



OPEN

Blending controlled-release urea and urea under ridge-furrow with plastic film mulching improves yield while mitigating carbon footprint in rainfed potato

Mengyuan Sun^{1,2}, Bin Ma³, Peina Lu⁴, Jianhui Bai¹, Junzhen Mi¹ & Jinghui Liu^{1✉}

Ridge-furrow with plastic film mulching and various urea types have been applied in rainfed agriculture, but their interactive effects on potato (*Solanum tuberosum* L.) yield and especially environments remain poorly understood. A three-year experiment was conducted to explore the responses of tuber yield, methane (CH₄) and nitrous oxide (N₂O) emissions, net global warming potential (NGWP), carbon footprint (CF), and net ecosystem economic budget (NEEB) of rainfed potato to two mulching practices [plastic film mulching (RM) and no plastic film mulching (NM)] and three urea types [conventional urea (U), controlled-release urea (C), and a mixture of equal amounts of conventional urea and controlled-release urea at a ratio of 1:1 (CU)] and their interactions. The results showed that RM significantly decreased cumulative N₂O emissions and CH₄ uptake by 4.9% and 28.4%, but significantly increased NGWP by 8.9% relative to NM. Compared with U, the C and CU produced much lower cumulative N₂O emissions and NGWP and higher CH₄ uptake. The interaction of mulching methods and urea type had significant influence on tuber yield and NEEB. Considering both environment and production, RMCU could not only achieve a high tuber yield and NEEB (by up to 26.5% and 42.9%, respectively), but also reduce the CF (by up to 13.7%), and therefore should be considered an effective strategy for dryland potato.

Global warming, caused primarily by a remarkable increase in the atmospheric concentrations of greenhouse gases (GHG), namely methane (CH₄) and nitrous oxide (N₂O), and food security problems, have become global issues^{1,2}. Two of the most significant GHG are CH₄ and N₂O, which have a strong infrared absorption capacity and large warming effects in the atmosphere. In addition, the global warming potential (GWP) of CH₄ and N₂O are 34 and 298 times greater than carbon dioxide (CO₂) over a 100-year timeframe, respectively³. In particular, agriculture soils have been estimated to contribute 84% and 52% to the global anthropogenic N₂O and CH₄ emissions, respectively^{4,5}. More than 70% of the arable land in north and northwest China is used for rainfed agriculture, mainly located in arid and semiarid areas⁶. Potato (*Solanum tuberosum* L.) is one of the main crops in dry farmland of China⁷, but crop production is limited by water shortage and suboptimal nutrient management⁸. Thus, there is an urgent need to determine optimal strategies to improve crop production while minimizing environmental costs^{9,10}.

Ridge-furrow with plastic film mulching system (RM) is a low-cost micro-field rainwater-collecting technique, which has been widely applied to crop production, especially in the arid and semiarid areas^{11,12}. Previous studies found that RM increased tuber yield, water productivity, and nitrogen (N) use efficiency^{13,14}, by increasing soil temperature and moisture, and improving the availability of soil nutrients in dry farmland¹⁵. Plastic film mulching has a complex effect on the production, consumption, and transport of CH₄ and N₂O in soils by altering the hydrothermal conditions^{16,17}. In particular, Yu et al.¹⁷ found that plastic film mulching significantly reduced CH₄

¹National Outstanding Agriculture Research Talents Innovation Team, Inner Mongolia Agricultural University, Hohhot, Inner Mongolia 010019, People's Republic of China. ²Inner Mongolia Academy of Agricultural & Animal Husbandry Science, Hohhot 010010, People's Republic of China. ³Institute of Forestry and Grassland Ecology, Ningxia Academy of Agriculture and Forestry Sciences, Yinchuan, Ningxia 750002, People's Republic of China. ⁴State Key Laboratory of Aridland Crop Science, Gansu Agricultural University, Lanzhou, Gansu 730070, People's Republic of China. ✉email: cauljh@aliyun.com

Soil physicochemical	2018	2019	2020
Soil water content (%)	7.0a	6.8a	2.4b
Available potassium (mg kg ⁻¹)	103.1a	80.3c	96.2b
Available phosphorus (mg kg ⁻¹)	7.1a	4.9c	5.8b
Organic matter (g kg ⁻¹)	9.8a	4.9c	6.6b
Total nitrogen (g kg ⁻¹)	0.8a	0.4c	0.5b
Total carbon (g kg ⁻¹)	10.9a	8.7c	9.7b
TC/TN	13.4c	19.8a	18.3b

Table 1. The physical chemical properties at 0–20 cm depth at the experimental field. Numbers followed by different letters in each row indicate significant differences at $\alpha = 0.05$ based on ANOVA test.

emissions from paddy fields by 64.2% and CH₄ uptake in uplands by 16.1%; and increased N₂O emissions by 23.9%. However, until now, studies on GHG emissions under plastic film mulching showed inconsistent results in agricultural fields¹⁷. It has been reported that plastic film mulching significantly increased GHG emissions, greenhouse gas intensity (GHGI), and net global warming potential (NGWP)^{18,19}, but the opposite results still exist^{20–22}. The contradiction may be caused by inconsistent investigations of agronomical measures, as well as the corresponding soil texture and meteorological characteristics²³.

N fertilizers have been identified as a viable means to increase crop yield by 30–50%, and more than half the world's population depends on N fertilizers for food production^{23–25}. Urea is the most widely used N fertilizer globally because of its high N content, favorable cost, and ease of application^{26,27}. When applied to soil, urea quickly decomposes under the influence of precipitation, and it is easy to cause soil N losses through various pathways such as N₂O emissions, ammonia volatilization, and leaching, which cannot meet the crop demand for N at the later growth stages^{28,29}. Developing high-efficiency fertilizers, such as controlled-release urea (CRU) is thus a promising way to address these issues. CRU has been widely used to improve synchrony between soil N availability and crop N demand, thereby increasing crop yield and mitigating N₂O emissions^{23,30,31}. A meta-analysis by Zhang et al.²³ indicated that CRU can increase maize yield (5.3%) and N use efficiency (24.1%) and reduce N₂O emissions (23.8%), compared with urea. However, a single CRU is generally expensive, and the N release rate can be affected by soil moisture and temperature, which may inhibit crop growth at the early growth stage^{32–34}. In view of this, more and more researchers suggested that a better management strategy for mixed CRU and urea (CU) has been considered as a better alternative N management strategy to ensure N supply at the early stages and reduce fertilizer costs, thereby increasing crop yield and economic benefit^{29,35,36}. Previous study showed that the 1:1 ratio of CRU and common urea could not only achieve a high grain yield, but also enhance ecosystem economic benefit³⁷. In light of China's goal to implement the plan for zero growth of fertilizer, CU offers an excellent option for increasing N use efficiency while minimizing environmental pollution^{32,38}. For example, Bai et al.³⁹ observed that CU not only improved the economic efficiency of maize cultivation (increased by 4.9–12.1%) but also significantly decreased the NGWP and carbon footprint (CF) (decreased by 21.1–21.7% and 17.8–23.1%, respectively), but net ecosystem economic budget (NEEB) was not assessed.

Previous studies have not investigated the interactive effects of RM with various urea types for potato production on CF and NEEB in rainfed agriculture. Therefore, a comprehensive analysis of the environmental and agronomic effects of RM combined with various urea types are essential. We hypothesized that the combination of RM and various urea types could better balance the production and environmental benefits of rainfed potato in comparison with both strategies individually. This study was aimed to: (1) investigate the dynamics of CH₄ and N₂O emissions in a rainfed potato field under RM and various urea types; (2) determine the optimal combination of RM and urea types to increase tuber yield and NEEB, and reduce NGWP and CF; and (3) propose an appropriate combination of RM and urea type for sustainable potato production in dryland areas.

Materials and methods

Site description. A three-year (2018–2020) field experiment was conducted at the experimental farm of Qingshuihe County Research Centre (39°57'N, 111°39'E), Hohhot, Inner Mongolia, in north-central China. The preceding crop for each trial was maize (*Zea mays* L.), the most common potato rotational crop in Inner Mongolia. This region has a typical semi-arid mid-temperate continental monsoon climate in a loess hilly-gully region on the Loess Plateau of China. The site has an elevation of ~1374 m with an annual mean air temperature of 7.1 °C, total rainfall of 365 mm, and potential evaporation of 2577 mm⁴⁰. The field has a sandy loam texture, with soil fractions of 728 g kg⁻¹ sand, 134 g kg⁻¹ silt and 138 g kg⁻¹ clay content⁴⁰. The field experiment soil properties within 20-cm are shown in Table 1.

