Experimental Agriculture (2022), vol. 58, e18, 1–16
doi:10.1017/S0014479722000187

CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Narrowing maize yield gaps in the rainfed plateau region of Odisha

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(Received 15 November 2021; revised 21 April 2022; accepted 02 May 2022)

Abstract

Maize is the primary staple crop cultivated during the monsoon season in eastern India. However, yield gaps are large because of multiple factors, including low adoption rates of good agronomic management practices. This study aimed to narrow the maize yield gap using diverse agronomic and varietal interventions through field experiments over 2 years (2013–2014) in the rainfed plateau region of Odisha. As a result, maize yield increased by 0.9, 0.74, and 0.17 Mg ha^{-1} under optimum plant population, fertilizer management, and herbicide-based weed management, respectively, over farmers' current practices (Check). Moreover, when all three interventions were combined ('best' management practice), grain yields increased by 1.7 Mg ha^{-1} in conservation tillage and 2.2 Mg ha^{-1} in conventional tillage. We also observed that the combination of long-duration hybrids and best management practices (BMPs) increased grain yield by 4.0 Mg ha^{-1} and profitability by \$888 ha^{-1} over farmers' current practices. In addition, Nutrient Expert decision support tool-based fertilizer management along with BMPs increased grain yield by 1.7 Mg ha^{-1} and profitability by \$314 ha^{-1} over farmers' fertilizer practices (Check). These results suggest that the combination of maize hybrids and BMPs can improve the productivity and profitability of rainfed maize in the plateau region of Odisha. However, these entry points for intensification need to be placed in the context of varying investment requirements, input and output market conditions, and matched with farmer preferences and risk.

Keywords: Decision support tool; Maize hybrids; Nutrient Expert; Sustainable intensification; Weed management; Yield gap

Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated crops and plays a vital role in meeting world food and feed demand (FAO, 2018). India is the sixth-largest producer of maize in the world, and maize contributes 10% to the Indian dietary energy supply (Kumar *et al.*, 2013). In India, maize is the third most important crop after rice and wheat, grown on 9.0 million hectares with broad adaptability to many soil types and agro-climatic conditions (Kumar *et al.*, 2013). During the monsoon season in the plateau region of Odisha, rice is grown in the lowlands of the landscape toposequence with maize and other grain staples grown in the uplands (Pradhan *et al.*, 2016). In the rainfed uplands, a common cropping system is maize followed by short-duration mustard (*Brassica juncea* L.) if residual moisture is sufficient and then a long fallow period during the dry season (Ray *et al.*, 2016).

The average maize yield in the state of Odisha is low; 2.2 Mg ha^{-1} with hybrids and 1.3 Mg ha^{-1} with open-pollinated varieties (Agriculture Statistics, 2014). This low productivity is associated with nutrient-depleted lateritic soils, high monsoon rainfall variability coupled with the absence of irrigation, sub-optimal plant population, and poor knowledge of modern agronomic practices (CSISA, 2015). Due to low productivity, a large fraction of the uplands in the region is uncultivated during the monsoon (‘*kharif*’) cropping season (CSISA, 2014). Nevertheless, rice cultivation in the lowlands is also a risky proposition in this region (Panneerselvam *et al.*, 2020). As a result, crop diversification in upland areas in the region could be a possible option in this ecology.

Various socioeconomic and agronomic factors contribute to yield gaps, i.e., the difference between water-limited potential yield in rain-fed systems and average actual yield (Assefa *et al.*, 2020; www.yieldgap.org). The production factors in the rainfed upland areas in eastern India are analogous to rainfed hill ecologies of Nepal where adoption of best management practices (BMPs) increased grain yield by 4.5 Mg ha^{-1} (Devkota *et al.*, 2015). Decomposing yield gaps based on the individual technology or management practices (Devkota *et al.*, 2015) is essential because farmers rarely adopt full technology packages (Leathers and Smale, 1991) and entry points for intensification have different investment costs, expected benefits, levels of risk, and enabling conditions that facilitate adoption such as level of market integration (Shiferaw *et al.*, 2009).

Among the factors contributing to maize yield gaps, sub-optimal plant populations often have a strong influence on maize productivity (Van Roekel and Coulter, 2011). However, the plant population and yield relationship are highly variable (Assefa *et al.*, 2016) and can be affected by the maize variety, rainfall, soil fertility, and agronomic practices (DeBruin *et al.*, 2017). For instance, an increase in plant population without other best agronomic practices may reduce yield, especially in rainfed situations (Haarhoff and Swanepoel, 2018). Also, in rainfed situations, weed competition is often a serious problem with yield losses up to 50% (Page *et al.*, 2012; Zaidi *et al.*, 2017). The non-availability or high cost of labor for manual weeding during critical maize growth stages (Hussain *et al.*, 2019) provides strong incentives for mechanical and herbicide-based weed control methods (Ahmed *et al.*, 2008).

In Odisha, farmers typically cultivate maize with intensive tillage that causes soil erosion, deteriorates soil physical quality, and decreases organic carbon and soil moisture – factors that can contribute to low crop productivity (Alijani *et al.*, 2012; Hobbs and Gupta, 2003; Nandan *et al.*, 2019). Therefore, conservation tillage (strip-tillage) may have relevance for rainfed maize in the nutrient and water-depleted plateau soils of eastern India. Several studies suggest that conservation tillage is also energy, water, and labor efficient (Derpsch, 2011; Erenstein and Laxmi, 2008; Verhulst *et al.*, 2009). Moreover, conservation tillage helps maintain soil quality, enables timely sowing with less labor, and may increase interannual yield stability in rainfed production systems (Giller *et al.*, 2009; Govaerts *et al.*, 2005; Sidhu *et al.*, 2007). Nevertheless, the effect of strip tillage on maize productivity and profitability in the plateau region of eastern India has not been studied.

Furthermore, generalized soil fertility management practices fail to account for the high degree of condition-specificity required for productive nutrient management (Paul *et al.*, 2011). For this reason, Site-Specific Nutrient Management (SSNM) approaches have been developed to enable the precision management of organic and inorganic sources of fertility (Singh, 2019). Based on the principles of SSNM and experiences drawn from several years of on-farm research on maize (Satyanarayana *et al.*, 2011, 2013), International Plant Nutrition Institute (IPNI) developed the decision support system (DSS) tool-Nutrient Expert (NE) for maize in collaboration with the International Maize and Wheat Improvement Centre (CIMMYT) and National Agricultural Research and Extension Systems (NARES) partners in South Asia. NE for maize is a computer-based software that generates fertilizer recommendations based on farmer-elicited information on agronomic factors, nutrient management practices, and achieved crop yields from the previous year (Islam *et al.*, 2018; Pampolino *et al.*, 2012).

