizer rate significantly affected Nc and Pc, which were only affected significantly by the planting pattern in 2015. Nc and Pc generally decreased as the fertilizer rate increased, and compared with T, the mean Nc and Pc rates under R increased by 5.7% and 4.6% in 2014, respectively, and by 24.0% ($P < 0.05$) and 32.3% ($P < 0.05$) in 2015.

**Grain yield, resource use efficiency, and net economic income.**    The grain yield and WUE were significantly affected by fertilizer application in all three years and by the planting pattern in the last two years, i.e., 3.80 to 6.85 t ha$^{-1}$ in 2013, 3.98 to 6.04 t ha$^{-1}$ in 2014, and 2.84 to 5.69 t ha$^{-1}$ under various treatments (Table 4).

| Year | Planting pattern | Fertilizer rate | SWS at 0–120 cm soil profile (mm) | | | | SWS at 120–200 cm soil profile (mm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Seedling | Jointing | Filling | Harvest | Seedling | Jointing | Filling | Harvest |
| 2013 | R | F0 | 323a | 369a | 317a | 332a | 180a | 235a | 203ab | 191a |
| | | F1 | 317bc | 363ab | 310ab | 321b | 176ab | 240a | 205ab | 188ab |
| | | F2 | 314bc | 360ab | 300bc | 305cd | 174ab | 236a | 205ab | 188ab |
| | | F3 | 315b | 355b | 293cd | 298d | 173ab | 236a | 203a | 187b |
| | | **Mean** | **317A** | **362A** | **305A** | **314A** | **176A** | **237A** | **204A** | **188A** |
| | T | F0 | 308cd | 349bc | 306a | 311c | 180a | 223b | 199b | 186b |
| | | F1 | 306d | 343c | 296b | 295d | 176ab | 227b | 202ab | 185b |
| | | F2 | 304d | 347c | 288c | 281e | 176ab | 225b | 201ab | 185b |
| | | F3 | 305d | 341c | 280d | 270f | 174b | 226b | 201ab | 184b |
| | | **Mean** | **306B** | **345B** | **292A** | **289B** | **177A** | **225B** | **201A** | **185A** |
| | Analysis of Variance | P | * | * | * | * | ns | * | ns | ns |
| | | F | ns | ** | ** | ** | ns | ns | ns | ns |
| | | P × F | ns | ns | ns | ns | ns | ns | ns | ns |
| 2014 | R | F0 | 300a | 243a | 201a | 337a | 179a | 169ab | 161a | 158a |
| | | F1 | 297ab | 229bc | 194b | 330b | 179a | 167ab | 162a | 155ab |
| | | F2 | 296ab | 224bc | 187c | 325bc | 176ab | 166ab | 158ab | 151bc |
| | | F3 | 296ab | 221c | 183cd | 324bc | 178ab | 166ab | 157b | 149cd |
| | | **Mean** | **297A** | **229A** | **191A** | **329A** | **178A** | **167A** | **159A** | **153A** |
| | T | F0 | 292bc | 230b | 189bc | 330b | 178ab | 170a | 159ab | 147cd |
| | | F1 | 293bc | 219c | 179e | 325bc | 174b | 167ab | 159ab | 144d |
| | | F2 | 289c | 216c | 178d | 318cd | 175ab | 165b | 157bc | 138e |
| | | F3 | 291c | 215c | 170e | 311d | 178ab | 166ab | 153c | 142e |
| | | **Mean** | **291B** | **220A** | **179B** | **321A** | **177A** | **167A** | **157A** | **143B** |
| | Analysis of Variance | P | * | ns | * | ns | ns | ns | ns | * |
| | | F | ns | ** | ** | ** | ns | * | * | ** |
| | | P × F | ns | ns | ns | ns | ns | ns | ns | ns |
| 2015 | R | F0 | 310a | 278a | 244a | 243a | 179a | 168ab | 162ab | 156a |
| | | F1 | 305ab | 269b | 220c | 221b | 179a | 168ab | 159b | 156a |
| | | F2 | 305ab | 263b | 212d | 212c | 180a | 165b | 160b | 155a |
| | | F3 | 301bc | 261bc | 210d | 209c | 178a | 165b | 160b | 156a |
| | | **Mean** | **305A** | **268A** | **221A** | **221A** | **179A** | **167A** | **160A** | **156A** |
| | T | F0 | 298bc | 256c | 233b | 225b | 180a | 167ab | 165a | 157a |
| | | F1 | 292cd | 242de | 206d | 192d | 180a | 171a | 164ab | 157a |
| | | F2 | 292cd | 246d | 194e | 180e | 182a | 169ab | 162ab | 154a |
| | | F3 | 287d | 239e | 190e | 168f | 178a | 168ab | 162ab | 156a |
| | | **Mean** | **292B** | **246B** | **206B** | **191B** | **180A** | **169A** | **163A** | **156A** |
| | Analysis of Variance | P | * | * | * | * | ns | ns | ns | ns |
| | | F | ** | ** | ** | ** | ns | ns | ns | ns |
| | | P × F | ns | ns | ns | ns | ns | ns | ns | ns |

**Table 1.** Soil water storage (SWS, mm) at different growth stages according to the fertilizer rate and planting pattern during the foxtail millet growing seasons in 2013–2015. Within a column, means followed by the same letter for each year are not significantly different at the 0.05 probability level according to the least significant different test (LSD 0.05); lowercase and uppercase letters indicate comparisons among different treatments and between two planting patterns, respectively. ns denotes no significant different; *significant different at the 0.05 probability level; **significant different at the 0.01 probability level; P is the planting pattern, F is the fertilizer rate. The same symbols and abbreviations are used in the other tables.

The WUE exhibited similar trends to the grain yield. In general, higher fertilizer inputs significantly increased the grain yield, but when the fertilizer rate exceeded F2, there was no significant increase under R planting. The interaction between the planting pattern and fertilizer application rate had a consistent effect on the grain yield in 2014 and 2015. However, in 2013, there were no significant differences in the grain yields among the two planting patterns under F0, F1, and F2, where the highest yield was obtained under T/F3, which was significantly higher than that under R/F3. In 2014 and 2015, considerably higher grain yields were obtained under R planting, with significant increases under F1 and F2 compared with T planting. The high fertilizer rate generally had a positive effect on the WUE regardless of the planting pattern, but the effect was not always significant. There were no significant differences in the increases under F2 and F3. In 2014 and 2015, the average WUE under R planting combined with fertilizer (F1, F2, and F3) increased significantly by 14.5% ($P < 0.05$) and 15.7% ($P < 0.05$), respectively, compared with T.