Rainfall and average monthly temperature during the potato growing seasons was shown in Table 2. The highest average monthly temperature and precipitation of the past 37 years were recorded in July and August, respectively (1981–2017). From May to September, total precipitation was 354.4, 300, and 268.9 mm in 2018, 2019, and 2020, and the average air temperature was 19.9, 19.1, and 19.5 °C, respectively.

Experimental design. The experiment was a randomized split-plot design with two mulch practices—plastic film mulching (RM) and no plastic film mulching (NM)—as main plots, and three urea types (conventional urea (U), controlled-release urea (C), and a mixture of equal amount of conventional urea and con-

Month	Rainfall (mm)				Temperature (°C)			
	2018	2019	2020	LTA	2018	2019	2020	LTA
May	71.4	29.8	3.0	29.5	17.7	15.7	17.3	16.8
Jun	7.1	49.9	36.0	56.7	22.1	21.9	22.3	20.7
Jul	160.1	97.2	105.7	105.6	23.5	22.1	22.3	23.0
Aug	84.3	66.1	81.2	85.6	23.3	19.5	21.0	20.9
Sep	31.5	57.0	43.0	59.5	13.0	16.3	14.9	15.2
May-Sep	354.4	300	268.9	336.9	–	–	–	–

Table 2. The rainfall and monthly mean air temperature at the experimental site in 2018–2020 growing seasons. LTA the average value for the last 37 years (from 1981 to 2017).

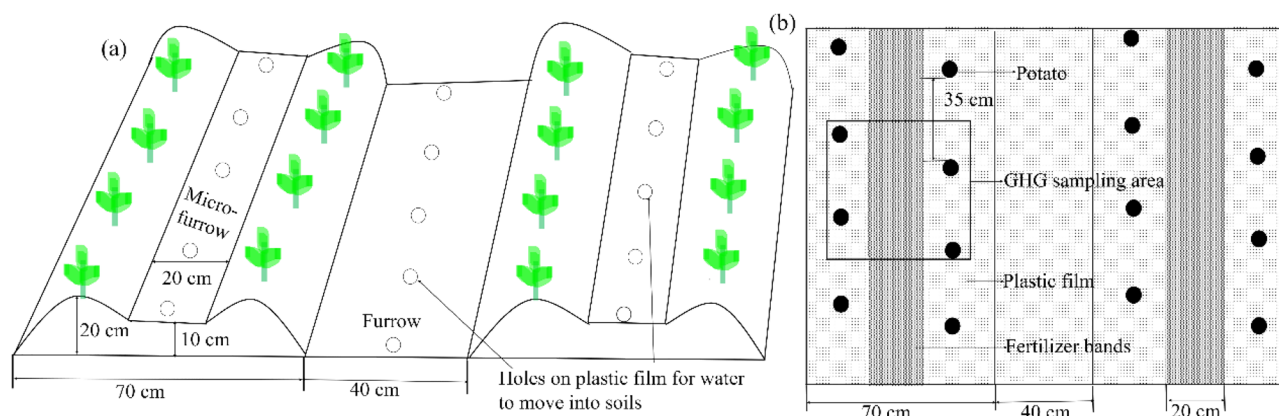


Figure 1. Experimental layout for ridge-furrow with plastic film mulching cultivation systems.

trolled-release urea at 1:1 ratio (CU)) as split plots. There were six treatments: RMU, RMC, RMCU, NMU (local conventional agricultural management), NMC, and NMCU. Each plot was replicated three times. Each plot was 7 m × 7 m, and was surrounded by ridges to prevent surface runoff. Ridge-furrow with plastic film mulching system were used to cultivate potato (Fig. 1a). The width of the ridges base was 70 cm, while the height of the ridges was 20 cm. The furrow width was 40 cm. The width and depth of the micro-ditch within the ridge were 20 cm and 10 cm, respectively.

Plant materials and agronomic practices. We acknowledge the use of plant materials in this manuscript complies with all relevant institutional, national, and international guidelines and legislation. The potato ('Kexin 1') is widely cultivated in dryland regions of China. All seed tubers were obtained from Inner Mongolia Zhengfeng Seed Potato Company, Hohhot of China. Potato was planted on May 13th, 2018, May 20th, 2019, and May 22th, 2020, and harvested on September 18th, 2018, September 23th, 2019, and September 28th, 2020, respectively. Two rows of potato were planted in the ridges with a plant spacing of 35 cm, resulting in a planting density of 52,000 plants ha⁻¹. The plastic film was white polyethylene film with 120 cm wide and 0.01 mm in thickness. All fertilizers were applied as basal fertilization in the middle of the ridges at 15 cm soil depth before planting at a rate of 180-120-150 (N-P₂O₅-K₂O) kg ha⁻¹. The N fertilizer was in the form of conventional urea (46% N) or controlled-release urea (44.5% N). The latter was a polyurethane-coated urea granules with a nutrient release cycle of approximately 90 days (VIKO Global Technology Ltd, Ningxia, China). The controlled-release urea is coated with nano resin technology; the coating micropore diameter is only a few hundred nanometers, which is an ecofriendly material in the production process with good nutrient release properties. A series of holes were pierced through the surface of the plastic films by iron wires at an interval of 30 cm in each plot. All plastic films were removed by farmers after harvest. No irrigation was performed through the three growing seasons.

Gas sampling and analysis. A static closed-chamber method was used to estimate the GHG (CH₄ and N₂O) emissions for the potato growing seasons⁴¹. The static closed-chamber consisted of a stainless-steel top chamber (50 × 50 × 60 cm) and a stainless-steel base frame with a groove (50 × 50 × 15 cm) (Fig. S1). Each side of the top chamber was covered with Styrofoam thermal insulation to prevent the air temperature within the chamber from sharply rising during the sampling period in the summer. In addition, the stainless-steel top chamber was equipped with a digital thermometer on the outside, and two small electric fans were installed at the top of each chamber in opposite locations to ensure complete air mixing. There was equipped with a sampling gas channel with a three-way stopcock on the side of the chamber to connect the syringe. After planting the potato,

the stainless-steel base frame was inserted at a depth of 12 cm into the soil on the ridge so that the troughs were parallel to the surface and did not move throughout the growing season (Fig. 1b). Chambers were maintained in the open state, except for gas sampling time in the field throughout the potato cultivation period.

Gas samples were collected five times at 1, 3, 5, 7, and 15 days after potato sowing, then about every 15 days thereafter in 2018 and 2019, while at 7 days intervals in 2020, excluding the fallow season. At each measurement, the chambers were placed into the base frame groove filled with water, and then four gas samples were collected for each flux measurement at 10 min intervals from 8:30 to 11:30 am using a 50 mL plastic syringe. The temperature in the chamber was also recorded during each gas extraction. The collected gases were stored in 300 mL gas bags, and the gas samples were taken back to the laboratory for determination of N₂O and CH₄ content by PicarroG2308N₂OCH₄H₂O analyzer from Picarro, USA.

Gas emission fluxes were estimated using the increased gas concentration per unit chamber area for a specific time interval¹⁹:

$$F = \rho \times H \times 273 / (273 + T) \times dc/dt \quad (1)$$

where F is the flux of the (mg m⁻² h⁻¹ for N₂O and CH₄); dc/dt is the difference of gas concentration inner the chamber headspace; H is the chamber height (m); ρ is the density of each gas at the standard condition (kg m⁻³); T is chamber temperature (°C).

The cumulative GHG emissions for the entire growing season were computed using the following equation:

$$G = \left(\sum_{i=1}^n \frac{F_i \times d_i}{d} \times 24 \times d \right) / 100 \quad (2)$$

where G (kg ha⁻¹) is the cumulative emissions of N₂O and CH₄; F_i is the GHG emission flux at the i sampling; d_i is the number of days between the i sampling and the next sampling; d is the total number of days in the growth period; 100 is the unit conversion coefficient.