There is a lack of field experiments on the role of maize hybrids and agronomic practices on narrowing the maize yield gap in the plateau region of Odisha. Therefore, three types of field

https://doi.org/10.1017/S0014479722000187 Published online by Cambridge University Press

Table 1. Soil properties from the experimental sites in the study region, Mayurbhanj, Odisha, India

Sites (villages)	pH	EC (dSm^{-1})	Organic carbon (%)	Available nitrogen ($kg\ ha^{-1}$)	Available phosphorus ($kg\ ha^{-1}$)	Available potassium ($kg\ ha^{-1}$)
Badbil	4.90	0.17	0.14	150	63	228
Deogaon	4.77	0.13	0.32	112	66	117
Kashipal	5.42	0.09	1.00	162	26	308
Majigaon	4.94	0.12	0.56	137	30	364
Dhanguriposi	5.00	0.12	0.26	150	28	197
Panasi	5.25	0.09	0.82	200	92	328
Batapondugondi	4.84	0.09	0.36	150	38	247
Dayaposi	4.82	0.1	0.36	150	80	86
Mean	5.00	0.11	0.48	151	53	234
SD	0.22	0.027	0.29	24	25	98

experiments were conducted in our study in 2013 and 2014 to explore the contribution of maize hybrids and agronomic practices on narrowing the maize yield gaps. These experiments evaluated (1) the effect of single (individual agronomic practice) and combination of agronomic practices (Experiment I); (2) the performance of maize hybrids with different maturity class under BMPs (Experiment II); and (3) different nutrient (macro and micro nutrients) management practices under BMPs (Experiment III).

Materials and Methods

Study area

The experiments were conducted in farmers' fields, research station of *Krishi Vigyan Kendra*, and Agricultural Department of Odisha during *kharif* (monsoon) season in 2013 and 2014 in Mayurbhanj district (22.0087° N, 86.4187° E) of Odisha State in India. Generally, farmers in this area grow rice in lowland and maize in upland during the rainy season (June–October). Only 15% of the area is cultivated with mustard or pulses in the post-rainy season (November–February) and is left fallow during summer (March to May) (Agriculture Statistics, 2014). This region is predominantly dominated by resource-poor tribal farmers constituting 59% of the population. These tribal farmers mainly grow maize for their home consumption and generate income by selling excess grains to the local traders (CSISA, 2016). The productivity of maize in this region is low because of sub-optimal crop management, lack of availability of seed drills, hybrid seeds, and herbicides due to poor market development, and lack of assured output markets (CSISA, 2014).

The soils of the experimental sites are red, lateritic, and acidic in nature (mean value of soil pH = 5.0) (Table 1). High variability with regards to organic carbon, available nitrogen (N), phosphorus (P), and potassium (K) was observed among the experimental sites from the different villages (Table 1). The climate of Mayurbhanj is tropical with *kharif* (June–October) rainfall of 1511 mm in 2013 and 1252 mm in 2014 with good distribution of rainfall during critical phase of maize growth in July and August (Figure 1). The average daily maximum and minimum temperatures were 34 and 24° C, respectively, during the cropping season as shown in Figure 1.

Experimental sites and management

Farmers who were willing to participate in the researcher-managed experiments were selected with the help of local agricultural extension agents from the Department of Agriculture, Government of Odisha. The selected farmers spread across eight villages and the land selected have varying soil characteristics. Farmer practices (check) were determined by conducting focus

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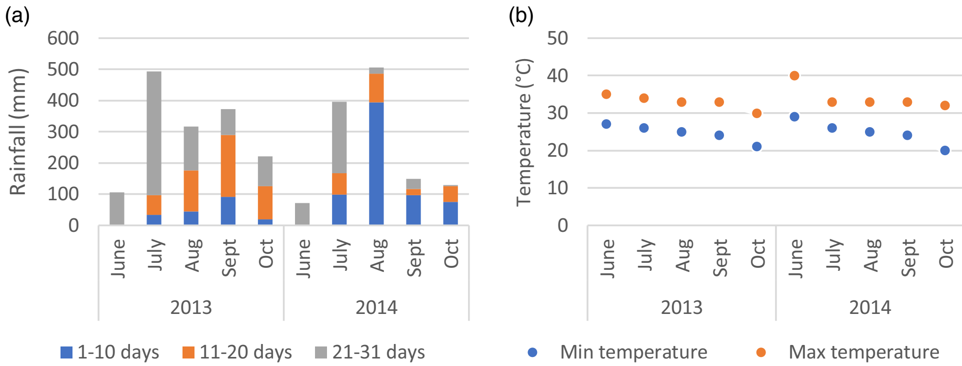

Figure 1. Average monthly rainfall in mm (A) and minimum (min) and maximum (max) temperatures in °C (B) during the maize growing period in 2013 and 2014 in Mayurbhanj district.

group discussions with farmers and agricultural extension staff in the study area before the cropping season. The experiments were managed by the researchers in the farmers' fields including imposing of treatments and critical inputs application in the Check (farmers practice), whereas the farmers supported the experiments by providing land, regular monitoring, and taking back the output after yield estimation from each treatment.

Maize is cultivated in the region with sub-optimal crop management practices. In general, farmers prepare the land with the help of bullock-drawn country plough and 3–4 times ploughing is carried out before sowing. Then the seeds are sown manually behind the plough followed by one light planking to cover the seeds placed in the furrows (Supplementary Material Figure S1). Consequently, weeds were controlled by hand weeding and earthing-up manually at 25–30 days after sowing (DAS). Farmers generally apply N, P_2O_5, K_2O fertilizers at the rate of 80, 40, and 40 kg ha^{-1}, respectively. Half of N and K_2O, and full P_2O_5 as basal application, and the remaining half of N and K_2O were applied at 30 DAS.

Experimental details

Experiment I. Single vs combined agronomic interventions for reducing the yield gap

Six treatments composed of single intervention (either plant population, fertilizer, or weed management) and combined intervention of these three BMPs under conventional (CT-BMP) and strip tillage (ST-BMP) were evaluated at 13 sites in 2 years. A farmer's practice as a check or control was also included. The experiment was established in nine sites in 2013 and four sites in 2014. All six treatments described below were evaluated at each site in a randomized complete block design with three replications.

Treatment (T)1: Check (farmers' practice): – Conventional tillage, seeding of DKC 9133 (medium-duration hybrid) manually behind the plough with an average plant population of 52,000 ha^{-1}, hand weeding and earthing-up manually at 25–30 DAS, and fertilizer applications (80:40:40 kg N: P_2O_5:K_2O ha^{-1}) as explained above. Half N and K_2O and full P_2O_5 were applied as basal, and the remaining half of N and K_2O were applied at 30 DAS.