| Year | Planting pattern | Fertilizer rate | N uptake (kg ha$^{-1}$) | | | P uptake (kg ha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Straw | Grain | Total plant | Straw | Grain | Total plant |
| 2013 | R | F0 | 17.1e | 38.3d | 55.4e | 5.7e | 8.6e | 14.3e |
| | | F1 | 36.5d | 68.2c | 104.7d | 8.5d | 14.7d | 23.2d |
| | | F2 | 59.2c | 86.8b | 146.0c | 12.6c | 22.6c | 35.1c |
| | | F3 | 67.5ab | 91.1ab | 158.6ab | 14.5ab | 25.5ab | 40.1ab |
| | | Mean | 45.1A | 71.1A | 116.2A | 10.3A | 17.8A | 28.2A |
| | T | F0 | 16.8e | 38.2d | 55.0e | 6.3e | 8.9e | 15.2e |
| | | F1 | 34.7d | 69.6c | 104.3d | 8.7d | 14.3d | 23.0d |
| | | F2 | 59.3bc | 94.0a | 153.2bc | 12.9bc | 23.6bc | 36.9bc |
| | | F3 | 69.9a | 96.1a | 166.0a | 15.8a | 27.5a | 43.3a |
| | | Mean | 45.2A | 74.5A | 119.6A | 10.9A | 18.6A | 29.6A |
| | Analysis of Variance | P | ns | * | ns | ns | ns | ns |
| | | F | ** | ** | ** | ** | ** | ** |
| | | P × F | ns | ns | ns | ns | ns | ns |
| 2014 | R | F0 | 32.0f | 67.0de | 99.0d | 1.7f | 10.2d | 12.0f |
| | | F1 | 39.8de | 89.0c | 128.9c | 2.4e | 13.9c | 16.3de |
| | | F2 | 56.9c | 107.5ab | 164.4ab | 4.0d | 16.5ab | 20.5bc |
| | | F3 | 61.3b | 111.5a | 172.8ab | 5.0b | 17.3a | 22.3a |
| | | Mean | 47.5B | 93.7A | 141.3A | 3.3B | 14.5A | 17.8A |
| | T | F0 | 35.4ef | 63.1e | 98.5d | 2.0f | 10.2d | 12.2f |
| | | F1 | 46.7d | 75.1d | 121.7c | 2.8e | 11.0d | 13.8ef |
| | | F2 | 65.8b | 95.6bc | 161.5b | 4.9c | 14.2bc | 19.1cd |
| | | F3 | 73.7a | 102.7ab | 176.4a | 5.9a | 16.0ac | 21.9ab |
| | | Mean | 55.4A | 84.1B | 139.5A | 3.9A | 12.9B | 16.7A |
| | Analysis of Variance | P | * | ** | ns | ** | * | ns |
| | | F | ** | ** | ** | ** | ** | ** |
| | | P × F | ns | ns | ns | ** | ns | ns |
| 2015 | R | F0 | 12.9e | 44.2d | 57.1e | 1.3f | 7.9cd | 9.2e |
| | | F1 | 23.4d | 78.7b | 102.1c | 1.9de | 12.1b | 14.1c |
| | | F2 | 38.8c | 97.3a | 136.1b | 3.4c | 14.7a | 18.0b |
| | | F3 | 48.3b | 98.2a | 146.6ab | 4.4b | 15.4a | 19.9a |
| | | Mean | 30.9B | 79.6A | 110.5A | 2.8B | 12.5A | 15.3A |
| | T | F0 | 13.3e | 42.1d | 55.3e | 1.7ef | 7.2d | 8.9e |
| | | F1 | 27.3d | 60.6c | 87.9d | 2.6cd | 9.3c | 11.9d |
| | | F2 | 45.0b | 87.3ab | 132.4b | 4.2b | 13.1b | 17.4b |
| | | F3 | 57.6a | 92.6a | 150.2a | 5.8a | 14.0a | 19.8a |
| | | Mean | 35.8A | 70.7B | 106.4A | 3.6A | 10.9B | 14.5A |
| | Analysis of Variance | P | ** | * | ns | ** | * | ns |
| | | F | ** | ** | ** | ** | ** | ** |
| | | P × F | ns | * | * | * | * | * |

**Table 2.** Effects of planting pattern and fertilizer rate on nitrogen (N) and phosphorus (P) uptake by foxtail millet at harvesting during 2013–2015.

The nitrogen and phosphorus uptake efficiency (NupE and PupE), NUE, phosphorus use efficiency (PUE), and the nitrogen and phosphorus harvest indices (NHI and PHI) varied significantly among different fertilizer rates, where they tended to decrease as the fertilizer input rate increased. However, the differences between the two planting patterns were not always significant in the three years, and there was no significant difference in 2013 (Table 4). In 2014 and 2015, NupE, NUE, and NHI increased on average by 4.5%, 8.2% ($P < 0.05$), and 7.9% ($P < 0.05$), respectively, under R planting compared with T, while PupE, PUE, and PHI increased on average by 8.6% ($P < 0.05$), 5.6%, and 7.0% ($P < 0.05$), respectively.

Fertilization also significantly increased the net economic income (NEI) regardless of the planting pattern over the three year (Table 4). Under R planting, the maximum NEI was achieved using the F2 fertilizer application rate, which increased NEI by 56.8%, 35.9%, and 76.1% compared with no fertilizer in 2013, 2014, and 2015, respectively, and the NEI decreased ($P > 0.05$) as the fertilizer application rate increased further. In addition, the F3 fertilizer application rate obtained the maximum NEI under T planting. In the rainy year of 2013, T planting obtained a higher NEI than R, and the highest NEI was achieved by T/F3. However, in the dry years of 2014 and 2015, R planting increased the NEI compared with T under the same fertilizer application rate, and the maximum NEI was achieved by R/F2.

| Year | Planting pattern | Fertilizer rate | N uptake (kg ha$^{-1}$) | Nt (kg ha$^{-1}$) | Nc (%) | P uptake (kg ha$^{-1}$) | Pt (kg ha$^{-1}$) | Pc (%) |
|---|---|---|---|---|---|---|---|---|
| 2014 | R | F0 | 85.7e | 53.7de | 80.2ab | 7.4e | 5.6ce | 55.2bc |
| | | F1 | 116.4d | 76.5bc | 85.9a | 10.4d | 8.0bc | 57.7abc |
| | | F2 | 137.9bc | 81.0ab | 75.4b | 13.3bc | 9.3a | 56.2abc |
| | | F3 | 147.5a | 86.2a | 77.3ab | 14.5a | 9.5a | 54.7bc |
| | | Mean | 121.9A | 74.3A | 79.7A | 11.4A | 8.1A | 55.9A |
| | T | F0 | 82.9e | 47.5e | 75.3b | 6.8e | 4.8d | 47.1c |
| | | F1 | 110.1d | 63.5cd | 84.6a | 9.8d | 7.0c | 63.7a |
| | | F2 | 136.0c | 70.2bc | 73.4b | 12.8c | 7.9b | 56.0b |
| | | F3 | 145.8ab | 72.1b | 70.2b | 14.1ab | 8.2ab | 51.6bc |
| | | Mean | 118.7A | 63.3B | 75.9A | 10.9A | 7.0B | 54.6A |
| | Analysis of Variance | P | ns | * | ns | ns | 0.012 | ns |
| | | F | ** | ** | * | ** | ** | * |
| | | P × F | ns | ns | ns | ns | ns | ns |
| 2015 | R | F0 | 36.3e | 23.5d | 53.1bcd | 4.4e | 3.1cd | 38.9a |
| | | F1 | 73.5cd | 50.1b | 63.7a | 6.5c | 4.6ab | 37.9ab |
| | | F2 | 107.4b | 68.6a | 70.5a | 8.9a | 5.5a | 37.5ab |
| | | F3 | 115.8a | 67.4a | 68.7a | 9.2a | 4.8ab | 31.1bcd |
| | | Mean | 83.3A | 52.4A | 64.0A | 7.3A | 4.5A | 36.4A |
| | T | F0 | 31.0e | 17.8d | 42.3d | 3.9e | 2.2d | 31.0bc |
| | | F1 | 62.8d | 35.6c | 58.7ab | 5.6d | 2.9c | 31.6ab |
| | | F2 | 94.3c | 49.3b | 56.4bc | 7.8b | 3.5bc | 26.8cd |
| | | F3 | 103.0b | 45.4b | 49.1cd | 8.7a | 2.9cd | 20.6d |
| | | Mean | 72.8B | 37.0B | 51.6B | 6.5B | 2.9B | 27.5B |
| | Analysis of Variance | P | ** | ** | ** | * | * | * |
| | | F | ** | ** | ** | ** | ** | * |
| | | P × F | ns | 0.004 | ns | ns | ns | ns |

**Table 3.** Nitrogen and phosphorus uptake, translocation (Nt and Pt), and contribution to grain ratio (Nc and Pc) at anthesis according to the fertilizer rate and planting pattern during 2014–2015.