The net global warming potential (NGWP) is commonly used to estimate the relative potential for GHG emissions from agricultural practices³⁹. CO₂-eq emissions are generated by crop production processes, including the production and transportation of plastic film mulch, N, P, and K fertilizers, and herbicides, as well as from diesel used in farm operations. The NGWP equations employed were as follows³⁹:

$$\begin{aligned} \sum \text{GWP (others)} = & \text{EF}_{\text{Herbicide rate}} \times \text{Herbicide rate (kg ha}^{-1}\text{)} + \text{EF}_{\text{N rate}} \times \text{N rate} \\ & + \text{EF}_{\text{P}_2\text{O}_5 \text{ rate}} \times \text{P}_2\text{O}_5 \text{ rate (kg ha}^{-1}\text{)} \\ & + \text{EF}_{\text{K}_2\text{O rate}} \times \text{K}_2\text{O rate (kg ha}^{-1}\text{)} + \text{EF}_{\text{Plastic film}} \\ & \times \text{Plastic film (kg ha}^{-1}\text{)} + \text{EF}_{\text{Diesel fuel}} \times \text{Diesel fuel (kg ha}^{-1}\text{)} \end{aligned} \quad (3)$$

where the estimated average coefficient factors of EF_{Herbicide rate}, EF_{N rate}, EF_{P₂O₅ rate}, EF_{K₂O rate}, EF_{Plastic film}, and EF_{Diesel fuel} were 8.3³⁹, 0.79⁴², 0.55⁴², 2.80⁴³, 3.75⁴² and 10.15⁴⁴, respectively.

$$\text{NGWP} = G(\text{N}_2\text{O}) \times 298 + G(\text{CH}_4) \times 34 + \sum \text{GWP (others)} + \Delta\text{SOC} \quad (4)$$

where NGWP is the net global warming potential (kg CO₂-eq ha⁻¹); G (N₂O) and G (CH₄) were the cumulative CH₄ emissions and cumulative N₂O emissions, respectively. Factors 298 and 34 are the default GWP of N₂O and CH₄, respectively, for a 100-year time horizon^{4,5}. Due to the short duration of this experiment, ΔSOC was neglected.

The carbon footprint (CF) is expressed as the intensity of greenhouse gases produced per unit of production and was calculated using the following equation:

$$\text{CF (kg CO}_2\text{-eq t}^{-1}\text{)} = \text{NGWP/Yield} \quad (5)$$

Soil water content and temperature. At the same time as the gas samples were collected, three soil samples (0–20 cm) were randomly collected from the areas between two plants in the ridges using a 5-cm diameter soil auger. Next, three samples were combined to obtain a single aggregated sample for each plot, which was dried at 105 °C for soil gravimetric water content. An automatic temperature recorder (Fotel L93-4 Thermal Instruments, Shanghai China) was buried between two plants in the ridges of each plot and used to record hourly soil temperature at 10 cm soil depth during the potato growing seasons.

Tuber yield and net ecosystem economic budget. At harvest, 10 plants were randomly sampled from each plot and all the tubers were weighed and recorded to determine yield. The total tubers were weighed for yields and were divided into two classes: commercial tuber > 150 g per tuber and small tuber < 150 g per tuber.

Potatoes with a tuber fresh weight > 150 g were sold at a price of ~0.25 USD kg⁻¹ and tuber fresh weight < 150 g was sold at a price of ~0.16 USD kg⁻¹. The price of urea and CRU was estimated at 0.28 USD kg⁻¹ and 0.5 USD kg⁻¹, respectively. The costs of agricultural operations (sowing + harvest + herbicide), plastic film mulching, fertilizer (P and K fertilizer), and seeds were 634.2, 369.0, 199.7, and 1268.5 USD ha⁻¹, respectively. CO₂-eq was sold at a price of ~16.2 USD t⁻¹.

The net ecosystem economic budget (NEEB) is an important reference index for crop production and agricultural activities. The NEEB (USD ha⁻¹) was calculated using the following equation⁴⁵:

$$\text{NEEB} = \text{Yield} \times \text{Tuber price} - \text{Input} - \text{NGWP cost} \quad (6)$$

$$\text{Input} = \text{Costs of sowing} + \text{herbicide} + \text{plastic film mulching} + \text{fertilizer (N, P and K)} + \text{seeds} + \text{harvest} \quad (7)$$

$$\text{NGWP cost} = \text{NGWP} \times \text{CO}_2\text{-eq price} \quad (8)$$

Statistical analysis. Statistical analyses were carried out in the R environment (version 4.1.1), ANOVA (PERMANOVA) with the “lme4” and “lmerTest” packages to evaluate the influence of different treatments on the tuber yield, NEEB, GHG emissions, NGWP, and CF. Differences were considered statistically significant when $p \leq 0.05$. The correlation between gas emissions and soil water content and temperature was performed using the Pearson correlation analysis. Figures were drawn using the Origin 2021 software (Origin Lab, USA, <http://www.originlab.com/>).

Results

Soil water content and temperature. Topsoil (0–20 cm) water content for various treatments during the potato growth stage was graphed in Fig. S2. The soil water content varied from 4.4% to 12.2% in 2018, 3.3% to 9.2% in 2019, and 2.6% to 9.6% in 2020. On average, soil water content was 8.0%, 6.6%, and 7.0% under RM, 7.3%, 6.0%, and 6.2% under NM in 2018, 2019, and 2020, respectively. The soil water content was higher under RM than that under NM during the growing seasons. The average temperature for different treatments during the potato growth period was shown in Fig. S2. The soil temperature ranged from 15.4 to 27.1 °C, with an average of 22.4 °C in 2018, from 16.1 to 27.7 °C, with an average of 22.7 °C in 2019, and from 18.4 to 29.3 °C, with an average of 23.4 °C in 2020. On average, soil temperature was 23.2, 23.7, and 24.2 °C under RM, 21.5, 21.8, and 22.7 °C under NM in 2018, 2019, and 2020, respectively. RM increased soil temperature by an average of 1.6–1.9 °C compared with NM over the three growing seasons.

Soil CH₄ uptake. Seasonal variations of soil CH₄ fluxes were basically consistent in all treatments, but showed an inconspicuous seasonal variation (Fig. 2a–c). Temporal variations of CH₄ fluxes were negative in various treatments, indicating that the soil absorbed CH₄ from the atmosphere over the three growing seasons. The CH₄ fluxes were significantly and positively correlated with the soil temperature, while a significant negative correlation was observed between CH₄ fluxes and soil water content during the growing seasons (Table S1).

Mulching (M), urea type (T), year (Y), and M × Y significantly affected the cumulative CH₄ uptake (Table 3). The cumulative CH₄ uptake varied from 658.3 to 1074.2 g ha⁻¹ under various treatments in 2020, which were lower than the corresponding values in 2018 (722.3 to 1112.6 g ha⁻¹) and 2019 (882.7 to 1161.5 g ha⁻¹) (Table 3). On average, the cumulative CH₄ uptake was 29.0% lower under RM than under NM. In addition, the cumulative CH₄ uptake was increased by 4.4% under C and 3.5% under CU in comparison to U, respectively. However, no significant difference was observed among C, U, and CU for the cumulative CH₄ uptake under the same mulching practices. The RMU, RMC, and RMCU had significantly lower cumulative CH₄ uptake, with average reductions of 29.4%, 25.2%, and 27.4%, relative to NMU, respectively. Cumulative CH₄ uptake under NMCU reached the maximum values of 1112.6 g ha⁻¹ and 1161.5 g ha⁻¹ in 2018 and 2019, while the corresponding values were 1074.2 g ha⁻¹ under NMC in 2020.

Soil N₂O emissions. Similar seasonal dynamics of soil N₂O fluxes were observed in different treatments, which were mainly dependent on fertilization applications during the potato growing seasons and also driven by rainfall events (Fig. 2d–f). The N₂O fluxes peaked approximately 7 days after fertilization in 2018 and 2019, and peaked about 15 days after fertilization in 2020. The fluxes then gradually declined and maintained a relatively low level except for some small peaks after rainfall. The N₂O fluxes increased after fertilization application, with maximum peaks of 0.13 mg m⁻² h⁻¹ in 2018, 0.09 mg m⁻² h⁻¹ in 2019, and 0.12 mg m⁻² h⁻¹ in 2020. The N₂O fluxes were significantly and positively correlated with the soil water content and temperature during the growing seasons (Table S1).