T2: Plant population (single intervention): – All the agronomic practices were same as T1 except line sowing with a seed drill (plant population 75,000 ha^{-1}) was adopted rather than sowing manually behind the plough.

T3: Fertilizer management (single intervention): – All the agronomic practices were same as T1 except nutrient management which was based on the recommendation of Nutrient Expert (NE) – a site-specific nutrient management decision support tool. For this treatment, plots received 140 kg N, 51 kg P_2O_5, and 76 kg K_2O ha^{-1} rather than farmers' fertilizer rate of 80 kg N,

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40 kg P_2O_5, and 40 kg K_2O ha^{-1}. A full dose of P_2O_5, 20 kg N, and half K_2O was applied as basal application. The remaining N (120 kg ha^{-1}) was applied in two equal splits at 20 and 45 DAS, whereas remaining K_2O was applied at 45 DAS. There was no previous study on site-specific nutrient management in maize in Odisha, and hence, the prototype NE fertilizer recommendation 140:51:76 kg N: P_2O_5: K_2O ha^{-1} for a medium-duration hybrid (DKC 9133) was applied across all the sites as NE was in a development stage during 2013 and 2014.

T4: Weed management (single intervention): – All the agronomic practices were same as T1 except herbicide-based integrated weed management (IWM) was adopted by application of atrazine at 1.0 kg ai ha^{-1} as pre-emergence followed by one hand weeding and earthing-up at 18–20 DAS rather than hand weeding and earthing-up manually at 25–30 DAS.

T5: CT-BMP (combined interventions as BMPs under conventional tillage): – All three single interventions (plant population, fertilizer, and weed management) as described above were combined as BMPs under conventional tillage. The field was ploughed two times using a four-wheeled tractor attached with a cultivator followed by one pass of rotavator and seeds were sown by a seed drill.

T6: ST-BMP (combined interventions as BMPs under strip tillage): – Plant population and fertilizer interventions as described above were combined as BMPs under strip tillage and weeds were managed by pre-plant application of glyphosate at 1.0 kg ai ha^{-1} sprayed 7–10 days before sowing followed by atrazine at 1.0 kg ai ha^{-1} as post-emergence at 15–20 DAS. In this treatment, one pass of a power tiller with blades removed to create narrow (5 cm wide, 5 cm deep) tilled strips done for maize sowing in rows separated from each other by 60 cm of untilled soil.

Plot sizes for each treatment varied according to field dimensions and ranged from 30 to 50 m^2. During the onset of the monsoon, maize hybrid-DKC 9133 was seeded manually behind the plough using 15 kg seed ha^{-1} in the treatments of check (T1), fertilizer (T3), and weed (T4), whereas seeds were sown with a seed drill using 20 kg seed ha^{-1} with row spacing of 60 cm in the treatments of plant population (T2), CT-BMP (T5), and ST-BMP (T6). The seeds were sown in all the sites between 30th June and 16th July. A seed- cum-fertilizer planter was used to sow the maize and applied a basal dose of fertilizer within the tilled rows. Harvesting of maize was completed between 18th October and 30th October in all the sites in both years.

Experiment II. Evaluation of different maturity classes of hybrids under BMPs

The yield performance of different maturity classes of hybrids was evaluated on-station in 2013 and on-farm in 2014. Seven hybrids, described below, were compared in each site under BMPs. These included sowing by seed drill with row spacing of 60 cm to maintain plant population of 75,000 ha^{-1}, herbicide-based IWM by application of atrazine 1.0 kg ai ha^{-1} as pre-emergence followed by one hand weeding and earthing-up at 18–20 DAS, and Nutrient Expert-based fertilizer recommendation (170:67:86 kg N: P_2O_5: K_2O ha^{-1}).

Short-duration hybrid (<100 days maturity): T1: DKC 7074

Medium-duration hybrids (110–120 days maturity): T2: DKC 9133, T3: NK 6240, T4: P 3441, T5: NMH 713

Long-duration hybrids (>120 days maturity): T6: DKC 9126, T7: P 3501

Since there were no significant yield differences within the medium-duration hybrids as well as within long-duration hybrids, the data were compiled duration wise (short-duration hybrid, SDH; medium-duration hybrid, MDH; long-duration hybrid, LDH) and presented in the results. Each hybrid was sown in the plot of 248 m^2 (31 × 8 m) with three replications at experimental farm at Krishi Vigyan Kendra, Jashipur and at state agricultural department's experimental farm in Karanjia in 2013. In 2014, the hybrids were replicated in four farmers' fields in plots of 30–60 m^2. Researchers managed the evaluation experiments of hybrids by keeping all other crop management practices the same in on-station and on-farms. The field was ploughed 2–3 times

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with a four-wheeled tractor attached with a cultivator and one light planking was done before sowing by a mechanical planter. NE-based fertilizer recommendation of 170:67:86 kg N: P_2O_5: K_2O ha^{-1} was applied considering long-duration hybrids and BMPs followed in this experiment. The full rate of P_2O_5 and K_2O and one-third of the N fertilizer was applied at sowing and the remaining N was applied equally into two splits at 20–25 DAS and 40–45 DAS. The seeds were sown in all the sites between 21st June and 16th July and harvesting was completed between 18th October and 30th October in both years.

Experiment III. Evaluation of different nutrient (macro and micro nutrients) management practices under BMPs

This experiment was conducted to determine the effect of different rates of macronutrients (NPK), micronutrients [Boron (B), Sulphur (S), and Zinc (Zn)], and lime on grain yield, profitability, and agronomic efficiency (AE). Six treatments as explained below were laid out in each farmer's field for 2 years (10 fields in 2013 and 8 fields in 2014).

Treatment (T)1: Check (Farmers' fertilizer practice): – Applied N, P_2O_5, and K_2O at 80, 40 and 40 kg ha^{-1}, respectively. The full rate of P_2O_5 and half of the N and K_2O fertilizers were applied at sowing, and the remaining half of N and K_2O was applied at 30 DAS.

T2: State fertilizer recommendation (SFR): – Applied N, P_2O_5, and K_2O at 120, 60, and 60 kg ha^{-1}, respectively. The full rate of P_2O_5 and half of the N and K_2O fertilizers were applied at sowing, and the remaining half of N and K_2O was applied at 30 DAS. Zn sulfate 25 kg ha–^{1}, S 25 kg ha^{-1}, B 10 kg ha^{-1} as Borax, and lime 500 kg ha^{-1} as paper mill sludge were applied at the time of sowing.