**Soil NO$_3$-N and available phosphorus content.** The dynamics of the soil NO$_3$-N content in the 0–200 cm soil layer at anthesis and at harvesting are shown in Figs 2 and 3, respectively. The vertical distribution of NO$_3$-N in the soil profile varied among different years, where it was related to the depth of soil water infiltration (Fig. 1). In all three experimental years, high fertilizer application rates significantly increased the accumulation of NO$_3$-N in the soil layers, where R planting considerably increased the soil NO$_3$-N content and leaching depth compared with T, especially under F2 and F3. At anthesis, the NO$_3$-N was distributed mainly in the 0–40 cm soil layer in 2014 and 2015 (Fig. 2c–f), but a large amount of NO$_3$-N leached into the deep soil layer below 80 cm in 2013 (Fig. 2a and b). At harvest time, the NO$_3$-N leached further into the deeper soil layer, where the peak NO$_3$-N accumulation rates under R planting occurred in the 140 cm, 100 cm, and 60 cm soil layers, and the highest NO$_3$-N contents reached 20.6, 38.2, and 25.8 mg kg$^{-1}$ under F3 in 2013, 2014, and 2015, respectively (Fig. 3a,c and e). With T planting, the highest NO$_3$-N contents occurred in the 120 cm, 80 cm, and 80 cm soil layers, where they reached 15.0, 27.5, and 17.8 mg kg$^{-1}$ in 2013, 2014, and 2015, respectively (Fig. 3b,d and f).

The available soil P was distributed mainly in the 0–20 cm soil layer, as shown in Fig. 4, and the available P content in the 20–40 cm soil layer was less than 2.0 mg kg$^{-1}$, except in 2013. The variation among the different treatments was similar in the three years. The available P content in the 0–20 cm soil depth tended to increase as the fertilizer application rate increased. Compared with T planting, R significantly increased the available P content in the topsoil when the fertilizer application rate exceeded F1. High available phosphorus residue levels were found under R/F3 in all three years, where the available P contents were 11.3, 11.8, and 9.36 mg kg$^{-1}$ in 2013, 2014, and 2015, respectively.

## Discussion

Rainfall is the key to successful agricultural production in dryland farming. The rainwater harvesting system is an effective method for utilizing rainfall and improving the soil moisture content in semiarid regions[1, 10]. Our results indicated that R planting mainly improved the SWS in the top 0–120 cm depth compared with T, as also reported by Wen et al.[28]. In addition, we detected significantly higher SWS levels in the 120–200 cm soil layer under R planting at the jointing stage in 2013 and at the harvesting stage in 2014 when continual and strong rainfall occurred (Fig. 5). Many studies have shown that the application of fertilizer can promote the absorption of soil water[29]. Similar results were obtained in our study, as shown in Table 1, which suggests that fertilizer application favoured biomass growth and increased the transpiration rate, thereby reducing the available soil water[9, 19, 30]. A higher fertilizer application rate leads to higher crop water consumption and lower residual SWS, and our

| Year | Planting pattern | Fertilizer rate | GY (t ha⁻¹) | WUE (kg ha⁻¹ mm⁻¹) | NupE (kg kg⁻¹) | NHI (%) | NUE (kg kg⁻¹) | PupE (kg kg⁻¹) | PHI (%) | PUE (kg kg⁻¹) | NEI (USD ha⁻¹) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | R | F0 | 3.80d | 9.90c | — | 69.1a | 68.7a | — | 60.1bc | 266.3a | 2097d |
| | | F1 | 5.21c | 13.31b | 1.13a | 65.2ab | 49.6b | 0.25a | 63.5a | 224.0b | 2817c |
| | | F2 | 6.20b | 15.01a | 0.78b | 59.5bc | 42.5c | 0.19b | 64.2a | 176.4c | 3287b |
| | | F3 | 6.37b | 15.13a | 0.57c | 57.4b | 40.5c | 0.14c | 63.7a | 160.4d | 3285b |
| | | Mean | 5.40A | 13.34A | 0.83A | 62.8A | 50.3A | 0.19A | 62.9A | 206.8A | 2872B |
| | T | F0 | 3.83d | 9.15c | — | 69.5a | 69.9a | — | 58.5c | 252.2a | 2234d |
| | | F1 | 5.14c | 11.99b | 1.12a | 66.7ab | 49.3b | 0.25a | 62.3ab | 223.9b | 2896c |
| | | F2 | 6.49ab | 14.46a | 0.82b | 61.4b | 42.0c | 0.20b | 64.0a | 174.6c | 3578a |
| | | F3 | 6.85a | 15.01a | 0.59c | 57.9a | 40.7c | 0.16c | 63.5a | 155.9d | 3687a |
| | | Mean | 5.58A | 12.65A | 0.85A | 63.9A | 50.5A | 0.20A | 62.1A | 201.7A | 3099A |
| | Analysis of Variance | P | ns | ns | ns | ns | ns | ns | ns | ns | * |
| | | F | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | | P × F | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| 2014 | R | F0 | 4.25d | 13.09cd | — | 67.7ab | 43.9a | — | 85.5a | 362.2a | 2355d |
| | | F1 | 5.38b | 16.06b | 1.39a | 69.0a | 42.5a | 0.17a | 85.2a | 336.1ab | 2976b |
| | | F2 | 5.94a | 17.27a | 0.88b | 65.4bc | 37.2b | 0.11b | 80.5b | 298.2c | 3201ab |
| | | F3 | 6.04a | 17.42a | 0.62c | 64.5c | 36.4b | 0.08c | 77.8c | 280.9de | 3163a |
| | | Mean | 5.40A | 15.96A | 0.96A | 66.7A | 40.0A | 0.12A | 82.3A | 319.3A | 2924A |
| | T | F0 | 3.98d | 11.62d | — | 64.0cd | 42.0a | — | 84.0a | 339.1ab | 2321d |
| | | F1 | 4.77c | 13.63c | 1.31a | 61.6d | 37.3b | 0.15a | 79.5bc | 329.1b | 2678c |
| | | F2 | 5.50b | 15.12b | 0.87b | 59.2e | 33.5c | 0.10b | 74.3d | 283.0cd | 3000b |
| | | F3 | 5.72a | 15.59b | 0.63c | 58.2e | 32.7c | 0.08c | 73.0d | 264.2e | 3030ab |
| | | Mean | 4.99B | 13.99B | 0.94A | 60.8B | 36.4B | 0.11A | 77.7B | 303.8B | 2757A |
| | Analysis of Variance | P | * | * | ns | ** | * | ns | * | * | ns |
| | | F | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | | P × F | ns | ns | ns | ns | * | * | ** | ns | * |
| 2015 | R | F0 | 3.01e | 7.60d | — | 77.4a | 62.7a | — | 86.0a | 388.2a | 1701d |
| | | F1 | 4.83c | 11.51b | 1.10a | 77.1ab | 48.8b | 0.15a | 86.2a | 354.4b | 2656b |
| | | F2 | 5.58a | 13.04ab | 0.73b | 71.5bc | 41.1cd | 0.10b | 81.3b | 310.4cd | 2995a |
| | | F3 | 5.69a | 13.16a | 0.53c | 67.0de | 39.3cd | 0.07c | 77.7cd | 289.8ef | 2957a |
| | | Mean | 4.78A | 11.33A | 0.78A | 73.2A | 48.0A | 0.11A | 82.8A | 335.7A | 2577A |
| | T | F0 | 2.84e | 6.92d | — | 76.0ab | 58.0a | — | 81.4b | 360.3b | 1655d |
| | | F1 | 4.18d | 9.45c | 0.95a | 69.1cd | 44.5bc | 0.13a | 77.9c | 327.3c | 2336c |
| | | F2 | 5.21b | 11.33b | 0.71b | 66.0d | 39.2d | 0.09b | 75.6cd | 299.3de | 2833ab |
| | | F3 | 5.54a | 11.81b | 0.54c | 61.7e | 36.5d | 0.07c | 70.8e | 275.6f | 2923a |
| | | Mean | 4.44B | 9.88B | 0.73B | 68.2B | 44.5A | 0.10B | 76.4B | 315.6B | 2437A |
| | Analysis of Variance | P | * | * | ** | * | ns | * | ** | * | ns |
| | | F | ** | ** | ** | ** | ** | ** | ** | ** | ** |
| | | P × F | * | * | * | ns | Ns | * | * | ns | * |

