Journal of Plant Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/lpla20

Slow but sure: the potential of slow-release nitrogen fertilizers to increase crop productivity and farm profit in Nepal

Naba Raj Pandit, Yam Kanta Gaihre, Dyutiman Choudhary, Roshan Subedi, Surya Bahadur Thapa, Shashish Maharjan, Dinesh Khadka, Shree Prasad Vista & Leonard Rusinamhodzi

To cite this article: Naba Raj Pandit, Yam Kanta Gaihre, Dyutiman Choudhary, Roshan Subedi, Surya Bahadur Thapa, Shashish Maharjan, Dinesh Khadka, Shree Prasad Vista & Leonard Rusinamhodzi (2022): Slow but sure: the potential of slow-release nitrogen fertilizers to increase crop productivity and farm profit in Nepal, Journal of Plant Nutrition, DOI: 10.1080/01904167.2022.2067053

To link to this article: https://doi.org/10.1080/01904167.2022.2067053

JOURNAL OF PLANT NUTRITION
https://doi.org/10.1080/01904167.2022.2067053

Taylor & Francis
Taylor & Francis Group

Slow but sure: the potential of slow-release nitrogen fertilizers to increase crop productivity and farm profit in Nepal

Naba Raj Pandit[a], Yam Kanta Gaihre[b], Dyutiman Choudhary[a], Roshan Subedi[a], Surya Bahadur Thapa[a], Shashish Maharjan[a], Dinesh Khadka[c], Shree Prasad Vista[c], and Leonard Rusinamhodzi[d]

[a]International Maize and Wheat Improvement Center (CIMMYT), 1st Floor, National Plant Breeding and Genetics Research Center, NARC Research Station, Lalitpur, Nepal; [b]International Fertilizer Development Center (IFDC), 1st Floor, National Plant Breeding and Genetics Research Center, NARC Research Station, Lalitpur, Nepal; [c]National Soil Science Research Center (NSSRC), Lalitpur, Nepal; [d]International Institute of Tropical Agriculture (IITA), CSIR Campus, Accra, Ghana

ABSTRACT
Reduction of nitrogen (N) input in cropping systems is critical to reduce environmental pollution and achieve sustainable development goals. Multi-location field trials for maize ($n = 120$) and rice ($n = 84$) were conducted across nine districts in Nepal during 2018 and 2019 to assess the potential of polymer coated urea (PCU) and urea briquette (UB) to increase agronomic N use efficiency (AE_N), crop productivity and farm profits over conventional urea (CU). Nitrogen rates applied in PCU and UB treatments were 22% to 50% lower than CU (120 and 100 kg N ha^{-1} for maize and rice respectively). In maize, both PCU (8.4 t ha^{-1}) and UB (8.5 t ha^{-1}) applied at 50% and 25% lower N rates respectively produced similar grain yields compared with CU (7.9 t ha^{-1}). Similar results were observed in rice where PCU and UB applied at 22% less N led to a productivity of 5.4 and 5.5 t ha^{-1} respectively over CU (5.1 t ha^{-1}). Moreover, both PCU and UB increased maize and rice yields significantly compared with current farmer's practices (FP). In both maize and rice, PCU and UB significantly increased partial factor productivity of N (PFP_N) and agronomic NUE (AE_N) compared with CU. Furthermore, PCU and UB increased farmer's net income by US$88 and US$148 in maize and by US$10 and US$87 in rice respectively. These results suggest that PCU and UB could save N input by 22-50% while maintaining similar or even higher yield and higher benefit to farmers compared with CU.

ARTICLE HISTORY
Received 4 May 2021
Accepted 3 December 2021

KEYWORDS
crop productivity; maize; Nepal; nitrogen use efficiency; polymer coated urea; rice; urea briquette

Introduction

Rice (*Oryza sativa L.*) and maize (*Zea mays L.*) are two major food crops in Nepal. Although these crops are cultivated across different geographic regions ranging from terai (lowland) to hills (upland), most rice is cultivated in the terai and maize in the mid-hills. Current production is not enough to meet domestic demand leading to large imports of grains for food and feed every year. The national average productivity of both rice (3.76 t ha^{-1}) and maize (2.84 t ha^{-1}) is lower compared with other South Asian countries (Devkota et al. 2016; Gadal et al. 2019). Lower crop productivity is mainly caused by declining soil fertility, imbalanced fertilization (too much N

CONTACT Naba Raj Pandit N.PANDIT@cgiar.org International Maize and Wheat Improvement Center (CIMMYT), 1st Floor, National Soil Science Research Center (NSSRC), NARC Research Station, Lalitpur, Nepal

Supplemental data for this article can be accessed online at http://dx.doi.org/10.1080/01904167.2022.2067053

compared to K and no or less use of micronutrients), low fertilizer use efficiency and poor farmer's awareness on improved crop management practices, among others (Baral, Pande, Gaihre, et al. 2020).

There is an urgent need to increase the productivity of cereal crops to meet the country's food security target. One of the strategies to increase crop productivity is the efficient use of fertilizers, particularly nitrogen (N) fertilizers. Farmers are not following the existing recommendations, they apply relatively higher amounts of N fertilizers, lower to medium P fertilizers and very low to a negligible amounts of K fertilizer leading to large yield gaps and lower fertilizer use efficiency (Devkota et al. 2018). The imbalanced use does not directly lead to high crop yields but rather reduces nitrogen use efficiency (NUE) and farm profit (Chen et al. 2020). The yield gap is much larger under rainfed management conditions, where crop yield are often less than 50% of potential yield (Lobell, Cassman, and Field 2009). Moreover, farmers often use urea as a single application as a basal fertilization, which results in low NUE due to increased losses from ammonia volatilization, surface runoff and leaching. Globally, the average NUE of cereal crops is 30-40%, particularly when conventional urea is applied through the surface broadcast method (Savant and Stangel 1990; Ladha et al. 2005). Thus, it is important to increase NUE along with the adoption of the best crop management practices to close these yield gaps (Jat et al. 2013; Devkota et al. 2016).

In recent years, several studies have focused on increasing NUE through different strategies including the use of slow and controlled release N fertilizers (SRF_N) such as fertilizers with nitrification inhibitors (Rose et al. 2018), coated fertilizers such as polymer coated urea (PCU) (Geng et al. 2016; Chen et al. 2020; Abd El-Aziz et al. 2021), sulphur-coated urea (SCU) (Pooniya et al. 2018), and improved application method such as urea briquette (UB) deep placement (Gaihre et al. 2015; Agyin-Birikorang et al. 2018). These alternate fertilizers sources are gaining popularity to meet crop nutrient demand, increase farm profitability and reduce environmental pollution including emissions of greenhouse gas (GHG) compared with conventional granular urea (Gaihre et al. 2015; Snyder 2017; Abd El-Aziz et al. 2019; Abd El-Aziz et al. 2021). However, the long-term use of SRF_N such as PCU can leave the residual polymer in the soil after exhausting N, which are non-degradable taking longer time for microbial decomposition (Lu et al. 2016). Considering the soil health and microbial activities, PCU with bio-degradable polymer coatings is preferable (Lu et al. 2016). In contrast, polymers in soil can have a beneficial effect on soil fertility due to their high water and nutrient retention capacity (Dvořáčková et al. 2018). SRF_N are often applied once (single application) as a basal fertilizer, thus, saves time and labor required for split application compared with conventional urea (Zheng et al. 2016). However, the cost of SRF_N products is relatively higher compared with conventional urea (Trenkel 1997). Despite high costs, use of SRF_N could increase net returns as a result of reduced labor cost (single application), higher NUE (reduce health and environmental cost) and increased crop yield (Gagnon, Ziadi, and Grant 2012; Zheng et al. 2016; Wang et al. 2020).

The benefits of using PCU and UB fertilizers over conventional urea in increasing yields, NUE and saving nitrogen across range of crops and management conditions are well documented in previous studies (Gaihre et al. 2015; Geng et al. 2016; Agyin-Birikorang et al. 2018). To the best of our knowledge, no study has assessed the effects of these SRF_N fertilizers on crop productivity, NUE and farm profits under the conditions of Nepal. Therefore, we conducted multi-locational field trials of maize and rice across nine districts (Surkhet, Dang, Doti, Palpa, Kavre, Banke, Bardiya, Kailali and Kanchanpur) to determine the potential of PCU and UB on increasing productivity and agronomic NUE in Nepal. The specific objectives of the study were to:

- Identify the effects of PCU and UB on grain yield, agronomic NUE and economic return of maize and rice compared with the application of conventional granular urea (CU).