T3: Ample (NPK + (S, B, Zn) + lime): – Applied N, P_2O_5, and K_2O at 150, 70, and 120 kg ha^{-1}, respectively. The full rate of P_2O_5 and one-third of the N and half of K_2O fertilizers were applied at sowing, and the remaining N was applied equally into two splits at 20–25 DAS and 40–45 DAS. The remaining half of K_2O was applied at 40–45 DAS. Zn sulfate 25 kg ha–^{1}, S 25 kg ha^{-1}, B 10 kg ha^{-1} as Borax, and lime 500 kg ha^{-1} as paper mill sludge were applied at the time of sowing.

T4: Ample-lime (NPK + (S, B, Zn)): – Same as T3 but no lime application.

T5: Ample-micro (NPK + lime): – Same as T3 but no application of micronutrients (S, B and Zn)

T6: NE tool: – Applied N, P_2O_5, and K_2O at 140, 51, and 76 kg ha^{-1}, respectively. The full rate of P_2O_5 and ~1/3rd of the N (50 kg) and half of K_2O fertilizer were applied at sowing, and the remaining N (90 kg) was applied equally into two splits at 20–25 DAS and 40–45 DAS. The remaining half of K_2O was applied at 40–45 DAS. Zn sulfate 25 kg ha^{-1}, S 25 kg ha^{-1}, B 10 kg ha^{-1} as Borax, and lime 500 kg ha^{-1} as paper mill sludge were applied at the time of sowing

A nutrient omission plot (-N, -P, -K) was also laid out in each site for estimating indigenous stock of plant-available nutrients. The data from omission plots are presented in supplementary data (Supplementary Material Table S1), which was used for calculating nutrient use efficiency (NUE) under different nutrient management practices. These treatments allow comparisons of different NPK application rates, the response to NPK with and without lime or the micronutrients, and the performance of site-specific nutrient recommendation (NE tool) compared to Check, SFR, and ample fertilizer treatments. BMPs, including sowing of hybrid-DKC 9133 at the seed rate of 20 kg ha^{-1} with the use of a seed drill at row spacing of 60 cm to maintain plant population of 75,000 ha^{-1}, and herbicide-based IWM by application of atrazine 1.0 kg ai ha^{-1} as pre-emergence followed by one hand weeding and earthing-up at 18–20 DAS were adopted in all the treatments including farmer fertilizer practice. The seeds were sown in all the sites between 25th June and 15th July and harvesting was completed between 18th October and 30th October in both years.

The yield response to N, P, or K was estimated as the grain productivity difference (Mg ha^{-1}) between the plots that received a full complement of nutrients and omission plots where a single nutrient is omitted. NUE for N, P, and K was estimated in terms of AE (kg increase in grain yield per kg nutrient applied) and calculated using the formula given by Kumar *et al.* (2010) as shown below.

Table 2. Unit cost of the inputs and price of the grain used for the calculation of total variable costs and gross margin

Input	Unit	Unit cost (US$)
A. Total variable cost		
1. Seed		
SDH	kg^{-1}	2.5
MDH	kg^{-1}	3.0
LDH	kg^{-1}	5.0
2. Establishment		
Cultivator	h–1	11.7
Rotavator	h–1	18.4
Power tiller	h–1	6.7
Seed drill	h^{-1}	10
3. Fertilizers		
Urea	50 kg^{-1}	4.58
SSP	50 kg^{-1}	7.5
MOP	50 kg^{-1}	13.3
DAP	50 kg^{-1}	20.8
4. Herbicides		
Atrazine	kg^{-1}	6.6
Glyphosate	L^{-1}	5.0
5. Labor cost	8 h^{-1}	2.0 – 2.5
B. Gross return		
Grain	kg^{-1}	0.22

DAP: diammonium phosphate; LDH: long-duration hybrids; MDH: medium-duration hybrids; MOP: muriatic of potash; SDH: short-duration hybrids; SSP: single super phosphate. Cost and prices were calculated based on local rates from input dealers, service providers, and extension agents during 2014.

$$AE_N = (YF - YC)/F_{app}$$

AE_N is the agronomic efficiency for N. YF and YC refer to grain yields (kg ha^{-1}) in the treatment where fertilizer N is applied and the N omission treatment, respectively, and F_{app} is the amount of fertilizer N applied (kg N ha^{-1}). Similarly, AE_P and AE_K were calculated for all fertilizer treatments.

Maize yield and economic analysis

Grain yield was estimated by harvesting maize cobs from 18 m^2 (3 m (5 rows) × 6 m length) for Experiments I and III to 30 m^2 (6 m (10 rows) × 5 m length) for Experiment II. Maize cobs were harvested at maturity in the center of the plots in each treatment in one spot and shelled manually. The grain moisture content was determined with a moisture meter and expressed at 15% moisture content. For economic analysis, variable costs, gross return, profitability, and benefit–cost ratio (BCR) were calculated for all three experiments. Variable cost was calculated by summing the costs of seed, establishment, fertilizers, herbicides, and labor (Table 2). Gross return was calculated as the product of grain yield and the farm gate price of maize grain (USA$0.22 kg^{-1}). Profitability for each treatment was calculated by deducting the variable cost from gross return. The BCR was computed by dividing the gross return with the variable cost incurred in each treatment.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) conducted in the R programming environment, version 3.6.1. LSD test was used at $p \leq 0.05$ to compare the differences among treatment means. There was no significant difference between 2013 and 2014 for all the parameters, and also

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Table 3. Effect of single and combined agronomic interventions on yield, input costs (seed, establishment, fertilizer, weed management, and variable costs), and profitability of maize (combined-2013 and 2014, Experiment I)

Treatment	Grain yield (Mg ha^{-1})	Seed cost ($ ha^{-1})	Establishment cost ($ ha^{-1})**	Fertilizer cost ($ ha^{-1})	Weed management cost ($ ha^{-1})	Variable cost ($ ha^{-1})	Profitability ($ ha^{-1})	BCR
Check	3.00^{e}	45^{b}	150^{a}	64^{b}	125^{a}	459^{b}	196^{e}	1.42^{e}
Plant population	3.88^{c}	60^{a}	100^{b}	64^{b}	125^{a}	424^{c}	421^{c}	1.99^{b}
Fertilizer	3.75^{c}	45^{b}	150^{a}	90^{a}	125^{a}	485^{a}	331^{d}	1.68^{d}
Weed	3.17^{d}	45^{b}	150^{a}	64^{b}	55^{b}	389^{d}	303^{d}	1.77^{c}
CT-BMP	5.21^{a}	60^{a}	100^{b}	90^{a}	55^{b}	380^{e}	755^{a}	2.98^{a}
ST-BMP	4.70^{b}	60^{a}	85^{c}	90^{a}	29^{c}	340^{f}	685^{b}	3.01^{a}
Grand mean	3.95					412	448	2.14
ANOVA*								
Sites	0.005	0.794	0.645	0.846	1.000	1.000	0.004	0.005
Treatments	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