**Table 4.** Effects of planting pattern and fertilizer rate on the grain yield (GY), WUE, N and P uptake efficiency (NupE and PupE), N and P use efficiency (NUE and PUE), N and P harvest indices (NHI and PHI), and net economic income (NEI) for foxtail millet during 2013–2015. Note: (1 USD = 6.855 Chinese yuan, Bank of China, 2017/2/17).

results also showed that were no significant reductions in the SWS when the fertilizer level exceeded F2 under the R planting pattern over the three years, thereby indicating that F2 was sufficient for the growth of foxtail millet. We also found that fertilization had greater effects on the SWS in 2013 and 2015 compared with 2014, which was related to the soil's basic fertility in each year.

The application of fertilizer can effectively increase the accumulation of plant nutrients, thereby indicating pronounced nutrient limitations for foxtail millet in some areas[9, 31]. According to the present study, F2 (186 kg N and 94 kg P ha⁻¹) could meet the nutrient requirements for crop growth regardless of the planting pattern, and only slight increases in the N and P uptake rates by grain were found with higher fertilizer input rates. In dry years (2014 and 2015), our results indicated that pre-anthesis N translocation into the vegetative organs was the main source of GNA, accounting for more than 50%, and similar results were reported by Qiu et al.[32] for winter wheat. However, the source of GPA was mainly attributable to P accumulation after anthesis. The results also showed that the amounts of translocated N and P did not increase significantly or decline with fertilizer application rates above F2. Moreover, the N and P translocation ratio and contribution decreased, which suggests that the excessive application of fertilizer does not facilitate nutrient translocation from the vegetative organs to grain, thereby
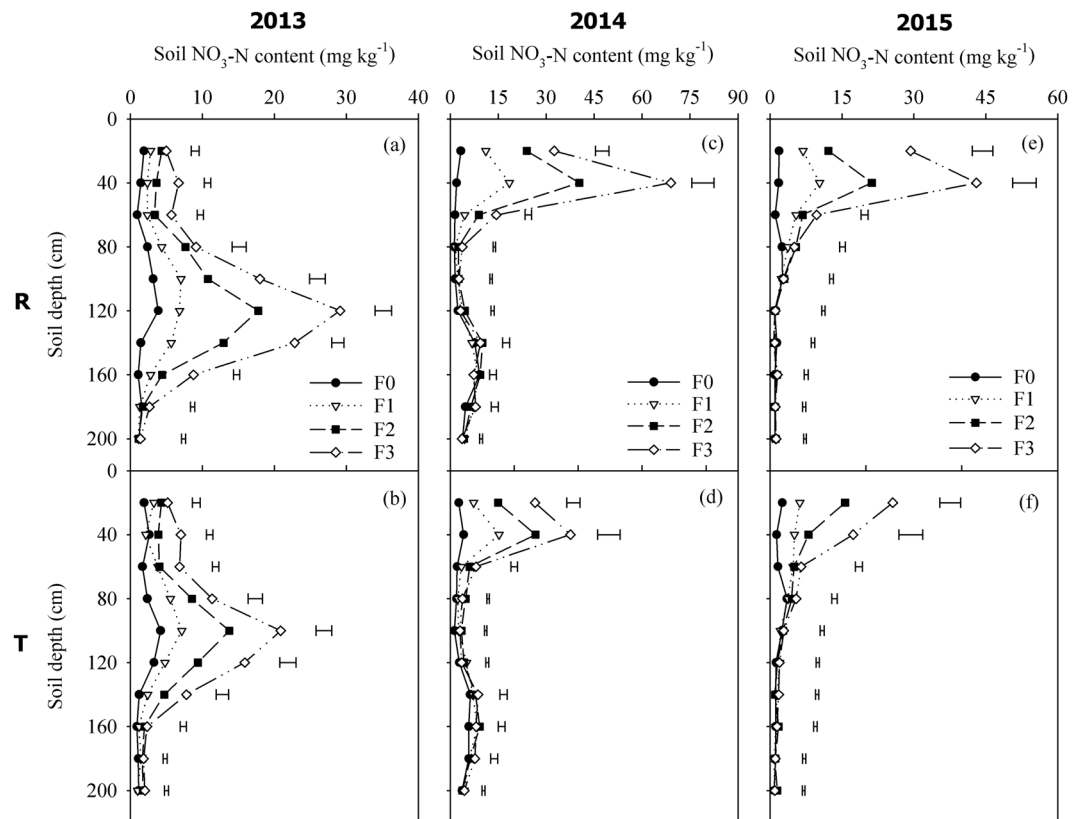
**2013**

Soil NO$_3$-N content (mg kg$^{-1}$)

**2014**

Soil NO$_3$-N content (mg kg$^{-1}$)

**2015**

Soil NO$_3$-N content (mg kg$^{-1}$)



**Figure 2.** Soil NO$_3$-N content at anthesis in the 0–200 cm soil layers according to the fertilizer rate under two planting patterns during 2013–2015. Note: R = ridge and furrow rainfall harvesting planting; T = traditional flat planting; F0, F1, F2, and F3 represent N:P at 0:0, 93:48, 186:96, and 279:144 kg ha$^{-1}$, respectively. Horizontal bars represent the LSD values at the $P = 0.05$ level.

reducing the NHI, which is consistent with previous findings[33–35]. In our study, we found no significant effects of the planting pattern on TNA and TPA. However, in dry years (2014 and 2015), R planting significantly improved the GNA and GPA compared with T planting, which was achieved in two main ways. First, the improved accumulation of plant nutrients at anthesis facilitated vegetative growth. Under the R planting pattern, the fertilizer and rainwater were concentrated in the planting furrow, which enhanced the absorption of nutrients (N and P) by plants. Second, R planting increased the amount and ratio of nutrients translocated from the vegetative organs to the grain, which is not consistent with the findings reported by Qiu et al.[32]. At the experimental site, low temperature limited nutrient translocation in the late growth stage for foxtail millet. R planting can accelerate the duration of plant growth due to the heat-retaining effect of plastic mulching[1, 9]. Compared with R, it was more difficult for foxtail millet to reach complete physiological maturity under T planting, thereby leading to relatively higher nutrient residues in the straw at harvest.