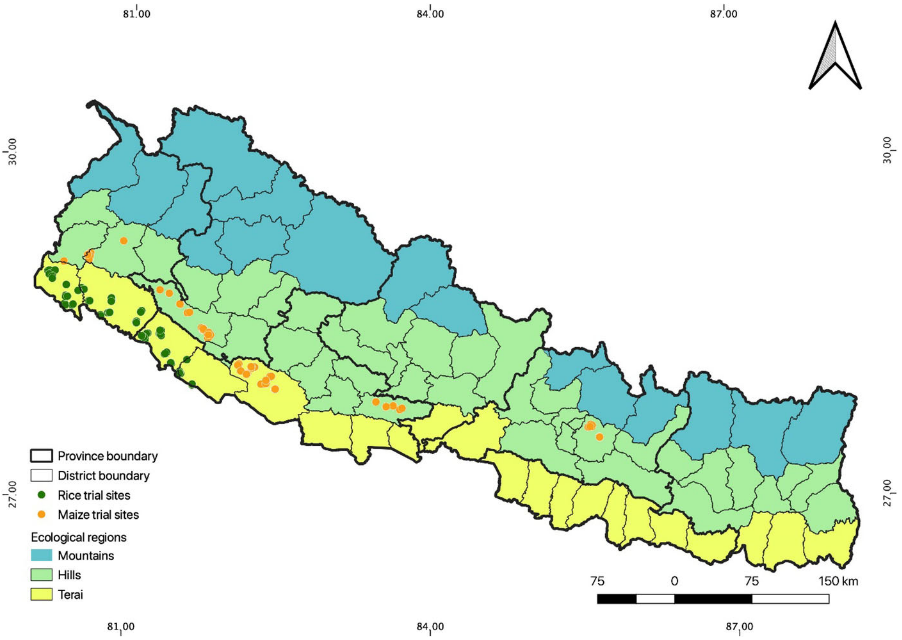

Figure 1. Map showing the location of maize and rice field trials across nine districts in Nepal. Source: Department of Survey, Nepal.

- Identify farmers nutrient management practices (FP) i.e., the rate of NPK fertilizers used by the farmers across the districts and assess the potential of PCU and UB to increase crop productivity and economic return compared with FP.

Materials and methods

Study sites and weather conditions

Field trials for maize were established in mid-hills (sub-tropical climate) across five districts viz. Dang, Surkhet, Doti, Palpa and Kavre with an average altitude of 580, 557, 1332, 1300 and 2512 MSL respectively during 2018-2019 (Figure 1). Similarly, rice trials were established in terai (tropical climate) across four districts viz. Banke, Bardiya, Kailali and Kanchanpur with an average altitude of 89, 117, 112, 134 MSL, respectively during 2018-2019 (Figure 1). The dominant cropping systems in maize trial sites were maize (April-September) - vegetables *(Brassica oleraca, Solanum lycopersicum)* and maize - wheat (November-March). The dominant cropping system in rice trial sites was rice (June-November) and *Triticum aestivum* (November-April).

In 2018, during the maize growing season, average minimum and maximum temperatures were 18.3 °C (ranges from 15.7 to 22.1 °C) and 29.2 (ranges from 25.1 to 33.9.1 °C), respectively (Figure 2). During the second year (2019), minimum (20.0 ± 1.0 °C) and maximum temperature (30.5 ± 0.8 °) ranges from 16.5 to 23.9 °C and from 26.1 to 34.2 °C, respectively. The average total rainfall was 1477 ± 6 (ranging from 1095 to 1657 mm) and 1294 ± 5 (ranging from 966 to 1394 mm) during the year 2018 and 2019 respectively (Figure 2). Both temperature and rainfall were observed lowest in Doti and highest in Dang districts.

During the rice-growing season, the average minimum and maximum temperature ranged from 20.6 to 22.3 °C and from 30.1 to 32.8 °C. in the year 2018 (Figure 2). A similar trend on minimum and maximum temperature was recorded during the second year 2019. The average total rainfall was

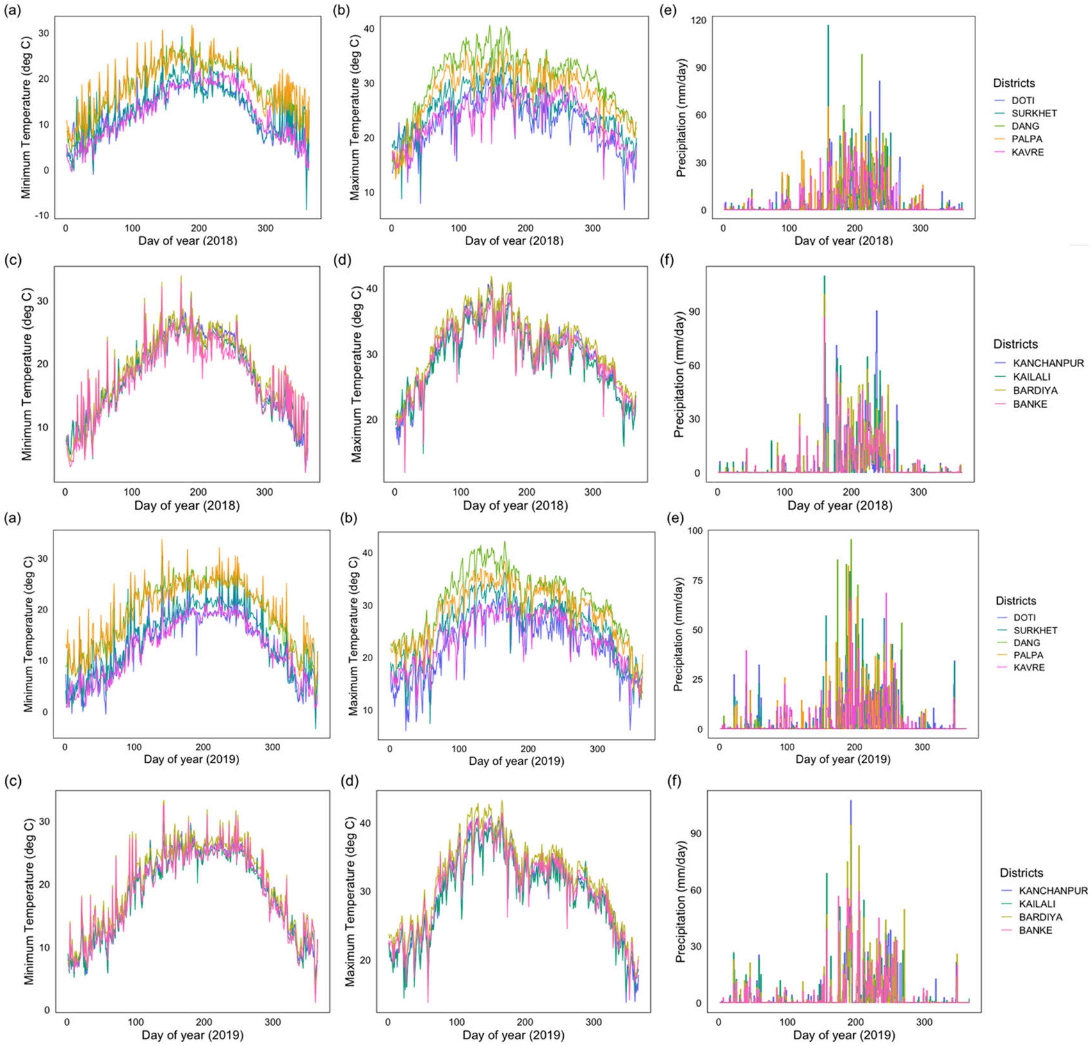

Figure 2. Annual minimum, maximum temperatures and precipitation of maize (a, b, e) and rice (c, d, f) trial location across the districts for the year 2018 and 2019. Temperature and rainfall data were extracted from National Oceanic and Atmospheric Administration (NOAA; *https://psl.noaa.gov*) and rainfall estimates from Rain Gauze and Satellite Observations (CHIRPS; *ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0*) respectively.

1494 ± 20 (ranging from 1170 to 1674 mm) and 1229 ± 14 (ranging from 1046 to 1374 mm) during the year 2018 and 2019 respectively, with the lowest rainfall observed at Banke district (Figure 2).

Soil sampling and analysis

Quadruplicate soil samples (0-15 cm depth) from different portions considering the heterogeneity of each plot were collected and pooled into one composite sample for each plot for the analysis. Soil samples were oven-dried at 40 °C for three days, passed through a 2 mm sieve and analyzed for soil pH, organic matter (OM), texture, total N, available P_2O_5 and K_2O by visible-near-infrared diffuse reflectance spectroscopy (VisNIR-DRS) (Table 1). About 20% of the samples were analyzed through wet chemistry to calibrate, build a partial least square regression (PLSR) model, and determine the soil physiochemical properties through spectroscopy. Soils were characterized

Table 1. Soil characterization across the study area for maize and rice trials (mean ± SE).