*ANOVA showed non-significant between 2013 and 2014 for all the variables. Means within a column for a variable followed by the different letter (a, b, c, d and e) are significantly different using *LSD test* at *p* value ≤ 0.05.
**Establishment cost include land preparation and sowing. BCR: Benefit-cost ratio; Check: representative farmers' practices; CT-BMP: conventional tillage best management practices; Fertilizer: nutrient expert decision support tool fertilizer rate; Population: optimum plant population; ST-BMP: strip tillage best management practices; Weed: herbicide-based IWM.

treatment × year interaction was non-significant for all the experiments, therefore, data were pooled for 2 years, analyzed, and presented accordingly.

Results

Experiment I. Single versus combined agronomic interventions for reducing yield gaps

The average grain yield under existing farmer's practice (check) was 3 Mg ha^{-1} (Table 3). Grain yield was significantly increased by single interventions of weed management, fertilizer management, and plant population as compared to check by 0.17, 0.74, and 0.87 Mg ha^{-1}, respectively. When all three interventions were combined into a best management package of practices, the yield gain was 2.2 Mg ha^{-1} under conventional tillage and 1.7 Mg ha^{-1} under strip-tillage over check. Altogether, the combined intervention under conventional tillage resulted in 0.4 Mg ha^{-1} greater grain yield than the additive effects of the individual interventions.

Treatments also differed in the cost of seed, crop establishment, fertilizer, and weed management. (Table 3 in USA$). Although the plant population intervention increased the seed cost by $15 ha^{-1}, the accompanying practice of mechanized sowing decreased crop establishment costs by $50 ha^{-1} compared to Check. Also, the fertilizer intervention increased the fertilizer cost by $26 ha^{-1} compared to Check. In contrast, weed management intervention decreased the weed control cost by $70 ha^{-1}. The crop establishment cost of strip-till treatment was lower than conventional till treatment by $15 ha^{-1}. As compared to farmers' practice, the variable cost increased only in fertilizer intervention by $26 ha^{-1} but in other single or combined intervention treatments, the variable cost decreased by $35–119 ha$^{-1.}$ Overall, variable costs varied in the following order: fertilizer intervention ($485 ha^{-1}) > farmers' practice ($459 ha^{-1}) > plant population ($424 ha^{-1}) > weed management ($389 ha^{-1}) > CT-BMP ($380 ha^{-1}) > ST-BMP ($340 ha^{-1}).

The profitability was significantly increased with all the experimental treatments as shown in Table 3. For instance, compared to farmers' practice, the profitability increased by $107 ha^{-1} with improved weed management, $135 ha^{-1} with fertilizer management, and $225 ha^{-1} with increased plant population. When these interventions were combined, the profitability increased to $559 ha^{-1} under CT-BMP and $489 ha^{-1} under ST-BMP. Thus, the combined interventions increased profitability by 350 to 400% compared to the farmers' practice. In CT-BMP, the increase in the

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Table 4. Grain yield, variable cost, and profitability from cultivars with contrasting growth durations (combined-2013 and 2014, Experiment II)

Treatment	Duration (days)	Grain yield (Mg ha^{-1})	Variable cost (\$ ha^{-1})	Gross return (\$ ha^{-1})	Profitability (\$ ha^{-1})	BCR
SDH (Rep = 6)	100	5.26^{c}	400^{c}	1146^{c}	745^{c}	2.8^{c}
MDH (Rep = 22)	110	6.09^{b}	410^{b}	1328^{b}	918^{b}	3.2^{b}
LDH (Rep = 20)	120	7.02^{a}	450^{a}	1531^{a}	1081^{a}	3.4^{a}
Grand mean		6.37	425	1390	964	3.25
ANOVA*						
Sites		0.402	0.026	0.410	0.410	0.417
Treatments		<0.001	<0.001	<0.001	<0.001	<0.001

*ANOVA showed non-significant between the 2013 and 2014 for all the variables. Means within a column for a variable followed by the different letter (a, b and c) are significantly different using *LSD test* at *p* value ≤ 0.05. BCR: benefit–cost ratio; LDH: long-duration hybrids; MDH: medium-duration hybrids; and SDH: short-duration hybrids.

profitability was greater than the additive effect of single interventions of plant population, fertilizer, and weed treatments (\$559 versus \$467 ha^{-1}). In short, the BCR was higher in ST-BMP when compared with the other experimental treatments (Table 3).

Experiment II. Evaluation of different maturity classes of hybrids under BMPs

Our data showed that there were significant differences among hybrids, with grain yield increasing with growth duration by approximately 80 kg ha^{-1} d^{-1} (Table 4). The highest grain yield was obtained with long-duration hybrids (7.02 Mg ha^{-1}), followed by medium-duration hybrids (6.09 Mg ha^{-1}), and short-duration hybrids (5.26 Mg ha^{-1}) under BMPs (Table 4). In addition, there was no significant difference in grain yield among the four medium-duration hybrids. Likewise, yield was similar between the two long-duration hybrids (Table 4).

The cost of hybrid seeds was high and varied by the duration of the hybrid; seed cost was \$2.5, 3.0, and 5.0 kg^{-1} for short-duration hybrids, medium-duration hybrids, and long-duration hybrids, respectively (Table 2). Variable cost, gross return, profitability, and the BCR were significantly affected by the duration of hybrids (Table 4). Given that the costs other than the seeds remained the same in this experiment, the gross return and profitability followed the same trend as that of grain yield. In conclusion, the profitability gains were \$335 ha^{-1} with long-duration hybrids, and \$163 ha^{-1} with medium-duration hybrids, over short-duration hybrids.

Experiment III. Evaluation of different nutrient (macro and micronutrients) management practices under BMPs

Grain yield was significantly influenced by different nutrient recommendations (Table 5). It is evident from the results that the grain yield was highest in Ample treatment (5.80 Mg ha^{-1}) followed by Ample-lime (5.6 Mg ha^{-1}), Ample-micro (5.5 Mg ha^{-1}), NE (5.38 Mg ha^{-1}), SFR (4.72 Mg ha^{-1}), and Check (3.66 Mg ha^{-1}). Also, the addition of micronutrients had a modest positive effect on maize grain yield (0.29 Mg ha^{-1}) but the addition of lime did not influence the grain yield.