Mulching (M), urea type (T), and year (Y) to the most extent affected the accumulated N₂O emissions over the three growing seasons (Table 3). Regardless of fertilization, the cumulative N₂O emissions under RM was decreased by 5.5% compared with NM. In addition, the cumulative N₂O emissions were in the following order: C < CU < U. As desired, the cumulative N₂O emissions was decreased by 14.0% and 5.9% under C and CU than U, respectively. However, no significant difference in cumulative N₂O emissions was observed between U and CU under the same mulching method. Over the three growing seasons, RMC, RMCU, and NMC had significantly lower cumulative N₂O emissions, with average reductions of 18.7%, 11.3%, and 14.3%, relative to NMU, respectively. Furthermore, RMC reached the minimum value of 891.7 g ha⁻¹, which was 5.1–18.7% lower than those in the other treatments.

Net global warming potential and carbon footprint. The relative contributions of components of NGWP for the potato growing seasons were compared across different treatments (Fig. 3). During the potato growing seasons, the production and transportation of N fertilizers was the largest contributor to NGWP, accounting for 61.1%. Emissions from diesel consumption by agricultural machinery operations from sowing to harvesting were the second largest component of NGWP, accounting for 16.3%. The GHGs were mainly dominated by N₂O emissions across the three growing seasons, and the absorption of CH₄ offset only a small portion of the NGWP, accounting for 10.8%. For RM (RMU, RMC, and RMCU) treatments, the fourth greatest contribu-

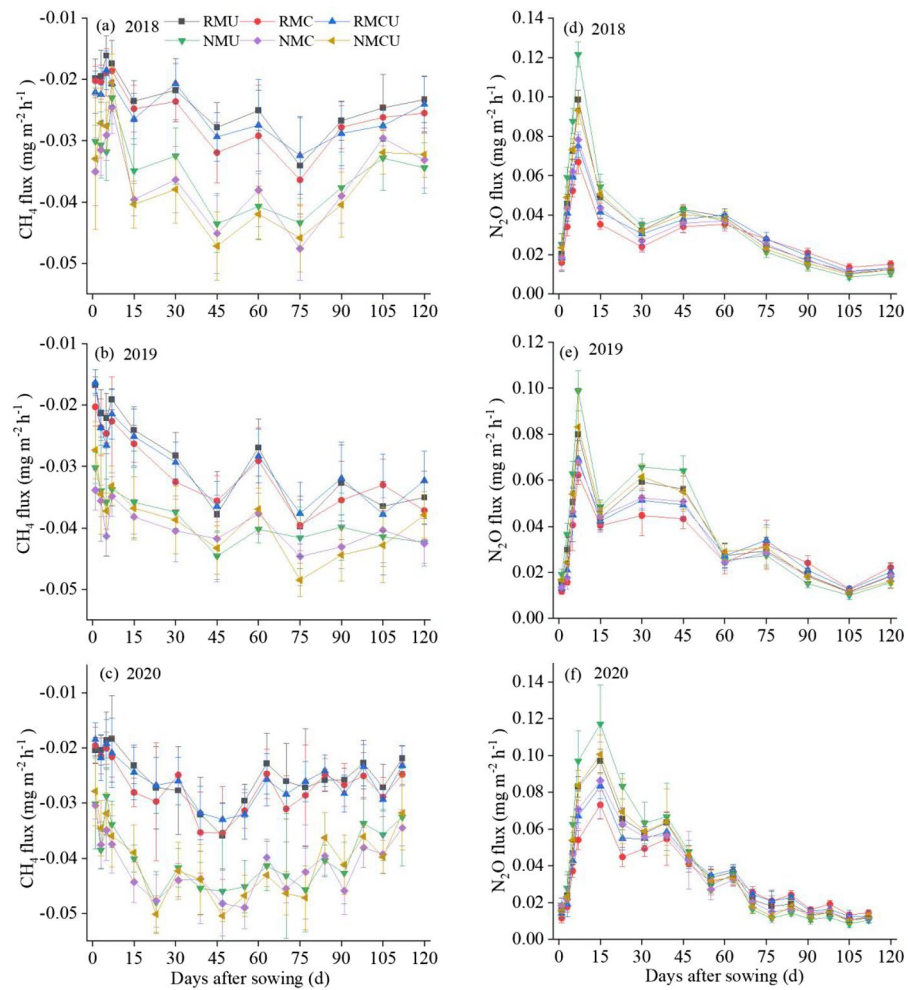


Figure 2. Dynamics of soil CH_4 fluxes (a–c) and N_2O fluxes (d–f) under different treatments in 2018–2020 growing seasons. *RM* plastic film mulching, *NM* no plastic film mulching, *U* conventional urea, *C* controlled-release urea, *CU* a mixture of equal amount of conventional urea and controlled-release urea at 1:1 ratio. The vertical bars represent the standard error, $n = 3$.

tor was plastic film, accounting for 8.4% of NGWP. In addition, applications of P and K fertilizers, and herbicides contributed only minimally to the NGWP of the potato cropping system. Mulching (M), urea type (T), and year (Y) significantly affected NGWP over the growing seasons (Table 3). Regardless of fertilization, NGWP was significantly higher under RM compared with NM (by 8.9%) across the three growing seasons. Irrespective of mulching, the order of magnitude of the NGWP for the three growing seasons was $U > CU > C$. Compared with U, averaged NGWP was significantly decreased under C by 1.9%, but there was no significant difference between U and CU. The RMU ($2576.7 \text{ kg CO}_2\text{-eq ha}^{-1}$), RMC ($2533.0 \text{ kg CO}_2\text{-eq ha}^{-1}$), and RMCU ($2557.9 \text{ kg CO}_2\text{-eq ha}^{-1}$) showed a significant increase of 8.7%, 6.8% and 7.9% in NGWP compared with NMU ($2370.7 \text{ kg CO}_2\text{-eq ha}^{-1}$), respectively. The lowest NGWP was obtained under NMC, on average $2322.8 \text{ kg CO}_2\text{-eq ha}^{-1}$ over the three growing seasons.

CF was also generally affected by mulching (M), urea type (T), year (Y), and $M \times Y$ (Table 3). The CF was $94.5\text{--}105.1 \text{ kg CO}_2\text{-eq t}^{-1}$ under RM, $101.3\text{--}109.5 \text{ kg CO}_2\text{-eq t}^{-1}$ under NM across the three growing seasons. Moreover, RM decreased CF by 2.8% under U, by 4.0% under C, and by 6.7% under CU respectively, compared to NM. On the other hand, on average, compared to C and U, the CU produced lower 8.8% and 7.4% of CF, respectively. RMCU and NMCU reached lower values, with decreases of 9.3–13.7% and 2.8–7.5% in CF compared with other treatments, respectively. On average, RMCU and NMCU significantly decreased CF by 11.8% and 5.5%, respectively, compared to NMU. CF under RMCU reached the minimum values of $76.8 \text{ kg CO}_2\text{-eq t}^{-1}$ in 2018, $112.7 \text{ kg CO}_2\text{-eq t}^{-1}$ in 2019, and $94.0 \text{ kg CO}_2\text{-eq t}^{-1}$ in 2020. The CF followed the order of $2019 > 2020 > 2018$.

Tuber yield and net ecosystem economic budget. Tuber yield was significantly influenced by mulching (M), urea type (T), and their interactions (Table 4). Compared with NM, the average tuber yield under RM increased by 9.4% in 2018, 17.2% in 2019, and 14.1% in 2020, respectively. Compared with U and C, the average tuber yield under CU significantly increased by 9.0% and 11.4% in 2018, by 5.8% and 10.7% in 2019, and by

Year	Treatment	Cumulative CH ₄ uptake (g ha ⁻¹)	Cumulative N ₂ O emissions (g ha ⁻¹)	NGWP (kg CO ₂ -eq ha ⁻¹)	CF (kg CO ₂ -eq t ⁻¹)
	RMU	722.3b	1011.0ab	2571.2a	87.2a
	RMC	785.3b	853.6e	2522.2b	86.8a
	RMCU	764.1 b	938.7cd	2548.3ab	76.8b
	NMU	1047.3a	1054.8a	2359.0c	85.1a
	NMC	1086.1a	904.6d	2313.0d	85.9a
	NMCU	1112.6a	984.2bc	2335.8cd	80.0b
2019	RMU	882.7b	1071.3ab	2583.8a	121.2b
	RMC	913.7b	941.9c	2544.1b	123.7b
	RMCU	891.5b	1015.6bc	2566.8ab	112.7c
	NMU	1126.2a	1148.7a	2384.3c	129.5ab
	NMC	1152.0a	984.0c	2334.4d	134.1a
	NMCU	1161.5a	1096.8ab	2367.7c	122.6b
2020	RMU	658.3b	1017.2ab	2575.3a	104.1ab
	RMC	701.1b	879.5c	2532.8b	104.7ab
	RMCU	673.2b	962.4bc	2558.4ab	94.0c
	NMU	1034.3a	1085.7a	2368.7c	106.9a
	NMC	1074.2a	930.4bc	2321.0d	108.4a
	NMCU	1058.0a	1012.3ab	2346.0cd	101.2b
Significance of factor					
Mulching (M)		***	***	***	***
Urea type (T)		*	***	***	***
Year (Y)		***	***	**	***
M × T		NS	NS	NS	NS
M × Y		***	NS	NS	***
T × Y		NS	NS	NS	NS
M × T × Y		NS	NS	NS	NS