We found that fertilization had a major effect on the production of foxtail millet regardless of the year, where the highest grain yield of 6.85 t ha$^{-1}$ was achieved under T planting combined with the highest fertilizer application rate in 2013, which might be the yield ceiling for foxtail millet under current conditions. In dry years, the maximum yield was achieved under R/F3, but no significant difference in yield was found between R/F2 and R/F3, which indicates that 186 kg N 94 kg P ha$^{-1}$ is sufficient for foxtail millet under RFRH planting in this area. It has been reported that an adequate supply of fertilizer is critical for fully exploiting the benefits of summer rainfall, and the WUE also improved dramatically compared with that without fertilizer, which correlated with the grain yield[36]. Under R planting, there is a trade-off between the ridge width reducing the annual grain yield, and rainwater harvesting by ridges increasing the soil moisture content, grain yield, and WUE[37]. Thus, when the rainfall is lower than a threshold amount, R planting can improve the grain yield, but when the rainfall exceeds this threshold, R planting is unnecessary and the ridges are not useful because soil water is not a key factor that constrains crop growth[1]. Li et al.[8] indicated that it is unnecessary to employ R planting for foxtail millet production in regions with more than 400 mm rainfall. Our results also showed that the use of R planting in dry years (2014 and 2015) significantly improved the grain yield, WUE, and nutrient use efficiency for foxtail millet compared with T planting, which is consistent with previous findings[5, 8, 38, 39]. However, there was no significant improvement in the grain yield under R planting in the rainy year (2013) and there was even a remarkable reduction in the yield with an adequate fertilizer application level. In dry years (2014 and 2015), we found that significant interactions between the planting pattern and fertilizer rate affected the grain yield and WUE for foxtail millet in the present study. Our results also showed that R planting could obtain higher increases in the yield and WUE compared with T planting under a relatively low fertilizer level, which could have two explanations. First, R planting may be more
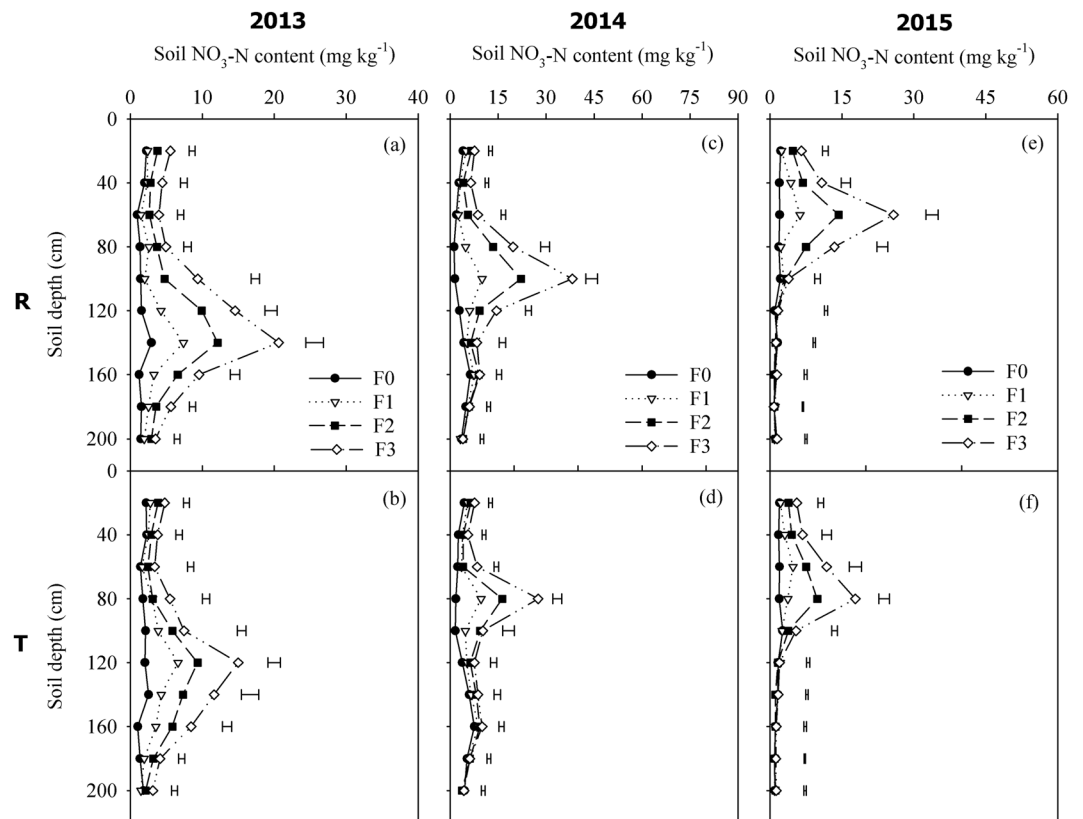
**Figure 3.** Soil $NO_3$-N content at harvesting in the 0–200 cm soil layers according to the four fertilizer rates under two planting patterns during 2013–2015. Note: R = ridge and furrow rainfall harvesting planting; T = traditional flat planting; F0, F1, F2, and F3 represent N:P at 0:0, 93:48, 186:96, and 279:144 kg ha$^{-1}$, respectively. Horizontal bars represent the LSD values at the $P = 0.05$ level.

effective under low fertilizer rates, which could enhance the uptake and utilization of nutrients (Table 2). Second, compared with T planting, R planting may be considered a quantitative measure for improving the moisture content, where the maximum synergistic effect can be obtained when combined with an appropriate fertilizer rate.

It has been widely reported that precipitation/irrigation and fertilization influence $NO_3$-N leaching in farmland ecosystems[40, 41]. In the present study, the application of N fertilizer at higher than 93 kg ha$^{-1}$ greatly increased the accumulation of $NO_3$-N in the soil, which was gradually leached by precipitation into deeper soil layers, especially in the rainy year of 2013 (Figs 2 and 3). It is difficult for summer crops to use $NO_3$-N in deep layers because their main root systems are distributed above the 60 cm soil depth, thereby indicating a risk of $NO_3$-N leaching[42]. Under R planting, the fertilizer was concentrated in the planting furrow, which occupied only half of the total area, so the excess fertilizer would lead to more $NO_3$-N and available P accumulating in the soil compared with T planting. Furthermore, it should be noted that the leaching depth was deeper under R planting, which was caused mainly by the deeper soil infiltration compared with T planting[43]. Therefore, it is necessary for R planting to be combined with an appropriate fertilizer rate in order to reduce the risk of N losses. Feng *et al.*[44] found that fertilization under the ridge could reduce the risk of $NO_3$-N leaching as well as improving the fertilizer use efficiency with R planting, which is highly recommended. Due to the low diffusion coefficient and poor mobility of phosphorus in soil[45], it is always difficult for crops to absorb phosphorus from the soil. We found that the available P in the soil was concentrated mainly in the top 0–20 cm layer of the topsoil (Fig. 4), where the P content was related to the fertilizer application rate, basic soil fertility, and precipitation. It should be noted that the plant P accumulation rate in 2013 was considerably higher than that in both 2014 and 2015, which is probably attributable to the abundant rainfall in 2013, where the higher soil moisture increased the available soil P content and facilitated the uptake of P by crops. In the present study, using F1, the soil residual available P content at harvest ranged from 4.5 to 6.9 mg kg$^{-1}$ under R planting, which is a moderate level for a calcareous soil in China[45]. The excessive application of fertilizer (nitrogen and phosphorus) would lead to high $NO_3$-N and available P residual levels, which might not be environmentally friendly and sustainable in the long term, with possible negative effects on farmland ecosystems.