Districts	Texture (%)			Textural Class[1]	pH	OM	Total N	Available P	Available K
	Sand	Silt	Clay			%	%	(mg kg^{-1})	(mg kg^{-1})
Maize trials									
Surkhet (n = 24)	40 ± 2	45 ± 1	15 ± 1	loam	6.41 ± 0.06 b	2.44 ± 0.10 b	0.13 ± 0.01ab	52.31 ± 4.2a	134.04 ± 8.70a
Dang (n = 22)	42 ± 1	37 ± 1	21 ± 0	loam	6.51 ± 0.03 b	2.67 ± 0.10 b	0.15 ± 0.01 b	56.51 ± 4.78a	140.68 ± 11.01a
Doti (n = 6)	46 ± 1	38 ± 2	16 ± 1	loam	5.90 ± 0.14a	3.02 ± 0.51 b	0.18 ± 0.03 b	105.29 ± 40.87 b	160.02 ± 24.02ab
Palpa (n = 8)	44 ± 2	41 ± 1	15 ± 1	loam	6.50 ± 0.1 b	3.01 ± 0.21 b	0.15 ± 0.01 b	38.10 ± 8.30a	234.00 ± 32.90c
Kavre (n = 8)	45 ± 1	38 ± 1	17 ± 1	loam	5.89 ± 0.02a	1.60 ± 0.04a	0.09 ± 0.01a	66.51 ± 11.91ab	199.58 ± 24.10bc
Rice trials									
Banke (n = 6)	35 ± 2	35 ± 2	30 ± 1	Clay loam	6.65 ± 0.07a	1.70 ± 0.12a	0.10 ± 0.00a	33.21 ± 6.42a	88.56 ± 4.80a
Bardiya (n = 13)	40 ± 2	40 ± 1	20 ± 1	Loam	6.84 ± 0.10a	2.05 ± 0.12a	0.11 ± 0.00a	32.54 ± 3.57a	73.20 ± 5.98a
Kailali (n = 15)	29 ± 3	48 ± 4	23 ± 2	Loam	6.69 ± 0.09a	1.80 ± 0.09a	0.10 ± 0.00a	30.39 ± 2.15a	77.66 ± 4.04a
Kanchanpur (n = 12)	30 ± 2	31 ±	37 ± 2	Clay loam	6.90 ± 0.11a	2.03 ± 0.13a	0.10 ± 0.00a	26.53 ± 2.58a	69.59 ± 4.97a
Analysis method	(Bouyoucos 1936)				H_2O	(Walkley & Black 1934)	Kjeldhal method	Modified Olsen bicarbonate	Flame photometric

1USDA soil textural classification.

Table 2. Description about the treatments of maize and rice field trials across the districts for the year 2018 and 2019.

Treatment	Description	N	P_2O_5	K_2O	CU/PCU/UB[1]	DAP/SSP[2]	MOP[3]	CU/PCU/UB	DAP/SSP	MOP
			Kg ha^{-1}			Kg ha^{-1}			g plot^{-1}	
Maize										
T1	Control (CK)	0	0	0	0	0	0	0	0	0
T2	N omission (N0)	0	60	40	0	375	67	0	937.5	167
T3	Conventional urea (CU)	120	60	40	205	130	67	525	326	167
T4	Polymer coated urea (PCU)	60	60	40	100	130	67	263	326	167
T5	Urea briquette (UB)	90	60	40	145	130	67	362	326	167
T6	Farmers practice (FP)									
Rice										
T1	Control (CK)	0	0	0	0	0	0	0	0	0
T2	N omission (N0)	0	30	30	0	187	50	0	374	50
T3	Conventional urea (CU)	100	30	30	192	65	50	384	130	100
T4	Polymer coated urea (PCU)	78	30	30	144	65	50	288	130	100
T5	Urea briquette (UB)	78	30	30	144	65	50	288	130	100
T6	Farmers practice (FP)									

[1] CU and UB contains 46% N and PCU contains 44% N. Amount of CU, PCU and UB after deduction of N from DAP supply (18% N).

[2] DAP contains 46% P_2O_5 and 18% N, SSP contains 16% P_2O_5

[3] MOP contains 60% K_2O

as loamy soil for maize sites (mid-hills) and loam (Bardiya and Kailali) to clay loam (Banke and Kanchanpur) for rice trial sites. Across the maize trial sites, soil pH ranges from 5.9 to 6.5, OM from 1.6 to 3.0%, total N from 0.09 to 0.14%, available P_2O_5 from 38.1 to 105.3 mg kg^{-1} and available K_2O from 134.0 to 234.0 mg kg^{-1}. Similarly, soil pH ranges from 6.6 to 6.9, OM from 1.7 to 2.0%, total N from 0.10 to 0.11%, available P from 26.5 to 33.2 mg kg^{-1} and available K from 69.5 to 88.5 mg kg^{-1} respectively across rice trial sites.

Treatments and experimental design

A total of 204 field trials which consisted of 120 for maize (April-May) and 84 for rice (June-July) were conducted during 2018 and 2019. For maize, out of 120 trials, 40 trials were established in Surkhet, 34 in Dang, 16 in Doti, 16 in Palpa and 14 in Kavre, respectively. Out of 84 trials in rice, 12 trials were conducted in Banke, 23 in Bardiya, 27 in Kailali and 22 in Kanchanpur, respectively. In each district, cooperatives dealing primarily with fertilizer procurement and distribution were selected purposively and experiments were conducted in farmer's fields by selecting three farmers ($n = 3$) from each cooperative.

For both maize and rice, six treatments including control (CK), N omission (N0), recommended conventional urea (CU), polymer coated urea (PCU, 44%N, 90 days release; PUREKOTE^{TM}, Pursell Agri-Tech LLC, AL 35150, USA), urea briquette (UB) and farmers nutrient management practice (FP), were arranged in a randomized block design in each farmer's field. Each farm was considered as a replication. In CU treatment, N was applied at the rate of 120 and 100 kg N ha^{-1} for maize and rice respectively. In PCU and UB, N was applied at the rate of 60 and 78 kg N ha^{-1} for maize and 90 and 78 kg N ha^{-1} for rice respectively, which is 22-50% less N compared to CU treatment considering higher NUE of those fertilizers (Gaihre et al. 2015; Agyin-Birikorang et al. 2018). The N0 treatment was used only in 2018 to identify if N was the limiting soil nutrient for maize and rice across the study districts. The size of the treatment plot for maize and rice was 25 m^2 (5 m × 5 m) and 20 m^2 (5 m × 4 m), respectively. Phosphorus (P_2O_5) and potassium (K_2O) fertilizers were applied at the existing recommended rates and the same for all treatments for both maize (60:60 kg P_2O_5: K_2O ha^{-1}) and rice (30:30 kg P_2O_5: K_2O ha^{-1}). Detail description of the treatments along with the fertilizer amount applied in each plot is shown in Table 2.

For the FP treatment, fertilizer rates and crop yields were obtained from a farmers' survey and crop-cut method across field trial sites. Farmers were interviewed to identify their fertilizer application rates at each experimental site by using a structured questionnaire administered via open data kit (ODK). The crop cut method involves yield estimation of farmers field by dividing the plot into different subplots and harvesting the crop, keeping the record of production and area under crop (Fermont and Benson 2011). During the crop cuts, three quadrats of 1 m^2 area (3 m^2 in total) were selected randomly from neighboring farms of trial sites and harvested. For maize, 72 crop cuts were performed in 2018 (Dang [n = 23], Surkhet [n = 26], Doti [n = 6], Palpa [n = 8] and Kavre [n = 9]. In 2019, grain yields were recorded from farmers' survey (n = 76). For rice, 69 crop cuts (48 in 2018 and 21 in 2019) were performed in Banke (n = 12), Bardiya (n = 21), Kailali (n = 21) and Kanchanpur (n = 15) districts.

Crop management

For land preparation, each plot was plowed two to three times with moldboard plow. For maize, a full dosage of phosphorus (DAP), potassium (MOP), and zinc (Zinc sulfate) was applied 5-7 cm apart from the seed sowing line and 5 cm below soil surface. While for rice, fertilizers were broadcasted manually using a precision earth way spreader (Park et al. 2018). In N0 plot, SSP (16% P_2O_5) was applied to ensure zero N input. Micronutrients B (1.7 kg ha^{-1}) and Zn (7.0 kg ha^{-1}) were applied in the form of $ZnSO_4.H_2O$ and Borax, respectively.

Hybrid maize variety with a seed rate of 25 kg ha^{-1} was sown at a depth of 5 cm with a spacing of 75 cm × 25 cm following line sowing methods, while 2-3 rice seedlings (20-25 days old) per hill were transplanted at the distance of 20 cm × 20 cm. In the UB treatment, UB of 2.7 g was applied at a depth of 7-10 cm (deep placement technology) as a single application during planting for maize and after 7-10 days after transplanting for rice (Agyin-Birikorang et al. 2018; Gaihre et al. 2015). Similarly, PCU was applied once during planting for both crops. Regular urea was top-dressed at two equal splits for both maize and rice in the CU treatment. Urea was applied as a top-dressing at 30 days after sowing (~ knee height) and 60 days after sowing (~ shoulder height stages), respectively in maize. Similarly, in rice, urea was top-dressed at tillering (21 days after transplantation) and panicle initiation stages (50 days after transplantation), respectively. Maize was grown under rainfed conditions and rice with the irrigated system. For rice, floodwater depth was maintained to 2 cm until panicle initiation stages and up to 5 cm from panicle initiation stage to one week before harvest. Weeding was carried out twice for both maize (30 and 60 days after sowing) and rice (20 and 40 days after transplantation). Other agronomical practices such as control of pests and diseases were consistent for all treatments and performed as and when needed.

Measurement of grain yields and nitrogen use efficiency

At maturity, both maize and rice crop were harvested from each plot. Harvesting was done manually by cutting stems at 2-5 cm above the soil surface (15-20% grain moisture percentage) excluding 50 cm the border. In each plot, maize and rice were harvested from three quadrants of 1 m^2 area (3 m^2 in total). The moisture content of grain was measured with a grain moisture meter, and moisture-corrected grain yield was recorded adjusting the moisture content at 14%.