Table 3. Cumulative CH₄ uptake and N₂O emissions, Net global warming potential (NGWP) and carbon footprint (CF) under different treatments in 2018–2020 growing seasons. *RM* plastic film mulching, *NM* no plastic film mulching, *U* conventional urea, *C* controlled-release urea, *CU* a mixture of equal amount of conventional urea and controlled-release urea at 1:1 ratio. Numbers followed by different letters in each column indicate significant differences at $\alpha = 0.05$ based on ANOVA test. The statistical significance is denoted by * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$, and *NS* not significant.

7.5% and 10.6% in 2020, respectively. The tuber yield of RMCU and RMU was significantly higher than other treatments. Especially, tuber yield under RMCU reached the maximum of 33.2 t ha⁻¹ in 2018, 22.8 t ha⁻¹ in 2019, and 27.2 t ha⁻¹ in 2020, which were respectively 12.5–23.3%, 6.8–30.7%, and 10.0–27.2% higher than other treatments. The tuber yield was the largest in 2018, followed by 2020 and 2019.

Mulching (M), urea type (T), year (Y) and their interactions had highly significant effects on NEEB, except for the M × T × Y (Table 4). The NEEB is an important reference indicator for crop production and agricultural activities. Over the three growing seasons, the mean NEEB varied from 2386.8 to 3410.9 USD ha⁻¹. The highest NEEB were recorded under RMCU, while NMC consistently had the lowest NEEB. On average, the NEEB of RMCU was significantly increased by 17.8–42.9% compared with the other treatments. The NEEB followed the order of 2018 > 2020 > 2019. In addition, mulching (M), urea type (T), and year (Y) had highly significant effects on NGWP cost (Table 4). The RMCU, RMU, and RMC were more NGWP cost than other treatments. Compared with NMU, the NGWP cost increased by 7.9%, 8.7%, and 6.8% for RMCU, RMU, and RMC, respectively.

Discussion

Effect of mulching practices and urea types on soil CH₄ uptake. Dryland soils normally are sinks for atmospheric CH₄, owing to methanotrophs in soils oxidizing CH₄ under dry conditions⁴⁶. In our study, the CH₄ uptake with small fluxes was observed in all treatments during the three growing seasons (Fig. 2a–c). This rate is almost consistent with that by Wang et al.⁷, who observed a CH₄ sink with an average annual methane absorption (negative emission) of 940.8 ± 103.2 g CH₄-C ha⁻¹ year⁻¹. Zhang et al.⁴⁷ reported that soil hydrothermal properties were the main factors that affecting soil gas emissions. Nan et al.¹⁶ found that CH₄ concentration was only weakly correlated with soil temperature and moisture because CH₄ consumption was not sensitive to temperature. In the present study, the CH₄ fluxes were significantly and positively correlated with the soil temperature, while a significant negative correlation was observed between CH₄ fluxes and soil water content.

For rainfed potato fields, we found that cumulative CH₄ uptake was decreased under RM in this study, in agreement with previous measurements^{21,48}. This result is consistent with those of Yu et al.¹⁷, who found that the soil CH₄ uptake was significantly lower under film mulching than under non-mulching in rainfed uplands. A

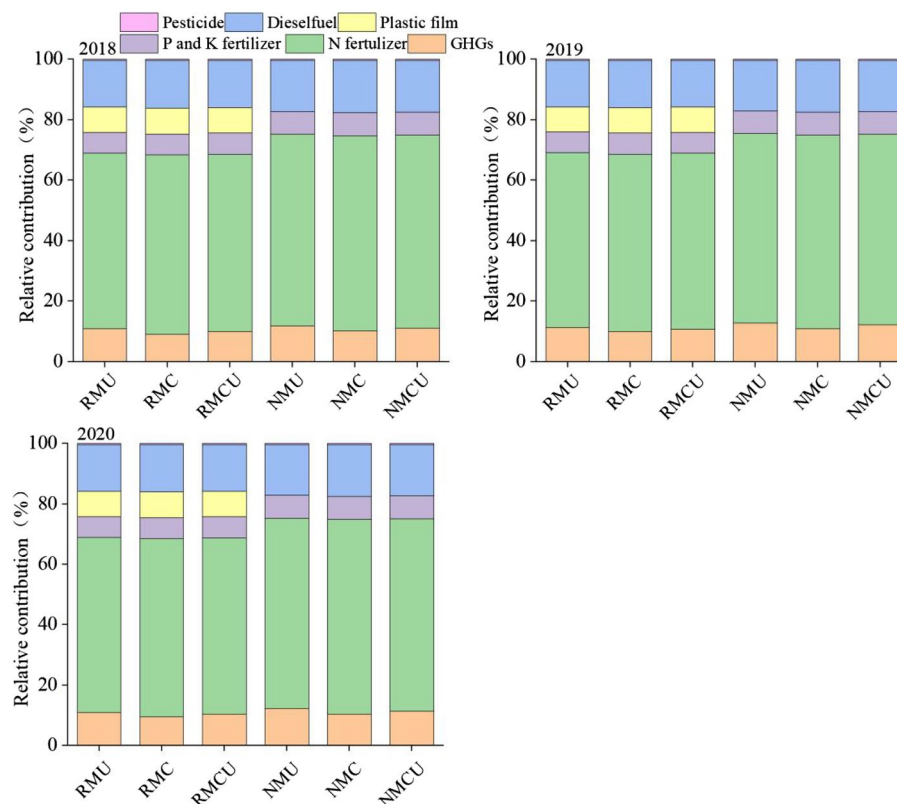


Figure 3. The relative contributions of different inputs to the total GHG emissions under different treatments in 2018–2020 growing seasons. *RM* plastic film mulching, *NM* no plastic film mulching, *U* conventional urea, *C* controlled-release urea, *CU* a mixture of equal amount of conventional urea and controlled-release urea at 1:1 ratio.

possible reason for the lower CH_4 uptakes in the *RM* was that the relatively low gaseous oxygen (O_2) availability and the restricted CH_4 gas exchange between the soils and the atmosphere under *RM* decreased CH_4 oxidation by methanotrophs¹⁹. On the other hand, plastic film mulching can maintain higher soil water content and $\text{NH}_4^+\text{-N}$ content, which can partially inhibit soil CH_4 uptake²¹. In contrast, Chen et al.⁴⁹ found that plastic film mulching increased CH_4 absorption. The contradiction could be a result of the inconsistent investigations of agronomical measures, as well as the corresponding soil type, soil conditions, and meteorological characteristics. Agricultural practices, such as fertilization management and planting patterns, can affect the soil's ability to act as a sink of atmospheric CH_4 ⁵⁰. Much research has been conducted on the relationship between fertilization and CH_4 emissions^{50,51}. Zheng et al.⁵² found that the difference in CH_4 flux between *CU* and *U* alone was also not significant over the two growing seasons. Our results show that the cumulative CH_4 uptake did not vary among the three urea types, which is consistent with the report by Bai et al.³⁹, due to the complex underlying mechanisms of methanogen activity.

Effect of mulching practices and urea types on soil N_2O emissions. In the present study, the flux of N_2O emissions under different treatments peaked about 7–15 days after the base fertilizer applications, and then maintained relatively low levels due to the soil absorption and plant uptake of N , in line with the findings by Li et al.⁵³. Fang et al.⁴¹ reported that the daily flux of N_2O emissions under film mulching and N fertilization treatments peaked about 8 days post-sowing. The N_2O is produced in soils essentially through the processes of nitrification and denitrification⁵⁴, which were closely related to soil moisture and temperature¹⁶. In our study, significant and positive correlations were observed between N_2O fluxes and soil water content and soil temperature during the growing seasons, indicating that improved soil moisture and temperature might become a more critical factor for soil N_2O emissions, which is consistent with the previous studies^{49,55}. It may be attributed to the fact that the high N_2O fluxes following the precipitation events and higher temperature in this study (Fig. S2 and Fig. 2).