In recent years, achieving a high yield has not been the only target of agricultural production because shortages of water and fertilizer resources have made it more important to prevent resource wastage and to maintain the sustainable development of agricultural ecosystems[46]. In the present study, the fertilizer was spread over the whole planting furrow, which only occupied half the area under the RFRH system, and thus the fertilizer application rate per unit area was doubled, i.e., the fertilizer rate in the planting furrow in the R/F3 plot was 558 kg N 288 kg P ha$^{-1}$, and this is an excessive level in semiarid regions. In dry years, we found that the RFRH system
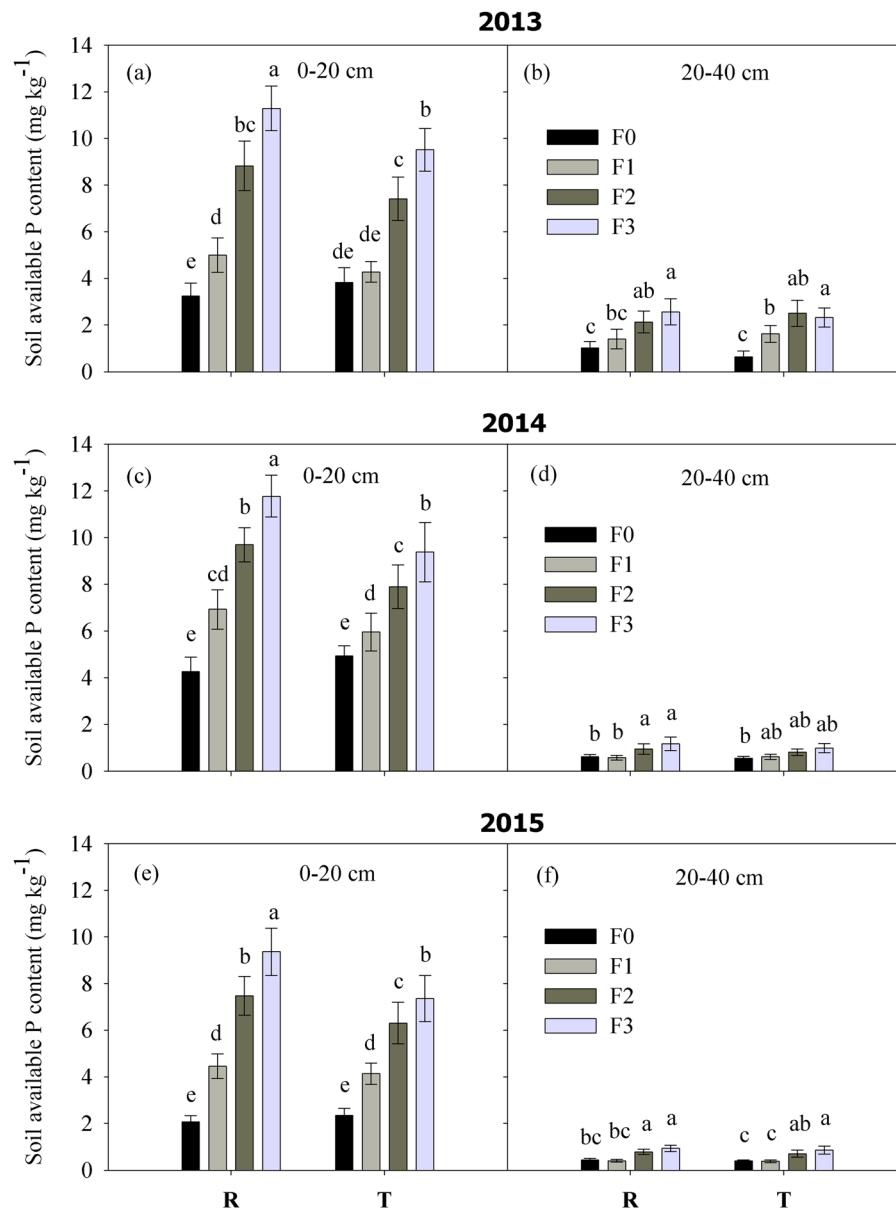
**Figure 4.** Soil available P contents in the 0–20 cm and 20–40 cm soil layers after harvest according to the fertilizer rate and planting pattern during 2013–2015. Note: R = ridge and furrow rainfall harvesting planting; T = traditional flat planting; F0, F1, F2, and F3 represent N:P at 0:0, 93:48, 186:96, and 279:144 kg ha$^{-1}$, respectively. Different letters indicate significant differences at the $P = 0.05$ level.

obtained a better yield than T under the same fertilizer application rate, and when the fertilizer application rate was reduced to F2, there were no significant reductions in the yield and WUE with the RFRH system, but there was a significant increase in the fertilizer use efficiency due to the significant reductions in NO$_3$-N and available residual P in the soil. Furthermore, in the dry years (2014 and 2015), R/F2 obtained a similar yield and improved WUE by 10.6% compared with T/F3, where NUE and PUE increased by 13.3% and 12.8%, respectively. Thus, a strategy that reduces the fertilizer rate is recommended for RFRH systems. In addition, R/F2 is a suitable planting strategy for foxtail millet in semiarid areas because it combines a high yield with the sustainable use of resources and the environment. Our results showed that the RFRH system had greater advantages than traditional flat planting in dry years, but an excessively low fertilizer application rate was not conducive to exploiting its potential for increasing the yield and WUE, and an excessively high fertilizer rate led to a low NUE and risk of fertilizer leaching. Therefore, our results provide useful guidance for improving the crop yield and reducing the losses of fertilizer resources in dryland farming throughout the world.