NUE was calculated for CU, PCU and UB as partial factor productivity of N (PFP_N) and agronomic N use efficiency (AE_N) as shown in equations 1 and 2.

$$PFP_N = Y_N/F_N. \qquad \text{Eq. (1)}$$

$$AE_N = (Y_N - Y_0)/F_N. \qquad \text{Eq. (2)}$$

where, Y_N is crop yield with applied nitrogen (kg ha^{-1}), Y_0 is the crop yield without nitrogen fertilizer, F_N is the amount of N applied (kg ha^{-1}).

Economic analysis

Economic analysis was performed based on the agronomic results obtained from the field trials and FP survey, calculating total variable cost (TVC), income from crop sale and gross margin (GM) (Devkota et al. 2016; Pandit, Mulder, Hale, Zimmerman, et al. 2018). TVC includes the cost of seed, fertilizers and labor required for fertilizer application and other agronomical practices such as weeding, pest management and harvesting (Tables S1 and S2). TVC and farm gate price of the crop was used based on local market price. The selling price of maize and rice was US\$219 t^{-1} and US\$182 t^{-1}) respectively. For FP, the cost for seed and fertilizers across the districts was calculated based on the seed rate and fertilizer amount used by farmers (Tables S1 and S2). The gross margin for each treatment was calculated as the differences of income from crop sale and TVC (GM = Return from crop sale - TVC) (Pandit, Mulder, Hale, Zimmerman, et al. 2018).

Statistical analysis

Data were analyzed using R statistical software, version 3.6.2. A two-way fixed effect linear ANOVA model (model I) was used to evaluate the effect of treatments, sites (district) and their interactions on crop yields. The model was reduced, omitting the interactions (treatment × district) that did not show significant effect on crop yield (model II). One factor ANOVA (model III) was used to assess the effect of CU, PCU and UB on N use efficiencies (PFP_N and AE_N). Model assumption (normal distribution and homogenous of variance) was tested through basic diagnostic plots (Normal Q-Q and fitted vs residuals plots). Significant differences between treatment means of crop yield and PFP_N or AE_N were evaluated through a post hoc Tukey test ($p = 0.05$). The difference between various treatments was significant at $p < 0.05$, unless stated otherwise. Multiple linear regression model (model IV) was used to assess the effect of soil factors (continuous explanatory variables) i.e., pH, OM, total N, and available P and K on crop yield. Regression model was reduced (model V) omitting the soil factors, which did not show a significant effect on crop yield. The aforementioned model (model I to V) equation and their assumptions for ANOVA and multiple regression are presented in the supplementary information (Description S1).

Results

Farmers' fertilizer management practice

In general, farmers across maize sites (mid-hills) applied lower amounts of NPK fertilizers compared with recommended fertilizer practice (RP) i.e., 120:60:40 kg N P_2O_5 K_2O ha^{-1} (Figure 3a–c). Nitrogen use in maize was 30% less than the RP (120 kg N ha^{-1}), except in Kavre district (Figure 3a). The use of potassium fertilizer was very low to negligible across the districts. Farmers did not use any fertilizers in the Doti district. Similarly, farmer's fertilizer use across rice trial sites was lower than the RP (100:30:30 kg N P_2O_5 K_2O ha^{-1}) except in Banke districts (Figure 3d–f). The rate of N fertilizer use was approximately 80% of the RP, while the rate of K fertilizer use was 10-60% of the RP. In both maize (Figure 3b) and rice trial sites (Figure 3e), farmers applied P fertilizer close to the recommended rate. The amount of fertilizer used by farmers across the study districts is shown in Figure 3.

Crop productivity

Both N source and site characteristics (district) exerted significant effects on maize grain yield, but their interaction was not significant. Across the years, application of PCU (8.4 ± 0.2 t ha^{-1}) and UB (8.5 ± 0.2 t ha^{-1}) produced a similar grain yield compared with CU (7.9 ± 0.2 t ha^{-1}) (Figure 4a). Both PCU (8.4 ± 0.2 t ha^{-1}) and UB (8.5 ± 0.2 t ha^{-1}) produced significantly higher grain yields compared with FP (6.0 ± 0.1 t ha^{-1}) (Figure 4a, Figure S1).

Similarly, N source and site characteristics had a significant effect on rice grain yields, but their interaction effect was not significant. PCU (5.5 ± 0.1 t ha^{-1}) and UB (5.6 ± 0.1 t ha^{-1}) produced similar grain yields compared with CU (5.1 ± 0.1 t ha^{-1}) for both years (Figure 5a). In comparison with FP (4.0 ± 0.1 t ha^{-1}), PCU and UB increased rice yield significantly by 38% and 40% respectively (Figure S1).

Nitrogen use efficiency - PFP_N and AE_N

In maize, across the districts and years, both PCU and UB increased PFP_N and AE_N significantly compared with CU (Table 3). PCU increased PFP_N ranging from 105 to 172 and AE_N from 22 to 82 kg grain kg^{-1} N, which is an average increase of 113% and 147%, respectively compared with CU (ranging from 54 to 76 and 13 to 27 kg kg^{-1} for PFP_N and $AE_{N,}$ respectively). Similarly, UB increased PFP_N (76 to 113 kg kg^{-1}) and AE_N (22 to 68 kg kg^{-1}) by 73% and 43% over CU, respectively.

In rice, across the years, both PCU and UB showed higher PFP_N and AE_N compared with CU (Table 3). Across the locations, PCU and UB increased PFP_N from 62 to 79 kg kg^{-1}, which is an average increase of 38% compared to CU (39 to 62 kg kg^{-1}) (Table 3). Similarly, AE_N was increased by 46% (17 to 44 kg kg^{-1}) with the use of PCU and UB over CU.

Economic benefits

Average gross margin (GM) aggregated from all districts was observed highest for UB application for both maize (US$1339) and rice crop (US$473) (Figure 6). Gross margin disaggregated by districts for maize (Table S1) and rice (Table S2) can be found in the supplementary information.

In maize, UB and PCU increased GM by 13% (US$1339) and 7% (US$1279) respectively compared to CU (US$1191) (Figure 6a). Furthermore, UB and PCU increased average GM by 45% and 39% respectively over FP (US$919).

Similarly, in rice, GM was increased by 23% (US$473) and 3% (US$397) with the use of UB and PCU respectively over CU (US$386) (Figure 6b). GM was increased by 131% and 94% with UB and PCU respectively over FP (US$203).

Discussion

Effect of PCU and UB on crop productivity

Application of PCU reduced N fertilizer use by 22-50%, while maintaining or increasing crop yields compared to CU (Figures 4 and 5). For rice, our results are consistent with previous studies (Geng et al. 2016; Chen et al. 2020). They reported similar rice grain yield with the use of 20-30% less N fertilizer compared with the split application of conventional granular urea. Xie et al. (2019) reported a similar maize grain yield with the use of PCU applied at 20% less N compared with normal urea (100% N). Increased grain yield despite the lower amount of fertilizer is due to the continuous availability of N as PCU releases N slowly. As PCU is coated with polymeric resin, which dissolves in soils very slowly, the rate of N release synchronizes with the plant's

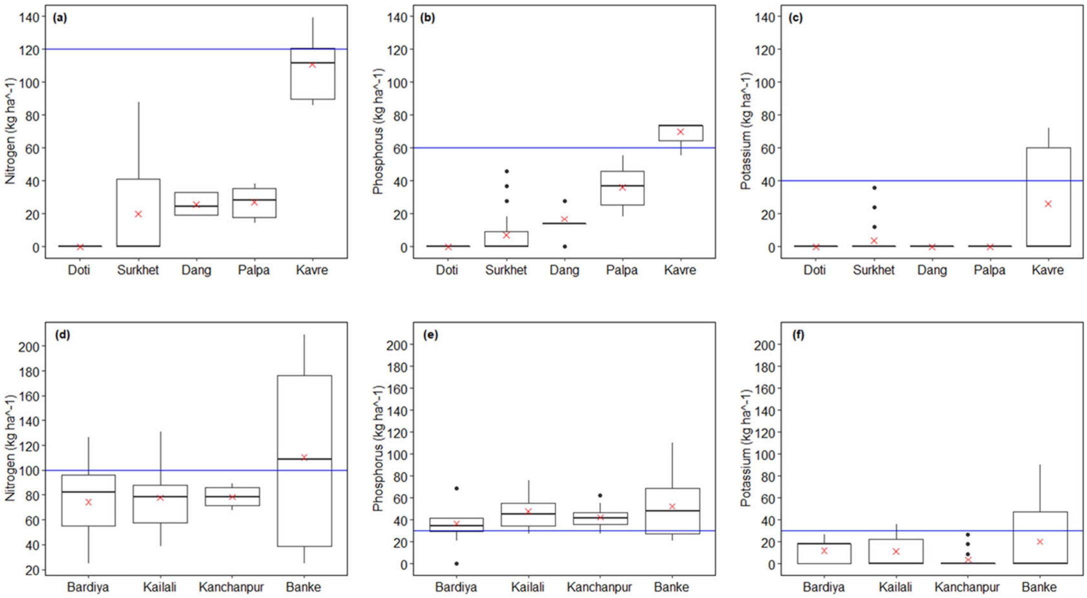

Figure 3. NPK fertilizers used by farmers for maize (figure; a, b and c) and rice (figure; d, e and f) across the districts. Sign (×) in the middle of the boxplot refer to the average amount of NPK fertilizers used by farmers. Blue horizontal line in each graph represents the existing recommended rate of fertilizers in Nepal.

physiological requirement (Trenkel 1997; Wang et al. 2020). Due to synchrony between N supply and plant demand, plant N uptake increases leading to increased grain yields (Geng et al. 2016; Wang et al. 2018; Chen et al. 2020).