RM improves soil hydrothermal conditions, which probably facilitate N_2O production through nitrification and/or denitrification processes²⁰. In the present experiment, the *RM* had higher soil temperature and moisture contents, but *RM* had a negative effect on N_2O emissions, supporting findings in previous studies^{22,56}. Similar results also were found by Li et al.²¹, who reported that plastic film mulching enhanced soil temperature and water content but did not increase N_2O fluxes. This result can be explained as follows. First, *RM* significantly reduced the soil mineral N content by increasing nitrogen use efficiency or the impervious barrier effects of the

Year	Treatment	Yield (t ha ⁻¹)	Input (USD ha ⁻¹)	NGWP cost (USD ha ⁻¹)	NEEB (USD ha ⁻¹)
2018	RMU	29.5b	2581.7	41.8a	3857.0c
	RMC	29.1b	2674.1	41.0b	3672cd
	RMCU	33.2a	2627.9	41.4ab	4621.3a
	NMU	27.7c	2212.7	38.3c	3786.2c
	NMC	26.9c	2305.1	37.6d	3529.3d
	NMCU	29.2b	2258.9	37.9cd	4064.6b
2019	RMU	21.3b	2581.7	42a	2203.1b
	RMC	20.6b	2674.1	41.3b	1931.4c
	RMCU	22.8a	2627.9	41.7ab	2518.8a
	NMU	18.4cd	2212.7	38.7c	1811.7c
	NMC	17.4d	2305.1	37.9d	1480.9d
	NMCU	19.3c	2258.9	38.4c	1938.0bc
2020	RMU	24.7b	2581.7	41.8a	2622.7b
	RMC	24.2b	2674.1	41.1b	2370.0c
	RMCU	27.2a	2627.9	41.5ab	3092.4a
	NMU	22.2d	2212.7	38.5c	2402.9c
	NMC	21.4d	2305.1	37.7d	2150.0d
	NMCU	23.2c	2258.9	38.1cd	2592.0b
Significance of factor					
Mulching (M)		***	–	***	***
Urea type (T)		***	–	***	***
Year (Y)		***	–	**	***
M × T		**	–	NS	***
M × Y		NS	–	NS	*
T × Y		NS	–	NS	*
M × T × Y		NS	–	NS	NS

Table 4. Tuber yield and net ecosystem economic budget (NEEB) under different treatments in 2018–2020 growing seasons. RM plastic film mulching, NM no plastic film mulching, U conventional urea, C controlled-release urea, CU a mixture of equal amount of conventional urea and controlled-release urea at 1:1 ratio. Numbers followed by different letters in each column indicate significant differences at $\alpha = 0.05$ based on ANOVA test. The statistical significance is denoted by * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$, and NS not significant.

plastic film mulching on the gas exchange between soil and atmosphere, thereby offsetting N₂O production^{20,41}. Second, the lower N₂O emissions in the RM could be attributed to increased soil denitrification by *Thiobacillus denitrificans*, which reduced some nitrous compounds further into nitrogen gas (N₂)²¹. Thus, in the RM, N₂O emissions are not only affected by soil temperature and moisture, but also may be related to soil nitrification and denitrification microorganisms and inorganic N content.

Increasing N₂O emissions from agriculture are heavily linked with the application of mineral N fertilization⁵⁷. It is very interesting that the soil N₂O fluxes were consistent under U, C, and CU, but the use of C reduced soil N₂O fluxes peaks. The application of C treatment significantly reduced cumulative N₂O emissions relative to U by 14.0%. Similar results also were found by Zhang et al.²³, who reported that the application of CRU instead of urea (same N rate) significantly decreased N₂O emissions by 23.8%. These results may be explained that the N in uncoated urea is released more quickly than in CRU, thus the available N contents under U treatment are presumable higher than under C treatment. However, direct evidence cannot be provided. Future studies on the relationship between soil available N contents (NH₄⁺-N and NO₃⁻-N) and soil N₂O fluxes need to be considered under various urea types. Moreover, the application of C, soil urease and the urea in the membrane were unable to directly contact, preventing the water transport required for urea dissolution in the membrane⁵⁸. In addition, our results showed that the application of CU did not significantly reduce cumulative N₂O emissions compared with U, this was consistent with the results observed by Bai et al.³⁹.

Effect of mulching practices and urea types on net global warming potential and carbon footprint.

Different inputs of chemical fertilizers, human activities, and fuels create variations in carbon emissions from agricultural inputs under different management practices, indirectly influencing the carbon cycling of systems^{59,60}. Many studies have reported that the net GWP is affected by the use of inorganic fertilizers, fuel, plastic film, and pesticides in the crop growing season^{39,61}. Akhtar et al.⁵⁵ reported that net GWP was significantly higher in the plots treated with straw mulch and N fertilizer. In our study, N fertilizer was the greatest contributor to the NGWP, and this result was consistent with the previous studies⁶². Therefore, optimizing N fertilizer application rates can be one of the key options to mitigate agricultural GHG emissions. In addition, diesel fuel also accounted for a large proportion of the NGWP. Our results showed that the total GHG emissions

were significantly higher under RM than under NM, which was calculated by summing two GHG (N_2O and CH_4) fluxes and CO_2 equivalent¹⁹. It should be kept in mind that each step involved in the use of plastic film, from manufacturing to its application under plastic film, leads to GHG emissions⁶³. Our results showed that RM significantly increased the NGWP, which might counteract its positive effects, such as increases in crop productivity. This occurred mainly as a result of changes in plastic film, maybe because of the effect of indirect GHG emissions caused by the input of plastic film materials⁶⁴ and lower soil CH_4 uptake. Lee et al.¹⁹ reported that plastic film mulching highly increased NGWP via increasing GHG emissions. In addition, NGWP was decreased under C and CU compared with U. The decrease in NGWP might be related to the reduction of N_2O emissions by the use of CRU.

In addition to a reduction in the NGWP, the main objective of this study was to maintain a low CF. CF based on the emission of CO_2 -eq per unit of crop production⁶³, has been widely popularized and applied in the field of agriculture for the evaluation of environmentally friendly and clean production⁶⁵. The factors influencing CF include the CO_2 emissions from farmland soils and crops and indirect CO_2 emissions from the production, storage, and transportation of agricultural production materials^{1,66}. In our study, RMCU, RMU, and NMCU were very effective to reduce CF than other treatments, due to the high tuber yield increase rather than the NGWP increase. The present study suggested that RMCU had the lowest CF and was eco-friendly, which may be due to the effect of RMCU increasing the yield and could therefore offset environmental impacts to a greater degree. Bai et al.³⁹ reported that the combination of urea and CRU in a one-time application significantly decreased the NGWP and CF of maize. Therefore, a better balance between production and environmental benefits can be achieved by RMCU in rainfed regions.

Effect of mulching practices and urea types on tuber yield and net ecosystem economic budget.

Plastic film mulching can improve grain yield by enhancing plant growth and nutrient absorption, especially in Northwest China⁶⁷. In our study, the RMU, RMC, and RMCU increased soil water content (Fig. S2), hence effectively maintaining the high yield of potato (Table 4), which is consistent with the report by Tang et al.³². The key to a trade-off between yield, profit, and the environment in crop production is to achieve synchronization between N supply and crop demand to avoid N excess or deficiency. Guo et al.¹⁰ reported that CU was better synchronized with the N demand of rainfed crop relative to U and C, thus could accomplish a high grain yield. Our results illustrated that the RMCU had the maximum tuber yield over the three growing seasons. This result was mainly due to CU under RM can provide better water, temperature, and nitrogen conditions for crop growth to realize relatively high yield in semiarid farmland³². Additionally, in our study, tuber yield in 2018 was greater than that in the 2019 and 2020 growing seasons, which can be largely attributed to the higher precipitation in 2018 (Table 2).