## Conclusion

In the typical semiarid area of the Loess Plateau, wet years are rare and dry years are normal. In the present study, we showed that in dry years, RFRH planting could enhance the WUE and nutrient use efficiency to obtain a
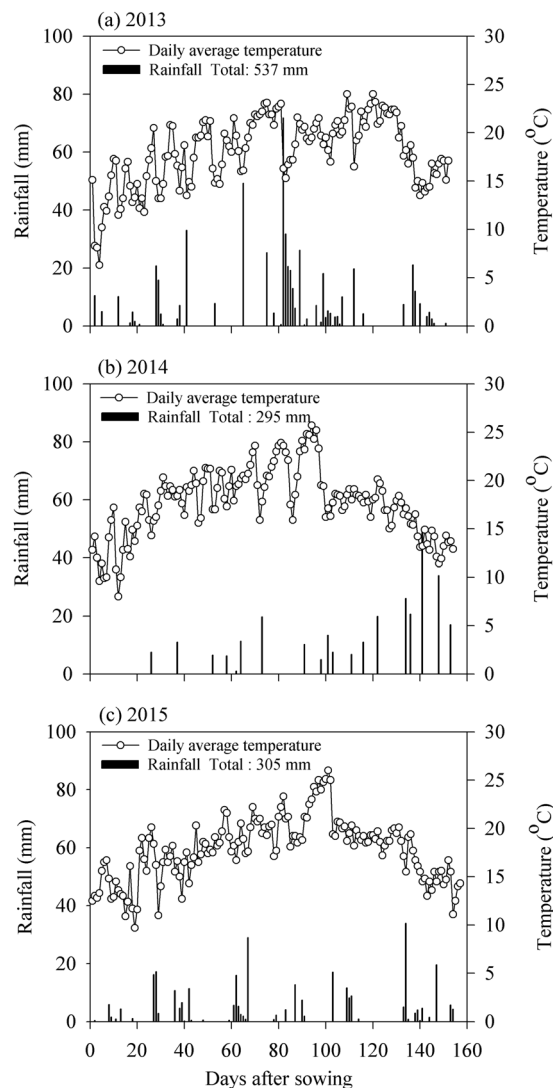
**Figure 5.** Daily average temperatures and rainfall during the foxtail millet growing seasons in the experimental fields at Pengyang Experimental Station, Ningxia Province, China in 2013–2015.

higher grain yield compared with T planting under the same fertilizer application rate. In addition, F2 was the most suitable fertilizer application rate for the RFRH system, which obtained a high yield and WUE compared with F3, thereby significantly improving the nutrient use efficiency as well as reducing the $NO_3$-N and available P residues in the soil. Thus, the RFRH system combined with F2 (186:96 kg N:P ha$^{-1}$) is recommended as a promising planting strategy for foxtail millet growing in semiarid regions.

## Methods

**Study site description.** The field experiments were conducted in three growing seasons from 2013 to 2015 at the Pengyang Dryland Agricultural Research Station, Ningxia Province, China (106°45′N, 35°79′E, 1800 m above sea level), which is characterized as a typical semiarid dryland agriculture region in a hilly and gully area of the Loess Plateau. This region is strongly governed by a semiarid, warm temperate, and continental monsoon climate. The average annual precipitation was determined as 410 mm, approximately 60% of which occurred from July to September, and the average annual free water evaporation was about 1000 mm. The annual temperature average was 8.1 °C and the total duration of sunshine hours was 2518 h year$^{-1}$, with a frost-free period of 155 days. The soil at the experimental site was confirmed as a loess soil with a pH of 8.5, mean bulk density of 1.34 g cm$^{-3}$, average field water-holding capacity (gravimetric) of 22.4%, and a permanent wilting point of 8.3%. Rainfall data were recorded using an automatic weather station (WS-STD1, Delta-T, UK) at the experimental site. The amounts of rainfall during the growth period were 537, 295, and 305 mm in 2013, 2014, and 2015, respectively, and the monthly rainfall distributions are shown in Fig. 5.

**Experimental design and field management.** Continuous cropping of foxtail millet can cause many problems with land, i.e., weeds, plant diseases, and insect pests, so we selected three different fields for the

| Year | Soil depth | TN (g kg$^{-1}$) | SOM (g kg$^{-1}$) | AN (mg kg$^{-1}$) | AP (mg kg$^{-1}$) | AK (mg kg$^{-1}$) |
|------|-----------|------------------|-------------------|-------------------|-------------------|-------------------|
| 2013 | 0–20 cm | 0.86 | 12.3 | 52.1 | 8.8 | 106 |
|      | 20–40 cm | 0.90 | 12.7 | 44.0 | 3.8 | 94 |
| 2014 | 0–20 cm | 0.98 | 14.9 | 63.2 | 11.8 | 152 |
|      | 20–40 cm | 0.90 | 13.4 | 49.5 | 4.0 | 113 |
| 2015 | 0–20 cm | 0.85 | 12.3 | 33.9 | 6.5 | 139 |
|      | 20–40 cm | 0.80 | 11.8 | 27.4 | 3.9 | 110 |

**Table 5.** Soil chemical properties in the 0–40 cm soil layer in experimental fields at Pengyang Experimental Station, Ningxia Province, China during 2013–2015. Note: TN = total nitrogen; SOM = soil organic matter; AN = available nitrogen; AP = available phosphorus; AN = available potassium.
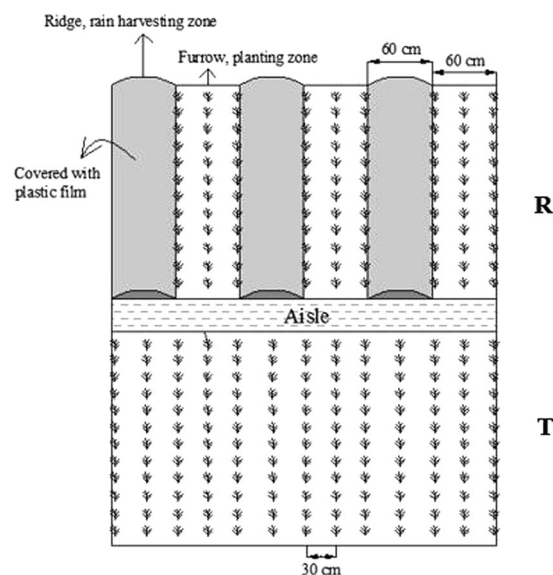


**Figure 6.** Layout of the field experiments with two planting patterns during the 2013–2015 foxtail millet growing seasons. Note: R = ridge and furrow rainfall harvesting planting; T = traditional flat planting.

fertilizer trials in 2013–2015, and the key chemical properties of the 0–40 cm soil layer in each year are listed in Table 5. The experiment was a split plot design with three replicates in each year. The main plots were the two planting patterns (R: RFRH planting, T: traditional flat planting). The subplots received four different fertilizer rates (F0: no fertilizer, F1: N:P at 93:48 kg ha$^{-1}$, F2: N:P at 186:96 kg ha$^{-1}$, F3: N:P at 279:144 kg ha$^{-1}$). The length and width of each plot were 5.0 m × 3.6 m, and they were cultivated by conventional tillage. The RFRH system used ridge and furrow widths of 60 cm, a ridge height of 15 cm, and the ridges were covered with plastic film mulch, where the fertilizer was applied in the furrow area. Schematics of the R and T plots are shown in Fig. 6. The plastic film had a thickness of 0.008 mm (Tianshui Tianbao Plastic Industry Ltd, Gansu, China) and the fertilizer comprised urea (N 46%; China Petroleum Ningxia Petrochemical Production Company) with diammonium phosphate (P$_2$O$_5$ 46.0%, N 18.0%; Yunnan Three Circles Sinochem Fertilizer Co. Ltd, US-sheng).

At 20 days before sowing each year, the entire experimental area was ploughed before marking out the plots. In order to reduce seepage between neighbouring plots, each plot was ridged edgeways and separated by a wide border measuring 60 cm. All of the nitrogen and phosphorus was applied by spreading it evenly over the plot (the whole area of plot for T and the furrows area for R) and ploughing it into the deep soil layer (20 cm) with a spade 10 days before sowing.