UB showed a similar magnitude of crop yield as PCU over recommended conventional urea application (Figures 4 and 5). In accordance with this, a recent study conducted by Baral, Pande, Gaihre, et al. (2020) reported similar rice yields with UB applied at a 22% less N rate compared with the recommended conventional urea practice. Our results are in close agreement with previous studies (Huda et al. 2016; Islam et al. 2016). Moreover, Adu-Gyamfi et al. (2019) and Agyin-Birikorang et al. (2018) reported similar maize yield with the use of UB applied at 25% less N compared with normal urea (100% N). In another study by Derrick, Etienne, and Mathusalem (2017), UB with 20% less nitrogen even showed significantly higher maize yield (25%) compared with conventional urea. Improved crop yield with less N input through UB is associated with a continuous supply of N as per plant demand as explained above. When N is deep placed in subsurface soils, N could be retained in the plant's root zone for a longer period and plant can avail N as and when needed (Agyin-Birikorang et al. 2018; Siddique et al. 2020; Wang et al. 2020).

Yield response to added N varied across districts, the response on maize grain yield was lower in Doti and Dang compared with other districts (Figure 4). This is possibly due to higher soil fertility which is evident from OM, total N and available P, all of them were higher in Doti and Dang compared with other districts (Table 1). Generally, fertilizer response is lower in fertile soils compared to soils with poor soil fertility (Vanlauwe et al. 2010). Among these soil properties, soil OM had shown a positive response on maize yield, particularly in Doti (R^2= 0.74) and Dang (R^2= 0.44) (Figure S2). In contrast, maize yield was not correlated with OM and other soil properties in other districts (results not shown). In rice, soil properties were distributed uniformly across the districts (Table 1) and a significant response of N addition (responsive soils) on crop yield was observed in all the districts.

In addition to fertilizer N source, the effect of location was significant on grain yields. Lower crop productivity was observed in Palpa (maize) and Banke (rice) compared with other districts (Figure 7). In Palpa, lower maize yield compared with other districts could be due to lower soil

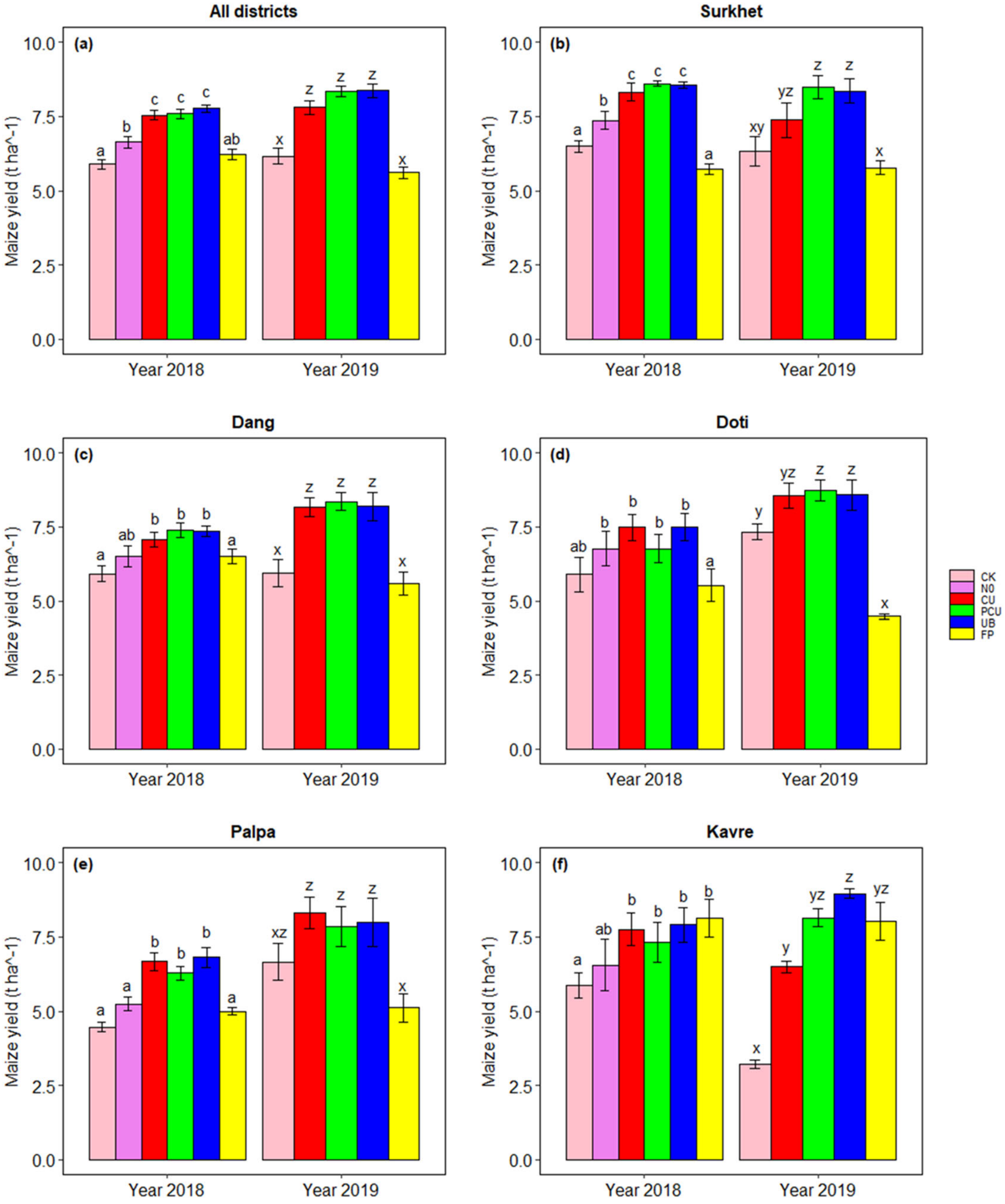

Figure 4. Maize yield (mean ± SE) in response to PCU and UDP across five districts (Surkhet, Dang, Doti, Palpa and Kavre) in 2018 and 2019. Different letters inside a bar and within a year represents significant difference at 5% probability level (post hoc-Tukey test, $p < 0.05$).

available P_2O_5 (Table 1). These results are in close agreement with previous studies where maize yield increased with available P_2O_5 (50-70 mg kg^{-1}) in a similar agroecological domains of Nepal (Pandit, Mulder, Hale, Martinsen, et al. 2018). In Banke, soil nutrient status was in the optimum range for rice production as observed for other districts (Table 1), thus, there could be other bio-physical factors (rainfall and temperature) influencing the crop yield (Lobell, Cahill, and Field