In the present study, RM (RMU, RMC, and RMCU) treatment increased NGWP cost, which was mainly attributed to the significant increase in the NGWP. Under certain agricultural measures, NEEB represents the relationship between economic feasibility and environmental sustainability²⁸. In this study, we found that RMCU, RMU, and NMCU were efficient ways to increase NEEB over the three growing seasons, due to high tuber yield would counterbalance the negative impact of increased input and ultimately increase the NEEB. This data shows that the RMCU can not only ensure high tuber yield but also reduce fertilizer costs, thereby achieving a high NEEB. Therefore, RM combination with CU (RMCU) could achieve the goal of high yield, NEEB, and low CF in rainfed regions.

Although our study indicated that RMCU practices have a lower carbon footprint and higher tuber yield and net ecosystem economic budget, the use of plastic film caused a large number of plastic film residues, which seriously pollute the environment (i.e., "white pollution" and "microplastic pollution"), damage soil structure, and hinder mechanical tillage⁶⁴. Fortunately, biodegradable film or straw mulching has similar properties to plastic film, and could take the place of conventional plastic film to ensure cleaner agricultural production in the future. Future studies should also evaluate the effects of U and CRU at different mixing ratios, focusing on tuber yield, GHG emissions, and carbon footprint under ridge-furrow with plastic film mulching, considering the present study included only one mixed ratio of U and CRU.

Conclusions

RM significantly decreased cumulative N_2O emissions and CH_4 uptake, but produced much higher NGWP when compared to NM. Among different urea types, the application of C was most significant in mitigating NGWP, which was mainly attributed to the reduced cumulative N_2O emissions and increased CH_4 uptake. However, the differences in cumulative N_2O emissions, CH_4 uptake, and NGWP were not significant between CU and U. In conclusion, the combined application of RM with CU (RMCU) not only helps achieve high yield and NEEB but also low CF for rainfed potato, which achieves a better balance between potato production and environmental benefits, was recommended as an efficient field management measure in dryland regions. Future studies should also evaluate the effects of U and CRU at different mixing ratios, focusing on tuber yield, GHG emissions, and carbon footprint under ridge-furrow with plastic film mulching. Furthermore, GHG emissions during fallow seasons may be measured and analyzed further to gain a comprehensive understanding of agricultural system emissions.

Received: 29 September 2022; Accepted: 6 December 2022

Published online: 10 March 2023

References

- Liu, C., Cutforth, H., Chai, Q. & Gan, Y. Farming tactics to reduce the carbon footprint of crop cultivation in semiarid areas. A review. *Agron. Sustain. Dev.* **36**(4), 69 (2016).
- Jath, M. L. *et al.* Climate change and agriculture: Adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. In *Advances in Agronomy* (ed. Sparks, D. L.) 127–235 (Academic Press, 2016).
- Yang, Y. *et al.* Winter tillage with the incorporation of stubble reduces the net global warming potential and greenhouse gas intensity of double-cropping rice fields. *Soil Tillage Res.* **183**, 19–27 (2018).
- Zheng, J. *et al.* Interactive effects of mulching practice and nitrogen rate on grain yield, water productivity, fertilizer use efficiency and greenhouse gas emissions of rainfed summer maize in northwest China. *Agric. Water Manage.* **248**, 106778 (2021).
- IPCC. *Climate Change 2014-Mitigation of Climate Change: Working Group I Contribution to the Fourth Assessment Report of the IPCC* Vol. 3 (Cambridge University Press, 2014).
- Lingling, L. *et al.* Evolution of soil and water conservation in rain-fed areas of China. *Int. Soil Water Conserv. Res.* **2**(1), 78–90 (2014).
- Wang, L. *et al.* The influence of nitrogen fertilizer rate and crop rotation on soil methane flux in rain-fed potato fields in Wuchuan County, China. *Sci. Total Environ.* **537**, 93–99 (2015).
- Li, Q. *et al.* Mulching improves yield and water-use efficiency of potato cropping in China: A meta-analysis. *Field Crops Res.* **221**, 50–60 (2018).
- Souza, E. F. C., Rosen, C. J. & Venterea, R. T. Co-application of DMP5A and NBPT with urea mitigates both nitrous oxide emissions and nitrate leaching during irrigated potato production. *Environ. Pollut.* **284**, 117124 (2021).
- Guo, J. *et al.* Synchronizing nitrogen supply and uptake by rainfed maize using mixed urea and slow-release nitrogen fertilizer. *Nutr. Cycl. Agroecosyst.* **122**(2), 157–171 (2022).
- Mo, F. *et al.* Yield-phenology relations and water use efficiency of maize (*Zea mays* L.) in ridge-furrow mulching system in semiarid east African Plateau. *Sci. Rep.* **7**(1), 3260 (2017).
- Liu, G. *et al.* Ridge-furrow with plastic film and straw mulch increases water availability and wheat production on the Loess Plateau. *Sci. Rep.* **8**(1), 6503 (2018).
- Wang, L. *et al.* Mulching-induced changes in tuber yield and nitrogen use efficiency in potato in China: A meta-analysis. *Agronomy* **9**(12), 1–15 (2019).
- Qin, S. *et al.* Effect of ridge-furrow and plastic-mulching planting patterns on yield formation and water movement of potato in a semi-arid area. *Agric. Water Manage.* **131**, 87–94 (2014).
- Ma, D. *et al.* Impacts of plastic film mulching on crop yields, soil water, nitrate, and organic carbon in Northwestern China: A meta-analysis. *Agric. Water Manage.* **202**, 166–173 (2018).
- Nan, W. G. *et al.* Effects of plastic film mulching on soil greenhouse gases (CO₂, CH₄ and N₂O) concentration within soil profiles in maize fields on the Loess Plateau, China. *J. Integr. Agric.* **15**(2), 451–464 (2016).
- Yu, Y. *et al.* A meta-analysis of film mulching cultivation effects on soil organic carbon and soil greenhouse gas fluxes. *CATENA* **206**, 105483 (2021).
- Ma, Q. J., Zhang, Q., Niu, J. & Gang Li, X. Plastic-film mulch cropping increases mineral-associated organic carbon accumulation in maize cropped soils as revealed by natural ¹³C/¹²C ratio signature. *Geoderma* **370**, 114350 (2020).
- Lee, J. G. *et al.* Different response of plastic film mulching on greenhouse gas intensity (GHGI) between chemical and organic fertilization in maize upland soil. *Sci. Total Environ.* **696**, 133827 (2019).
- Liu, J. *et al.* Response of nitrous oxide emission to soil mulching and nitrogen fertilization in semi-arid farmland. *Agric. Ecosyst. Environ.* **188**, 20–28 (2014).
- Li, Z. *et al.* Effects of plastic film mulching with drip irrigation on N₂O and CH₄ emissions from cotton fields in arid land. *J. Agric. Sci.* **152**(4), 534–542 (2014).
- Zhang, Y., Liu, D., Jia, Z. & Zhang, P. Ridge and furrow rainfall harvesting can significantly reduce N₂O emissions from spring maize fields in semiarid regions of China. *Soil Tillage Res.* **209**, 104971 (2021).
- Zhang, W. *et al.* The effects of controlled release urea on maize productivity and reactive nitrogen losses: A meta-analysis. *Environ. Pollut.* **246**, 559–565 (2019).
- Godfray, H. C. J. *et al.* Food security: The challenge of feeding 9 billion people. *Sci.* **327**(5967), 812–818 (2010).
- Grant, C. A. *et al.* Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. *Field Crops Res.* **127**, 170–180 (2012).
- Cambouris, A. N. *et al.* Potato response to nitrogen sources and rates in an irrigated sandy soil. *Agron. J.* **108**(1), 391–401 (2016).
- Zheng, T., Liang, Y., Ye, S. & He, Z. Superabsorbent hydrogels as carriers for the controlled-release of urea: Experiments and a mathematical model describing the release rate. *Biosyst. Eng.* **102**(1), 44–50 (2009).
- Li, C. *et al.* Impact of irrigation and fertilization regimes on greenhouse gas emissions from soil of mulching cultivated maize (*Zea mays* L.) field in the upper reaches of Yellow River, China. *J. Clean. Prod.* **259**, 120873 (2020).
- Guo, J. *et al.* Growth, grain yield, water and nitrogen use efficiency of rainfed maize in response to straw mulching and urea blended with slow-release nitrogen fertilizer: A two-year field study. *Arch. Agron. Soil Sci.* **68**(11), 1554–1567 (2022).
- Akiyama, H., Yan, X. & Yagi, K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N₂O and NO emissions from agricultural soils: Meta-analysis. *Glob. Change Biol.* **16**(6), 1837–1846 (2010).
- Venterea, R. T., Hyatt, C. R. & Rosen, C. J. Fertilizer management effects on nitrate leaching and indirect nitrous oxide emissions in irrigated potato production. *J. Environ. Qual.* **40**(4), 1103–1112 (2011).
- Tang, L. *et al.* Response of maize productivity and resource use efficiency to combined application of controlled-release urea and normal urea under plastic film mulching in semiarid farmland. *Agron. J.* **111**(6), 3194–3206 (2019).
- Farmaha, B. S. & Sims, A. L. The influence of polymer-coated urea and urea fertilizer mixtures on spring wheat protein concentrations and economic returns. *Agron. J.* **105**(5), 1328 (2013).
- Zheng, W. *et al.* Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system. *Field Crops Res.* **197**, 52–62 (2016).
- Tang, L., Li, S. & Shen, Y. Response of maize yield and nitrogen leaching to combining controlled-release urea and normal urea under different surface mulching. *J. Sci. Food Agric.* **101**(13), 5520–5528 (2021).
- Zheng, W. *et al.* Developing water and nitrogen budgets of a wheat-maize rotation system using auto-weighting lysimeters: Effects of blended application of controlled-release and un-coated urea. *Environ. Pollut.* **263**, 114383 (2020).
- Zhang, L. *et al.* Integrated assessment of agronomic, environmental and ecosystem economic benefits of blending use of controlled-release and common urea in wheat production. *J. Clean. Prod.* **287**, 125572 (2021).
- Guo, J. *et al.* Blending urea and slow-release nitrogen fertilizer increases dryland maize yield and nitrogen use efficiency while mitigating ammonia volatilization. *Sci. Total Environ.* **790**, 148058 (2021).
- Bai, J. *et al.* Straw returning and one-time application of a mixture of controlled release and solid granular urea to reduce carbon footprint of plastic film mulching spring maize. *J. Cleaner Prod.* **280** (2021).
- Ma, B. *et al.* Exploring soil amendment strategies with polyacrylamide to improve soil health and oat productivity in a dryland farming ecosystem: One-time versus repeated annual application. *Land Degrad. Dev.* **31**(9), 1176–1192 (2020).