Foxtail millet (variety Datong 29) was planted at a rate of 333333 plants ha$^{-1}$. The seeds were sown on April 23, 29, and 24 in 2013, 2014, and 2015, respectively, with an inter-row distance of 30 cm. The foxtail millet was harvested on September 20, 29, and 26 in 2013, 2014, and 2015, respectively. Irrigation was not provided during the experimental years in this study and weeds were controlled manually during each growing season.

**Measurements and data analysis.** Soil cores were manually sampled to a depth of 200 cm with increments of 20 cm at the sowing, seedling, jointing, heading, filling, and harvesting stages using a soil ferric auger in 2013–2015. The gravimetric (g g$^{-1}$) SWC of the 0–200 cm profile was measured by drying the soil to a constant weight at 105 °C. If rainfall occurred, we did not sample the soil until the rainwater leakage reached a balance within 2–5 days, which depended mainly on the amount of rainfall. The soil cores were sampled from the middle of a ridge, a furrow, and the side of a furrow in the R plots, where the SWC was calculated as the mean value of the three different positions. In the T plots, the soil cores were taken from the middle of two contiguous rows. SWS was calculated using the following Eq. (1):

$$SWS = \sum_{i}^{n} c_i \times \rho_i \times h_i / 10, \tag{1}$$

where SWS is the amount of soil water storage (mm), $c_i$ is the soil gravimetric water content (%), $\rho_i$ is the soil bulk density (g cm$^{-3}$), and $h_i$ is the soil depth (cm).

Evapotranspiration (ET, mm) for each plot was determined using the soil water balance equation as follows[5]:

$$ET = P + \Delta SWS - D - R + G + I, \tag{2}$$

where P is the amount of precipitation (mm), $\Delta$SWS is the change in the amount of 0–200 cm soil water storage (mm), D is the downward drainage (mm), R is the surface runoff from each plot (mm), G is the groundwater recharge (mm), I is the irrigation (mm). The experimental field was flat and the groundwater table was at a depth of about 50 m, so no irrigation was required, and I, G, and R in Eq. (2) were zero for all plots. Loess soil has a good water-holding capacity and at the experimental site, the upper 200 cm layer could normally store all of the rainfall; therefore, little drainage occurred below 200 cm, but the SWC at 200 cm exceeded the field water-holding capacity in 2013, and the drainage below 200 cm mainly occurred after strong and continuous rainfall (189 mm rainfall from 81 to 89 DAS). Over 95% of the foxtail millet root system was distributed in the upper 120 cm soil layer[47], and thus the change in the SWS at the 120–200 cm soil depth during 95 DAS to harvest could be used to estimate the drainage in 2013.

After the harvest, two rows of millet (3 m$^2$) were hand harvested from the middle of each plot, where the seed and aboveground biomass yields were determined based on a water content of 12% for the total land area used, including the combined area of the ridges and furrows. WUE was calculated as the foxtail millet yield (kg ha$^{-1}$) divided by the growing season ET (mm).

At the heading and harvesting stages in each year from 2013–2015, soil samples were collected manually to a depth of 200 cm with 20 cm intervals using a 54-mm diameter steel core-sampling tube (T-54, Yangling Machine Equipment Factory, China). For each replicate plot, the sampling positions were in the middle of two contiguous rows for R (furrow area) and T planting, and samples from four points were collected and mixed to obtain a composite profile at the same depth. The soil samples were placed in a plastic box and closed firmly immediately, before being transported and refrigerated (4–6 °C). After the harvest each year, the chemical properties of the soil samples were tested in the same manner. The soil samples obtained at depths of 0–200 cm were used to determine the $NO_3$-N content, which was extracted with 2 M KCl solution (20 g fresh soil soaked in 100 ml KCl solution), shaken for 1 h, and analyzed with a FIAstar 5000 Analyzer (FOSS, Sweden). The available phosphorus (Olsen-P) was extracted only from the top soil depths (0–20 and 20–40 cm) using 0.5 M $NaHCO_3$ solution adjusted to pH 8.5 and quantified using the Mo-Sb-Vc-method method.

Plant samples were collected during the periods of anthesis and maturity. On each sampling date, six representative foxtail millet plants were collected from each plot under T planting, whereas six plants were selected separately from the side and middle rows under R planting because there was an obvious difference in plant growth in the side and middle rows due to a border effect[48]. The samples obtained at maturity were separated into straw and grain. Tissue samples were subsequently dried to a constant weight in an oven at 65 °C and ground using a plant tissue grinder. After digesting with $H_2SO_4$-$H_2O_2$, the tissue samples were analyzed to determine the N concentration using an automatic Kjeldahl apparatus (FOSS Co., Sweden) and the P concentration was determined using the Mo-Sb-Vc-method method. At anthesis and maturity, the N or P uptake rate by foxtail millet was calculated as the dry matter weight multiplied by the N or P concentration.

NupE (PupE) was calculated as the ratio of N (P) uptake (kg ha$^{-1}$) by the aboveground biomass at maturity relative to the amount of N (P) fertilizer supplied (kg ha$^{-1}$). NUE (PUE) was calculated as the ratio of the grain yield (kg ha$^{-1}$) relative to the total N (P) uptake (kg ha$^{-1}$). NHI (PHI) was calculated as the ratio of grain N uptake relative to the total N (P) uptake[49].

The amount of N (P) transferred from vegetative organs to grain (Nt, Pt) was calculated using Eq. (3).

$$\begin{aligned} Nt(Pt) = {} & \text{crop total N (P) uptake at anthesis} - \text{crop total N (P) uptake at maturity} \\ & + \text{grain N (P) uptake} \end{aligned} \tag{3}$$

The contribution rate was calculated as the ratio of Nt (Pt) relative to the grain N (P) uptake.

Net economic income for each treatment was calculated using the following equations:

$$NEI = (GY \times J - TC) \times 0.149 \tag{4}$$

$$TC = (\text{fertilizer cost}) + (\text{plastic film cost}) + (\text{ridging and mulching cost}), \tag{5}$$

where NEI is the net economic income (USD ha$^{-1}$), GY is the grain yield (kg ha$^{-1}$), J is the local price of foxtail millet, which was 4 Chinese yuan kg$^{-1}$, 0.149 is the exchange rate (1 Chinese yuan = 0.149 USD, Bank of China, 2017/2/17), and TC is the total cost (Chinese yuan ha$^{-1}$). The local prices of urea and diammonium phosphate were 2 and 3.6 Chinese yuan kg$^{-1}$, respectively, and the total fertilizer cost was calculated based on the fertilizer application rate in different plots. The plastic film cost for the RFRH system was 375 Chinese yuan ha$^{-1}$. Ridging and mulching by machine cost 450 Chinese yuan ha$^{-1}$, and the other costs were the same for all treatments.

The data were tested by analysis of variance using SPSS 22.0, where the data obtained from each sampling event were analyzed separately. Mean values from treatments were compared based on the least significant difference test (LSD 0.05) if the F tests were significant at a probability level of 0.05. All of the figures were prepared using SigmaPlot 10.0.

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## Author Contributions

Y.L. wrote the main manuscript text. Z.J., Q.H., and X.R. conceived and designed the experiments, as well as revising the manuscript. Y.L., X.M., T.W., S.A., P.Z., and B.Y. obtained the experimental data, Z.Y. assisted in manuscript revise. All authors reviewed the manuscript.

## Additional Information