Next, we analyzed the cost of fertilizer, the main variable cost and found that it was proportionally related to the rate of NPK application, with the lowest cost recorded in Check and the highest cost in Ample treatment (Table 5). Also, the micronutrients (S, B, Zn) contributed to an additional cost of \$46 ha^{-1} to the cost of NPK fertilizer but had no significant effect on profitability as the increase in grain yield was only 0.29 Mg ha^{-1} (Ample vs Ample-micro) which was compensated by an increase in fertilizer cost. It should be noted that the fertilizer and variable cost between NE and SFR differed by only \$4 ha^{-1} but the profitability was \$150 ha^{-1} higher in NE

Table 5. Grain yield, variable cost, and profitability under different nutrient management practices under BMPs (combined-2013 and 2014, Experiment III)

Treatment	Grain yield (Mg ha^{-1})	Fertilizer cost (\$ ha^{-1})	Variable cost (\$ ha^{-1})	Gross return (\$ ha^{-1})	Profitability (\$ ha^{-1})	BCR
Check	3.67^{d}	57^{f}	391^{f}	799^{d}	408^{c}	2.0^{d}
SFR	4.72^{c}	133^{d}	456^{c}	1029^{c}	572^{b}	2.2^{c}
Ample	5.80^{a}	169^{a}	492^{a}	1263^{a}	771^{a}	2.5^{b}
Ample-lime	5.59^{ab}	167^{b}	490^{b}	1218^{ab}	728^{a}	2.5^{b}
Ample-micro	5.51^{b}	123^{e}	446^{e}	1200^{b}	754^{a}	2.7^{a}
NE	5.39^{b}	137^{c}	452^{d}	1174^{b}	722^{a}	2.6^{ab}
Grand mean	5.11	131	454	1114	659	2.4
ANOVA*						
Sites	<0.001	0.593	0.981	<0.001	<0.001	<0.001
Treatments	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

*ANOVA showed non-significant between the 2013 and 2014 for all the variables. Means within a column for a variable followed by the different letter (a, b, c, d, e and f) are significantly different using *LSD test* at *p* value ≤ 0.05. All treatments were replicated in 18 farmer fields in 2 years. BCR: benefit-cost ratio; NE: nutrient expert; SFR: state fertilizer recommendation. Check (Famers' fertilizer practices) = N80: $P_2O_5$40: K_2O40; SFR (State fertilizer recommendation) = N120: $P_2O_5$60: K_2O 60; Nutrient Expert (NE) = N140: $P_2O_5$51: K_2O 76; Ample = N150: $P_2O_5$70: K_2O 120; Ample-lime = N150: $P_2O_5$70: K_2O 120 + SBZn; Ample-micro = N150: $P_2O_5$70: K_2O 120 + lime. *Note*: Zn sulfate 25 kg ha^{-1}, Sulphur 25 kg ha^{-1}, Boron 10 kg ha^{-1} as Borax, and lime 500 kg ha^{-1} as paper mill sludge were applied at the time of sowing in all the treatments except Check. Micronutrients were not applied in Ample-micro, while lime was not applied in Ample-lime treatment.

than in SFR. In addition to this, when compared to Check, fertilizer and variable costs were higher in NE but profitability was also higher by \$314 ha^{-1}. Although higher grain yield was obtained in the Ample treatment, the profitability was similar in NE and Ample treatments. The BCR of fertilizer treatment decreased in the following order: Ample-micro (2.7), NE (2.6), Ample and Ample-lime (2.5), SFR (2.2), and Check (2.0).

Consequently, we analyzed the crop response to NPK fertilizer application and found that it differed significantly among the fertilizer recommendations and generally increased with the fertilizer application rate (Table 6). Crop response to N, P, and K was the highest in Ample treatments, followed by NE, SFR, and Check. Moreover, the crop response to K was lower and more variable than N or P irrespective of the treatments. Also, we observed that the crop response to N, P, and K was similar among the Ample, Ample-lime, and Ample-micronutrients. Crop response to N was increased with increasing N application rate of up to 150 kg ha^{-1}. Likewise, the crop response to P also increased with increasing P application rate of up to 70 kg ha^{-1} (Ample treatment). Whereas with the application of K above 76 kg ha^{-1} (NE), we did not observe any increase in crop response significantly (NE vs. Ample-lime/micro). Additionally, the omission of lime or micronutrients did not affect the crop response to N, P, and K application.

AE_N was not significantly different among treatments, between 29 and 31 kg grain yield increase kg^{-1} N applied (Table 6). However, the AE_P and AE_K were significantly different among treatments. The AE_P was highest with NE treatment (90 kg kg^{-1}), and was similar in Check and Ample treatments, followed by SFR. The AE_K was negative in Check, and similar in Ample treatments and NE. In summary, NE treatment had the highest AE_P and AE_K.

Discussion

It is crucial to narrow the yield gap of maize in the rainfed plateau region of Odisha because there is only one cropping season during monsoon (June–October) in a year. Therefore, our study aimed to narrow the maize yield gap using various agronomic and varietal interventions through field experiments in Odisha. The rainfed maize yield gap reported in the region was 7.8 Mg ha^{-1} (www.yieldgap.org). Our study showed that the water-limited yield gap can be narrowed

Table 6. Maize grain yield response (Mg ha^{-1}) and agronomic efficiency (kg increase in grain yield kg^{-1} nutrient applied) to NPK fertilizer application (Experiment III)

Treatment	N response	P response	K response	AE_N	AE_P	AE_K
Check	2.5^{d}	2.8^{d}	-0.98^{d}	31	71^{b}	-25^{c}
SFR	3.6^{c}	3.9^{c}	0.06^{c}	30	65^{c}	1^{b}
Ample	4.7^{a}	5.0^{a}	1.14^{a}	31	71^{b}	10^{a}
Ample-lime	4.4^{ab}	4.7^{ab}	0.93^{ab}	30	68^{b}c	8^{a}
Ample-micro	4.3^{ab}	4.7^{ab}	0.85^{ab}	29	67^{bc}	7^{a}
NE	4.2^{b}	4.5^{a}	0.73^{b}	30	90^{a}	10^{a}
Grand mean	3.9	4.3	0.45	30	72	1.72
ANOVA*						
Sites	<0.001	<0.001	0.004	<0.001	<0.001	0.185
Treatments	<0.001	<0.001	<0.001	0.473	<0.001	<0.001