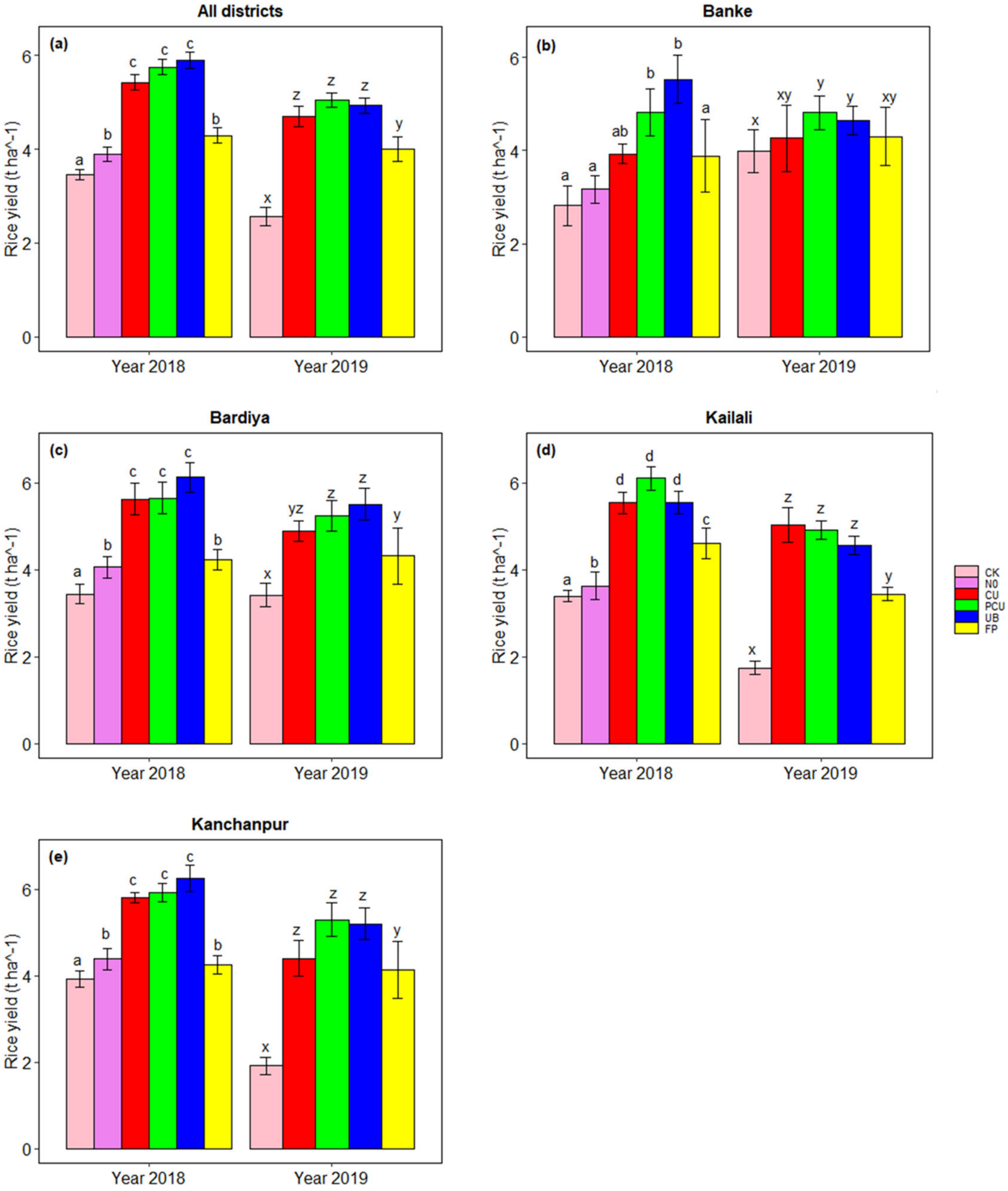

Figure 5. Rice yield (mean ± SE) in response to PCU and UDP across four districts (Banke, Bardiya, Kailali and Kanchanpur) in 2018 and 2019. Different letters inside a bar and within a year represents significant differences at 5% probability level (post hoc-Tukey test, $p < 0.05$).

2007). Average temperature and rainfall were lower in Banke compared with other districts, which might have resulted in reduced crop productivity. Similar results were reported by Cabas, Weersink, and Olale (2010), crop yield was increased with warmer temperature and higher rainfall.

Yields recorded in fertilized plots were much higher when compared with farmers' practices. Both PCU and UB applications showed significantly higher crop yields compared to FP in both

Table 3. Partial factor productivity of N (PFP_N) and agronomic N use efficiency (AE_N) in maize and rice across different N source treatments in 2018 and 2019. PFP_N and AE_N values are given as mean ± SE. Within a column and districts, means followed by different letters are significantly different at 5% probability level.

Maize (n = 120)					Rice (n = 84)				
	Year 2018 (n = 75)		Year 2019 (n = 45)			Year 2018 (n = 48)		Year 2019 (n = 36)	
Treatments	PFP_N	AE_N	PFP_N	AE_N	Treatments	PFP_N	AE_N	PFP_N	AE_N
All districts	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	**All districts**	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}	kg kg^{-1}
CU	63 ± 1a	16 ± 1a	71 ± 2a	23 ± 2a	CU	56 ± 2a	22 ± 1a	47 ± 2a	23 ± 2a
PCU	130 ± 3c	36 ± 2 b	156 ± 5c	58 ± 5 b	PCU	74 ± 2 b	31 ± 2a	65 ± 2 b	33 ± 3a
UB	87 ± 2 b	25 ± 1ab	104 ± 3 b	41 ± 4 b	UB	75 ± 2 b	31 ± 2a	64 ± 2 b	32 ± 3a
Surkhet					**Banke**				
CU	69 ± 1a	18 ± 1a	70 ± 4a	26 ± 3a	CU	39 ± 2a	13 ± 3a	42 ± 7a	8 ± 3a
PCU	143 ± 2c	35 ± 3 b	172 ± 9c	67 ± 8 b	PCU	62 ± 6 b	31 ± 8a	62 ± 7a	17 ± 4a
UB	96 ± 1 b	23 ± 2ab	113 ± 6 b	42 ± 6ab	UB	71 ± 7bc	28 ± 10a	60 ± 3a	12 ± 1a
Dang					**Bardiya**				
CU	59 ± 2a	13 ± 2a	76 ± 5a	27 ± 6a	CU	62 ± 7a	28 ± 3a	49 ± 2a	14 ± 1a
PCU	126 ± 6c	38 ± 4 b	156 ± 9c	60 ± 9 b	PCU	72 ± 5a	28 ± 3a	67 ± 4ab	21 ± 5a
UB	84 ± 2 b	22 ± 3ab	100 ± 6 b	35 ± 7ab	UB	79 ± 4a	39 ± 5a	79 ± 5 b	26 ± 4a
Doti					**Kailali**				
CU	62 ± 4a	18 ± 4a	75 ± 4a	15 ± 3a	CU	55 ± 2a	21 ± 2a	50 ± 4a	21 ± 2a
PCU	113 ± 8c	22 ± 6a	155 ± 6c	37 ± 6 b	PCU	78 ± 3 b	35 ± 3bc	63 ± 3a	35 ± 3a
UB	84 ± 5 b	23 ± 4a	105 ± 6 b	28 ± 6ab	UB	71 ± 3 b	28 ± 3ab	58 ± 3a	28 ± 3a
Palpa					**Kanchanpur**				
CU	55 ± 3a	18 ± 2 a	72 ± 4a	16 ± 7a	CU	58 ± 1a	18 ± 2a	44 ± 4a	25 ± 5a
PCU	105 ± 4c	31 ± 4 b	131 ± 11 b	35 ± 7 b	PCU	76 ± 3 b	28 ± 4a	68 ± 5a	44 ± 7a
UB	76 ± 4 b	26 ± 3ab	99 ± 9 b	28 ± 9ab	UB	75 ± 4 b	26 ± 4a	67 ± 4 b	42 ± 3a
Kavre									
CU	66 ± 5a	18 ± 3a	54 ± 1a	27 ± 2a					
PCU	141 ± 13 b	50 ± 9c	136 ± 5c	82 ± 6 b					
UB	91 ± 7a	34 ± 4bc	102 ± 3 b	68 ± 5 b					

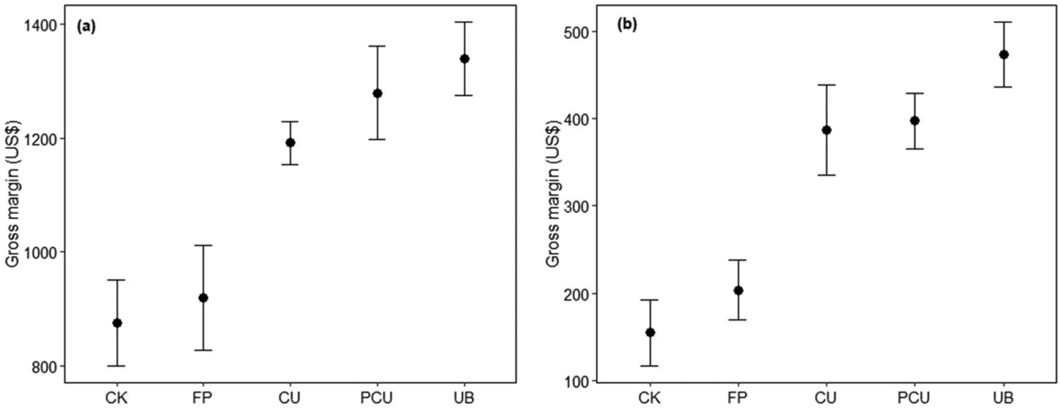

Figure 6. Average gross margin (mean ± SE) in different fertilizer treatments across districts (n = 9) in maize (A) and rice crop (B).

years (Figures 4 and 5). PCU and UB increased maize yield by 47% and 49% respectively compared with FP (Figure 4, Figure S1). Similar results were reported by Adu-Gyamfi et al. (2019), where maize yield was increased by more than 50% with the use of UB compared with the current farmers practices. The lower yields in FP were mainly attributed to less use of fertilizers by farmers. In maize, the average N application rate by farmer was about 1/3rd of recommended rate, which is in a similar range previously reported by Devkota et al. (2018) in the mid-hills region, Nepal. However, for rice in the terai region, applied N is close (20% less N) to the government recommended rate (100 kg N ha^{-1}). Farmers in the terai region apply a

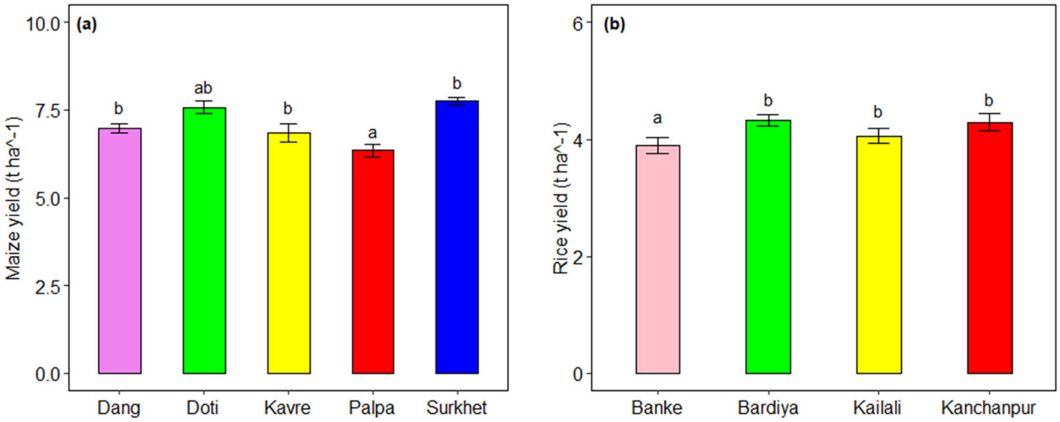

Figure 7. Average maize (A) and rice (B) productivity (mean ± SE) across the field trials districts. Different letters above the bar represents significant differences at 5% probability level (post hoc-Tukey test, $p < 0.05$).

higher amount of fertilizers compared to hill farmers in most of the agricultural activities (Takeshima et al. 2016; Devkota et al. 2018). These results suggest that the application of N in the form PCU and UB has a higher potential to raise the yield level and reduce the yield gap of both maize and rice.