41. Fang, H. *et al.* Optimizing the impact of film mulching pattern and nitrogen application rate on maize production, gaseous N emissions, and utilization of water and nitrogen in northwest China. *Agric. Water Manage.* **261**, 107350 (2022).
42. Cui, Z. L. *et al.* Closing the yield gap could reduce projected greenhouse gas emissions: A case study of maize production in China. *Glob. Change Biol.* **19**(8), 2467–2477 (2013).
43. Ye, L., Qi, C., Hong, J. & Ma, X. Life cycle assessment of polyvinyl chloride production and its recyclability in China. *J. Clean. Prod.* **142**, 2965–2972 (2017).
44. Wang, Z. *et al.* Lowering carbon footprint of winter wheat by improving management practices in North China Plain. *J. Clean. Prod.* **112**, 149–157 (2016).
45. Li, B. *et al.* Combined effects of nitrogen fertilization and biochar on the net global warming potential, greenhouse gas intensity and net ecosystem economic budget in intensive vegetable agriculture in southeastern China. *Atmos. Environ.* **100**, 10–19 (2015).
46. Le Mer, J. & Roger, P. Production, oxidation, emission and consumption of methane by soils: A review. *Eur. J. Soil Biol.* **37**(1), 25–50 (2001).
47. Zhang, D. *et al.* Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. *Chemosphere* **142**, 106–113 (2016).
48. Wang, H. *et al.* Grain yield and greenhouse gas emissions from maize and wheat fields under plastic film and straw mulching: A meta-analysis. *Field Crops Res.* **270**, 108210 (2021).
49. Chen, H. *et al.* Effects of straw and plastic film mulching on greenhouse gas emissions in Loess Plateau, China: A field study of 2 consecutive wheat–maize rotation cycles. *Sci. Total Environ.* **579**, 814–824 (2017).
50. Gao, B. *et al.* Nitrous oxide and methane emissions from optimized and alternative cereal cropping systems on the North China Plain: A two-year field study. *Sci. Total Environ.* **472**, 112–124 (2014).
51. Aronson, E. L. & Helliker, B. R. Methane flux in non-wetland soils in response to nitrogen addition: A meta-analysis. *Ecology* **91**(11), 3242–3251 (2010).
52. Zheng, J. *et al.* Wheat straw mulching with nitrification inhibitor application improves grain yield and economic benefit while mitigating gaseous emissions from a dryland maize field in northwest China. *Field Crops Res.* **265**, 108125 (2021).
53. Li, N. *et al.* Plastic film mulching mitigates the straw-induced soil greenhouse gas emissions in summer maize field. *Appl. Soil Ecol.* **162**, 103876 (2021).
54. Vilain, G., Garnier, J., Decuq, C. & Lugnot, M. Nitrous oxide production from soil experiments: Denitrification prevails over nitrification. *Nutr. Cycl. Agroecosyst.* **98**(2), 169–186 (2014).
55. Akhtar, K. *et al.* Straw mulching with inorganic nitrogen fertilizer reduces soil CO₂ and N₂O emissions and improves wheat yield. *Sci. Total Environ.* **741**, 140488 (2020).
56. Berger, S., Kim, Y., Kettering, J. & Gebauer, G. Plastic mulching in agriculture: Friend or foe of N₂O emissions?. *Agric. Ecosyst. Environ.* **167**, 43–51 (2013).
57. Wang, S. *et al.* Effect of split application of nitrogen on nitrous oxide emissions from plastic mulching maize in the semiarid Loess Plateau. *Agr. Ecosyst. Environ.* **220**, 21–27 (2016).
58. Liu, X. *et al.* Comparing ammonia volatilization between conventional and slow-release nitrogen fertilizers in paddy fields in the Taihu Lake region. *Environ. Sci. Pollut. Res.* **27**(8), 8386–8394 (2020).
59. Meier, E. A. *et al.* Greenhouse gas emissions from cropping and grazed pastures are similar: A simulation analysis in Australia. *Front. Sustain. Food Syst.* **3**, 121 (2020).
60. Song, Q. *et al.* Effect of straw retention on carbon footprint under different cropping sequences in Northeast China. *Environ. Sci. Pollut. Res.* **28**(39), 54792–54801 (2021).
61. Liu, Y. *et al.* Net global warming potential and greenhouse gas intensity from the double rice system with integrated soil–crop system management: A three-year field study. *Atmos. Environ.* **116**, 92–101 (2015).
62. Jat, S. L. *et al.* Energy auditing and carbon footprint under long-term conservation agriculture-based intensive maize systems with diverse inorganic nitrogen management options. *Sci. Total Environ.* **664**, 659–668 (2019).
63. Xiong, L. *et al.* Carbon footprint and yield performance assessment under plastic film mulching for winter wheat production. *J. Clean. Prod.* **270**, 122468 (2020).
64. Li, C. & Li, S. Energy budget and carbon footprint in a wheat and maize system under ridge furrow strategy in dry semi humid areas. *Sci. Rep.* **11**(1), 9367 (2021).
65. Yadav, G. S. *et al.* Energy budget and carbon footprint in a no-till and mulch based rice–mustard cropping system. *J. Clean. Prod.* **191**, 144–157 (2018).
66. Lal, B. *et al.* Energy and carbon budgeting of tillage for environmentally clean and resilient soil health of rice–maize cropping system. *J. Clean. Prod.* **226**, 815–830 (2019).
67. Fan, M. *et al.* Effects of mulching on soil CO₂ fluxes, hay yield and nutritional yield in a forage maize field in Northwest China. *Sci. Rep.* **9**(1), 14186 (2019).

Acknowledgements

This work was supported by the Inner Mongolia "Grassland Talent" Innovation Team, the National Outstanding Talents in Agricultural Research and their Science and Technology Innovation Team.

Author contributions

M.Y.S. Conceptualization, Methodology, Writing-original draft. J.H.L. Guided the experiment and helped to modify the manuscript. B.M. Writing-review & editing, Supervision. P.N.L. Created the figures, Investigation. J.H.B. Performed language corrections. J.Z.M. Reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-022-25845-4>.

Correspondence and requests for materials should be addressed to J.L.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2023