*ANOVA showed non-significant between 2013 and 2014 for all the variables. Means within a column for a variable followed by the different letter (a, b, c and d) are significantly different using *LSD test* at *p* value ≤ 0.05. All treatments were replicated in 18 farmer fields in 2 years. AE: agronomic efficiency; AE_K: agronomic efficiency of potassium (kg increase in grain yield kg^{-1} K applied); AE_N: agronomic efficiency of nitrogen (kg increase in grain yield kg^{-1} N applied); AE_P: agronomic efficiency of phosphorus (kg increase in grain yield kg^{-1} P applied); NE: Nutrient expert; SFR: state fertilizer recommendation; Check (Famers' fertilizer practices) = N80: $P_2O_5$40: K_2O40; SFR (State fertilizer recommendation) = N120: $P_2O_5$60: K_2O 60; Nutrient Expert (NE) = N140: $P_2O_5$51: K_2O 76; Ample = N150: $P_2O_5$70: K_2O 120; Ample-lime = N150: $P_2O_5$70: K_2O 120 + SBZn; Ample-micro = N150: $P_2O_5$70: K_2O 120 + lime.
Note: Zn sulfate 25 kg ha^{-1}, Sulphur 25 kg ha^{-1}, Boron 10 kg ha^{-1} as Borax, and lime 500 kg ha^{-1} as paper mill sludge were applied at the time of sowing in all the treatments except Check. Micronutrients were not applied in Ample-micro, while lime was not applied in Ample-lime treatment.

significantly by agronomic and varietal interventions in rainfed plateau region of Odisha. The combined agronomic interventions or BMPs can increase the yield by 1.7–2.2 Mg ha^{-1} over check (Experiment I). Moreover, maize yield gap can be further narrowed down by the adoption of long-duration hybrids with BMPs. The grain yield obtained was 7.02 Mg ha^{-1} under long-duration hybrids with BMPs (Experiment II) which is 4.82 Mg ha^{-1} higher than Odisha state average of 2.2 Mg ha^{-1} (Agriculture Statistics, 2014) and 4.02 Mg ha^{-1} higher than the check (Experiment I) in Mayurbhanj district of Odisha. Despite differences in total seasonal rainfall in 2013 and 2014, maize yield did not vary because of a good distribution of rainfall during the critical phase of maize growth in July to August in both years (Figure 1).

Application of Ample NPK at the rate of 150:70:120 kg ha^{-1} or NE-based fertilizer recommendation (NPK rate of 140:51:76 kg ha^{-1}) increased the grain yield by 2.1, and 1.7 Mg ha^{-1}, respectively, over farmers' fertilizer practice (NPK rate of 80:40:40 kg ha^{-1}) (Experiment III). Similar to this study, the combined use of BMPs and hybrids increased yield gain by 4.0–4.5 Mg ha^{-1} in the water-limited production ecology in Nepal (Devkota *et al.*, 2015, 2016). The well-distributed monsoon rainfall with more than 65 rainy days during June to September favor maize cultivation in this region (Ray *et al.*, 2016). Our study showed that the medium- and long-duration hybrids are better suited for this region and sowing should be completed before the first week of July (CSISA, 2019). However, due to poor input market development, timely access to hybrid seeds, herbicides, and seed drills at affordable cost by small farmers in the region is a major issue.

Interestingly, farmers can reduce the yield gap with medium-duration hybrids + BMPs without any extra cost compared to farmers' practice. The use of labor for manual planting of seeds and manual weeding has led to higher cost in Check (\$339 ha^{-1} without seed cost) compared to drill sowing and herbicide-based IWM under BMPs (\$245 ha^{-1} without seed cost) (Experiment I). Hence, there is a saving of \$94 ha^{-1} due to BMPs. This saving can be used for additional investment of \$27 ha^{-1} for seeds of medium-duration hybrids or \$67 ha^{-1} for seeds of long-duration hybrids if required. Therefore, investments in low-risk and relatively low-cost inputs such as hybrid seed could provide a sensible and scalable entry point for sustainable intensification of maize in this region. Public and private partners should ensure the timely availability of hybrids, herbicides, and seed drills for timely operation.

https://doi.org/10.1017/S0014479722000187 Published online by Cambridge University Press

The plant population in farmers' practice is typically around 52,000 plants ha^{-1} with manual sowing behind the plough. Optimum plant population can be achieved with line sowing by machine and this simple intervention increased the grain yield by 0.87 Mg ha^{-1} and profitability doubled to \$225 ha^{-1}. In a similar ecology in Nepal, optimum plant populations increased the grain yield by 0.9 Mg ha^{-1} compared to farmer's practice (Devkota *et al.*, 2015). Other studies have also found that the plant population has a strong influence on maize yield (8.5–21 %), especially in modern hybrids (Assefa *et al.*, 2016; DeBruin *et al.*, 2017; Van Roekel and Coulter, 2011). It should be noted that the number of seed drills in the region is very low, and mainly owned by a few large farmers or service providers. Hence, for the most part, the farmers adopt manual sowing behind the plough. Therefore, state government should encourage mechanical sowing and mechanical service provision through subsidy schemes and custom hiring centers.

One of the reasons for low profitability in the plateau region is the high cost of labor (Anonymous, 2019). Out-migration from this region is common to neighboring states, which creates a shortage of labor during the period of peak agricultural activities. Our study showed that the herbicide-based IWM can reduce the dependency on hired labor. With herbicide and one hand-weeding, the cost of weeding was reduced by \$70 ha^{-1}, grain yield was increased by 0.2 Mg ha^{-1}, and profitability by \$107 ha^{-1} compared to the farmer's practice of two manual weeding. Weed control at early growth stages is imperative and the application of pre-emergence herbicides can increase grain yields (Chopra and Angiras, 2008; Hussain *et al.*, 2019; Mekky *et al.*, 2002; Modak *et al.*, 2019). However, the availability of herbicides in the region is an issue and value chains must strengthen for provision of critical inputs.

Our results demonstrated that the N: P_2O_5: K_2O fertilizer rates from Check (80:40:40) and SFR (120:60:60) are inadequate to close the yield gap. We observed that the yield increased with the increase in NPK rate of up to N150:$P_2O_5$70: K_2O76 kg ha^{-1}. The soil in this region is red lateritic with low fertility and hence response to application of NPK fertilizers is high in maize crop. SSNM based-NE increased fertilizer cost by \$80 ha^{-1} but with profitability gains by \$314 ha^{-1} over Check. The higher rate of NPK fertilizer in Ample-lime and Ample-micro (10:19:44 kg NPK ha^{-1} more than NE) neither increased grain yield nor profitability over NE. Moreover, NE had high AE_P, whereas AE_N and AE_K were similar between Ample and NE. The application of micronutrients resulted in modest yield gains, but it is neither economical nor has any effect on crop response to applied NPK.