Effect of PCU and UB on agronomic NUE

Our results clearly illustrated that PCU and UB improved PFP_N and AE_N compared with CU in both crops (Table 3). These results are corroborated with previous studies (Geng et al. 2016; Agyin-Birikorang et al. 2018; Baral, Pande, Gaihr, et al. 2020; Chen et al. 2020). In maize, Geng et al. (2016) reported that PCU with 30% less N increased PFP_N and AE_N of maize by 43% and 37%, respectively over granular urea. Increased NUE was due to synchrony between N supply and plant demand, increasing plant uptake and reducing N losses to the environment (Geng et al. 2016; Wang et al. 2018; Chen et al. 2020). Chen et al. (2020) reported that PCU saved 20% N input and increased agronomic NUE from 15 to 84% without any yield penalty.

Increased agronomic NUE through UB is due to its root zone application, which can retain N for prolonged periods as explained above. Agyin-Birikorang et al. (2018) reported an increased AE_N with the use of UB in maize by 57% over granular urea. Similarly, Baral, Pande, Gaihre, et al. (2020) reported increased PFP_N and AE_N by 44% and 34% with the use of UB (22% less N input) respectively in rice compared with government recommended conventional urea (100 kg N ha^{-1}).

In this study, increased NUE (expressed as PFP_N and AE_N) in maize and rice indicates that the use of both PCU and UB can reduce a significant amount of N losses from plant-soil system to the environment, which is corroborated with several previous studies (Geng et al. 2016; Agyin-Birikorang et al. 2018; Adu-Gyamfi et al. 2019; Baral, Pande, Gaihre, et al. 2020; Chen et al. 2020). Generally, NUE of granular urea is 20-35% (Naz and Sulaiman 2016), which can be reduced further drastically with poor fertilizer management practices resulting up to 92% N lost from the system mainly through leaching, volatilization, nitrification/denitrification and runoff (Chen et al. 2008). A higher amount of N losses from the soil-plant system can have a negative impact on environment such as groundwater contamination and downstream water pollution and tropospheric pollution (N_2O emissions) contributing to global warming and climate change (Zhang et al. 2015; Wang et al. 2020).

Economic benefits

Our results confirm that the application of PCU and UB in both maize and rice could be more profitable compared with CU and FP (Figure 6). Application of PCU and UB could increase farmers' profits due to increased yields and reduced N inputs compared with CU (Figures 4 and 5). This is mainly due to single-time application (basal application) with reduced N rates, which saves fertilizer cost, time and labor compared with split application of conventional urea (Zheng et al. 2016; Wang et al. 2020). In accordance with this Zheng et al. (2016) reported that the application of controlled-release urea (33% less N input) increased gross margin from 14.5 to 19.9% while maintaining the same level of yield in maize compared with conventional urea (100% N). Similarly, Xie et al. (2019) reported that the reduced N input (30% N) with PCU could be one of the most cost-effective solutions fetching comparable returns for maize farming. Moreover, Adu-Gyamfi et al. (2019) reported that the application of UDP with 25% less N input in maize resulted in the greatest increase in gross margin by 46%, which was 18% higher compared with conventional urea (100% N). Similarly, Rahman and Barmon (2015) reported the increased economic return with the application of UDP (BC ratio of 1.36) in rice over conventional urea (BC ratio of 1.17) in Bangladesh.

Conclusions

This study suggests that the application of PCU and UB in rice and maize production could be agronomically and economically viable above the recommended conventional urea (CU). Compared with the conventional split application of urea, PCU and UB could reduce the amount of N fertilizers while maintaining or increasing grain yields. This suggests that the use of PCU and UB can be a sustainable approach to N management and has the potential in reducing the yield gap of both crops. Moreover, both PCU and UB can improve agronomic nitrogen use efficiencies attributing to lower N losses from the soil-plant systems, illustrating their potential role in reducing the environmental pollution. However, long-term studies with N mass balance calculation are needed to provide a better insight into N losses from soil-plant system and their impacts on soil fertility. As fertilizer procurement and distribution is controlled by the Government of Nepal, and as both the products are new to Nepal, their availability should be assured for making a wider recommendation. If farmers' adoption increases, there will be a reduction in N fertilizer use resulting in the reduction in subsidy burden to the government, farm-level savings, and a better environment.

Acknowledgements

The United States Agency for International Development (USAID) provided support for this research through "Feed the Future Nepal Seed and Fertilizer Project (Cooperative Agreement number AID-367-IO-16-00001)." Polymer coated urea and urea briquette were provided by IFDC through "Feed the Future Soil Fertility Technology Adoption, Policy Reform and Knowledge Management (Cooperative Agreement Number AID-BFS-IO-15-00001)." We thank cooperatives members/volunteers across the district for their support in selecting farmers field to conduct the trials. We would like to thank our field staff Mr. Roshan Shah, Mr. Uttam Kunwar, Mr. Dilli Chalisey, Mr. Resham KC, Mr. Rajendra Upadhyaya, Mr. Kedar Nath Nepal and Mrs. Srijana Poudel for their practical assistance to monitor and manage the field trials.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Naba Raj Pandit http://orcid.org/0000-0002-2140-7024
Dyutiman Choudhary http://orcid.org/0000-0001-5803-7015
Shree Prasad Vista http://orcid.org/0000-0002-9008-7001

Authors contribution

Naba Raj Pandit: Conceptualization, Methodology, Data curation, Formal analysis, Writing-Original draft**.** **Yam Kanta Gaihre:** Conceptualization, Supervision, Writing-Review & editing. **Dyutiman Choudhary:** Conceptualization, Supervision, Writing-Review & editing, Funding acquisition. **Roshan Subedi:** Investigation, Resources. **Surya Thapa:** Investigation, Resources. **Shashish Maharjan:** Software, Formal analysis. **Dinesh Khadka:** Resources, Formal analysis. **Shree Prasad Vista:** Resources, Writing-Review & editing. **Leonard Rusinamhodzi:** Conceptualization, Supervision, Writing-Review & editing.

References

Abd El-Aziz, M. E., D. M. Salama, S. M. M. Morsi, A. M. Youssef, and M. El-Sakhawy. 2021. Development of polymer composites and encapsulation technology for slow-release fertilizers. *Reviews in Chemical Engineering*. https://doi.org/10.1515/revce-2020-0044

Abd El-Aziz, M. E., S. M. M. Morsi, D. M. Salama, M. S. Abdel-Aziz, M. S. Abd Elwahed, E. A. Shaaban, and A. M. Youssef. 2019. Preparation and characterization of chitosan/polyacrylic acid/copper nanocomposites and their impact on onion production. *International Journal of Biological Macromolecules* 123:856–65. doi: 10.1016/j.ijbiomac.2018.11.155.

Adu-Gyamfi, R., S. Agyin-Birikorang, I. Tindjina, S. M. Ahmed, A. D. Twumasi, V. K. Avornyo, and U. Singh. 2019. One-time fertilizer briquettes application for maize production in Savanna agroecologies of Ghana. *Agronomy Journal*. 111 (6):3339–50. doi: 10.2134/agronj2019.04.0292.

Agyin-Birikorang, S., J. H. Winings, X. Yin, U. Singh, and J. Sanabria. 2018. Field evaluation of agronomic effectiveness of multi-nutrient fertilizer briquettes for upland crop production. *Nutrient Cycling in Agroecosystems* 110 (3):395–406. doi: 10.1007/s10705-018-9905-y.

Baral, B. R., K. R. Pande, Y. K. Gaihr, K. R. Baral, S. K. Sah, and Y. B. Thapa. 2020. Farmers' fertilizer application gap in ricebased cropping system: A case study of Nepal. *SAARC Journal of Agriculture* 17 (2):267–77. doi: 10.3329/sja.v17i2.45311.

Baral, B. R., K. R. Pande, Y. K. Gaihre, K. R. Baral, S. K. Sah, Y. B. Thapa, and U. Singh. 2020. Increasing nitrogen use efficiency in rice through fertilizer application method under rainfed drought conditions in Nepal. *Nutrient Cycling in Agroecosystems* 118 (1):103–12. doi: 10.1007/s10705-020-10086-6.

Cabas, J., A. Weersink, and E. Olale. 2010. Crop yield response to economic, site and climatic variables. *Climatic Change*. 101 (3-4):599–616. doi: 10.1007/s10584-009-9754-4.

Chen, D., H. Suter, A. Islam, R. Edis, J. R. Freney, and C. N. Walker. 2008. Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: A review of enhanced efficiency fertilisers. *Soil Research* 46 (4): 289–301. doi: 10.1071/SR07197.

Chen, Z., Q. Wang, J. Ma, P. Zou, and L. Jiang. 2020. Impact of controlled-release urea on rice yield, nitrogen use efficiency and soil fertility in a single rice cropping system. *Scientific Reports* 10 (1):1–10. doi: 10.1038/s41598-020-67110-6.

Derrick, B. E., I. Etienne, and K. Mathusalem. 2017. Comparative study of urea in prilled and briquette forms on rice production in Marshlands of Rwanda. *Journal of Fertilizers & Pesticides* 8:178.

Devkota, K. P., A. J. McDonald, L. Khadka, A. Khadka, G. Paudel, and M. Devkota. 2016. Fertilizers, hybrids, and the sustainable intensification of maize systems in the rainfed mid-hills of Nepal. *European Journal of Agronomy* 80:154–67. doi: 10.1016/j.eja.2016.08.003.

Devkota, K. P., M. Devkota, L. Khadka, A. Khadka, G. Paudel, S. Acharya, and A. J. McDonald. 2018. Nutrient responses of wheat and rapeseed under different crop establishment and fertilization methods in contrasting agro-ecological conditions in Nepal. *Soil and Tillage Research*. 181:46–62. doi: 10.1016/j.still.2018.04.001.

Dvořáčková, H., P. H. González, J. Záhora, and R. S. R. Sinoga. 2018. The effect of Hydropolymers on soil microbial activities in Mediterranean areas. *Rev MVZ Córdoba* 23 (1):6414–28. [Mismatch

Fermont, A., and T. Benson. 2011. Estimating yield of food crops grown by smallholder farmers. *International Food Policy Research Institute, Washingt DC* 1:68.

Gadal, N., J. Shrestha, M. N. Poudel, and B. Pokharel. 2019. A review on production status and growing environments of rice in Nepal and in the world. *Archives of Agriculture and Environmental Science* 4 (1):83–7. doi: 10.26832/24566632.2019.0401013.

Gagnon, B., N. Ziadi, and C. Grant. 2012. Urea fertilizer forms affect grain corn yield and nitrogen use efficiency. *Canadian Journal of Soil Science* 92 (2):341–51. doi: 10.4141/cjss2011-074.

Gaihre, Y. K., U. Singh, S. M. M. Islam, A. Huda, M. R. Islam, M. A. Satter, J. Sanabria, R. Islam Md, and A. L. Shah. 2015. Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. *Geoderma* 259–260:370–9. doi: 10.1016/j.geoderma.2015.06.001.

Geng, J., J. Chen, Y. Sun, W. Zheng, X. Tian, Y. Yang, C. Li, and M. Zhang. 2016. Controlled release urea improved nitrogen use efficiency and yield of wheat and corn. *Agronomy Journal* 108 (4):1666–73. doi: 10.2134/agronj2015.0468.

Huda, A., Y. K. Gaihre, M. R. Islam, U. Singh, R. Islam Md, J. Sanabria, M. A. Satter, H. Afroz, A. Halder, and M. Jahiruddin. 2016. Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. *Nutrient Cycling in Agroecosystems* 104 (1):53–66. doi: 10.1007/s10705-015-9758-6.

Islam, S. M. M., Y. K. Gaihre, A. L. Shah, U. Singh, M. I. U. Sarkar, M. A. Satter, J. Sanabria, and J. C. Biswas. 2016. Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh. *Nutrient Cycling in Agroecosystems* 106 (2):143–56. doi: 10.1007/s10705-016-9795-9.

Jat, M. L., T. Satyanarayana, K. Majumdar, C. M. Parihar, S. L. Jat, J. P. Tetarwal, and R. K. Jat. 2013. Fertiliser best management practices for maize systems. *Journal of Agricultural and Resource Economics* 36 (4):80–94.

Ladha, J. K., H. Pathak, T. J. Krupnik, J. Six, and C. van Kessel. 2005. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advanes in Agronomy* 87:85–156.

Lobell, D. B., K. G. Cassman, and C. B. Field. 2009. Crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources*. 34:179–204.

Lobell, D. B., K. N. Cahill, and C. B. Field. 2007. Historical effects of temperature and precipitation on California crop yields. *Climatic Change*. 81 (2):187–203. doi: 10.1007/s10584-006-9141-3.

Lu, P., Y. Zhang, C. Jia, Y. Li, and Z. Mao. 2016. Use of polyurea from urea for coating of urea granules. *SpringerPlus* 5 (1):1–6. doi: 10.1186/s40064-016-2120-x.

Naz, M. Y., and S. A. Sulaiman. 2016. Slow release coating remedy for nitrogen loss from conventional urea: A review. *Journal of Controlled Release: Official Journal of the Controlled Release Society* 225:109–20. doi: 10.1016/j.jconrel.2016.01.037.

Pandit, N. R., J. Mulder, S. E. Hale, A. R. Zimmerman, B. H. Pandit, and G. Cornelissen. 2018. Multi-year double cropping biochar field trials in Nepal: Finding the optimal biochar dose through agronomic trials and cost-benefit analysis. *Science of the Total Environment* 637:1333–1341.

Pandit, N. R., J. Mulder, S. E. Hale, V. Martinsen, H. P. Schmidt, and G. Cornelissen. 2018. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil. *Science of the Total Environment* 625:1380–1389.

Park, A. G., A. J. McDonald, M. Devkota, and A. S. Davis. 2018. Increasing yield stability and input efficiencies with cost-effective mechanization in Nepal. *Field Crops Research* 228:93–101. doi: 10.1016/j.fcr.2018.08.012.

Pooniya, V., Y. S. Shivay, M. Pal, and R. Bansal. 2018. Relative performance of boron, sulphur and zinc coatings onto prilled urea for increasing productivity and nitrogen use efficiency in maize. *Experimental Agriculture* 54 (4):577–91. doi: 10.1017/S0014479717000254.

Rahman, S., and B. K. Barmon. 2015. Productivity and efficiency impacts of Urea Deep Placement technology in modern rice production: An empirical analysis from Bangladesh. *The Journal of Developing Areas* 49 (3):119–34. doi: 10.1353/jda.2015.0158.

Rose, T. J., R. H. Wood, M. T. Rose, and L. Van Zwieten. 2018. A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. *Agriculture Ecosystems and Environment*. 252:69–73. doi: 10.1016/j.agee.2017.10.008.

Savant, N. K., and P. J. Stangel. 1990. Deep placement of urea supergranules in transplanted rice: Principles and practices. *Fertilizer Research* 25 (1):1–83. doi: 10.1007/BF01063765.

Siddique, I. A., A. Al Mahmud, M. Hossain, M. R. Islam, Y. K. Gaihre, and U. Singh. 2020. Movement and retention of NH 4-N in wetland rice soils as affected by urea application methods. *Journal of Soil Science and Plant Nutrition* 20 (2):589. doi: 10.1007/s42729-019-00148-2.

Snyder, C. S. 2017. Enhanced nitrogen fertiliser technologies support the '4R'concept to optimise crop production and minimise environmental losses. *Soil Research* 55 (6):463–72. doi: 10.1071/SR16335.

Takeshima, H. R. P. Adhikari, B. D. Kaphle, S. Shivakoti, and A. Kumar. 2016. *Determinants of chemical fertilizer use in Nepal: Insights based on price responsiveness and income effects*. [place unknown]: Intl Food Policy Res Inst.

Trenkel, M. E. 1997. *Controlled-release and stabilized fertilizers in agriculture*. [place unknown]: International Fertilizer Industry Association Paris.

Vanlauwe, B., A. Bationo, J. Chianu, K. E. Giller, R. Merckx, U. Mokwunye, O. Ohiokpehai, P. Pypers, R. Tabo, K. D. Shepherd, et al. 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39 (1):17–24. doi: 10.5367/000000010791169998.

Wang, C., J. Lv, J. A. Coulter, J. Xie, J. Yu, J. Li, J. Zhang, C. Tang, T. Niu, and Y. Gan. 2020. Slow-release fertilizer improves the growth, quality, and nutrient utilization of wintering Chinese Chives (Allium tuberosum Rottler ex Spreng.). *Agronomy* 10 (3):381. doi: 10.3390/agronomy10030381.

Wang, L., C. Xue, X. Pan, F. Chen, and Y. Liu. 2018. Application of controlled-release urea enhances grain yield and nitrogen use efficiency in irrigated rice in the Yangtze River basin, China. *Frontiers in Plant Science* 9:999. doi: 10.3389/fpls.2018.00999.

Xie, Y., L. Tang, Y. Han, L. Yang, G. Xie, J. Peng, C. Tian, X. Zhou, Q. Liu, X. Rong, et al. 2019. Reduction in nitrogen fertilizer applications by the use of polymer-coated urea: effect on maize yields and environmental impacts of nitrogen losses. *Journal of the Science of Food and Agriculture* 99 (5):2259–66. doi: 10.1002/jsfa.9421.

Zhang, X., E. A. Davidson, D. L. Mauzerall, T. D. Searchinger, P. Dumas, and Y. Shen. 2015. Managing nitrogen for sustainable development. *Nature* 528 (7580):51–9. doi: 10.1038/nature15743.

Zheng, W., M. Zhang, Z. Liu, H. Zhou, H. Lu, W. Zhang, Y. Yang, C. Li, and B. Chen. 2016. Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system. *Field Crops Research* 197:52–62. doi: 10.1016/j.fcr.2016.08.004.