AE_N in our study was 29–31 kg grain yield increase kg N^{-1} applied and did not vary among the treatments as shown in Table 6. This could be due to the adoption of BMPs such as the use of hybrids, high plant populations, and weed management in all the treatments (Piha, 1993; Tittonell *et al.*, 2007; Vanlauwe *et al.*, 2011). Other studies also reported that the AE_N could reach more than 25 kg grain kg N^{-1} in a well-managed system (Dobermann, 2007; Satyanarayana *et al.*, 2012). The highest AE_P was obtained with 51 kg P_2O_5 ha^{-1} (NE) despite high crop response at 70 kg P_2O_5 ha^{-1} (Ample). The reduction of AE_P at a higher level of P may be due to the diminished yield gains with increase in P application. The highest AE_K was recorded at 76–120 kg K ha^{-1}.

The higher rate of K in Ample treatments (Ample-lime and Ample-micro) did not increase grain yield or profitability compared to NE. The highest agronomic efficiency of potassium (kg increase in grain yield kg^{-1} K applied) was recorded under NE recommendation. Optimum rate of application of fertilizer K is important to maintain the soil K and obtain economic yield (Buresh *et al.*, 2010; Timsina *et al.*, 2010). Thus, our results clearly suggest that SSNM based-NE recommendations provide economic yield and high NUE. This is in agreement with the recent study from the eastern Gangetic Plains that also showed that Nutrient Expert recommendation increased yield, profit, and NUE over farmers fertilizer practice and state fertilizer recommendation (Timsina *et al.*, 2021).

Our results on combining the single intervention (BMPs) under conventional tillage not only has the synergistic effect on grain yield (2.2 Mg ha^{-1}) and profitability (\$559 ha^{-1}), but also lowers input costs (by \$79 ha^{-1}), mainly due to less labor for weed management. Also, the synergistic effect on yield under strip tillage is less than the conventional tillage. Since the experiment was conducted for only 2 years, the yield benefit under strip tillage was not noticed and yield benefits under conservation tillage only accrue in the longer term (Giller *et al.*, 2009; Thierfelder *et al.*, 2013). Devkota *et al.* (2015) reported higher maize yield under conventional tillage than strip tillage during the initial years in similar ecologies in Nepal.

The state government of Odisha wants to increase maize production, and this study has shown that there are several options such as genetics (seed), agronomic interventions, and combination of both to accomplish this. Based on the results obtained in our study, we combined best performing hybrids and BMPs for further evaluation and scaling from 2015 in partnership with state government of Odisha (CSISA 2016, 2017, 2018, 2019, 2020). From 2016, BMPs are being disseminated through messaging, training farmers groups, state extension agents, and development partners in partnership with Department of Agriculture. However, lack of availability of seed drills, hybrid seeds, and herbicides due to poor market development in the region, and lack of assured markets are the major issues in the study region (CSISA, 2020). For this, state government and development partners should facilitate small farmers to create farmer producer groups and women self-help groups. As a result, this will create market and business opportunities for private companies (seed, fertilizer, and herbicides), input dealers, and service providers for machinery (CSISA, 2019). Thus, it will support for scaling of BMPs and narrowing the yield gap in the region successfully.

Conclusion

In regions where there is only one cropping season, as in the plateau in Odisha, narrowing the yield gap through intensification of maize during the monsoon season is essential for improving food security of small farmers. Our results demonstrated a tremendous scope for narrowing the yield gap through adoption of BMPs such as long-duration hybrids, increased plant population using seed drills, site-specific nutrient management recommendations, and herbicides-based IWM to control weeds either independently or in combination. For example, our results showed that the yield gain from the three experiments ranged from 1.7 to 4.0 Mg ha^{-1} under combination of BMPs and hybrids. All these BMPs also increased profitability, an important determinant of adoption of these practices. The profitability gain was \$559 ha^{-1}, \$885 ha^{-1}, and \$314 ha^{-1} due to adoption of combination of BMPs (Experiment I), long-duration hybrids with BMP (Experiment II), and NE-based fertilizer recommendation (Experiment III), respectively. Overall, many different stakeholders, including state government, input dealers, seed companies, development partners, and farmer producers' groups need to develop a complementary partnership to support and promote the investments and interventions needed for sustainable maize cultivation including value chain and integrated marketing in these rainfed areas.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0014479722000187.

Acknowledgments. We acknowledge the Bill and Melinda Gates Foundation (BMGF) and the USA Agency for International Development (USAID) for funding this research through a project titled 'Cereal Systems Initiative for South Asia' (CSISA).

Financial support. None.

Conflicts of interest. The authors declare that they have no conflicts of interest/Competing interests.

References

Agriculture Statistics (2014). *Directorate of Agriculture and Food Production, Odisha.* –http://farmer.gov.in/imagedefault/handbooks/BooKLet/ODISHA/20151127132510_Agriculture%20Statistics_2013−14.pdf

Ahmed S.A., Shams H.M., El-Metwally I.M., Shehata M.N. and El-Wakeel M.A. (2008). Efficiency of some weed control treatments on growth, yield and its attributes of maize (*Zea mays* L.) plants and associated weeds. *Journal Agriculture Science Mansoura University* **33**, 4777–4789.

Alijani K., Bahrani M.J. and Kazemeini S.A. (2012). Short-term responses of soil and wheat yield to tillage, corn residue management and nitrogen fertilization. *Soil Tillage Research* **124**, 78–82. doi: 10.1016/j.still.2012.05.005

Anonymous (2019). *Agriculture Policy of Odisha, Directorate of Agriculture and Food Production, Odisha.* http://agriodisha.nic.in/Content/pdf/DRAFT%20AGRICULTURE%20POLICY%202019.pdf

Assefa B.T., Chamberlin J., Reidsma P., Silva J.V. and van Ittersum M.K. (2020). Unravelling the variability and causes of smallholder maize yield gaps in Ethiopia. *Food Security* **12**, 83–103. doi: 10.1007/s12571-019-00981-4

Assefa Y., Vara Prasad P.V., Carter P., Hinds M., Bhalla G., Schon R., Jeschke M., Paszkiewicz S., & Ciampitti I.A. (2016). Yield responses to planting density for US modern corn hybrids: A synthesis-analysis. *Crop Science 56*(5): 2802–2817. doi: 10.2135/cropsci2016.04.0215

Buresh R.J., Pampolino M.F. and Witt C. (2010). Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems. *Plant Soil* **335**, 35–64. doi: 10.1007/s11104-010-0441-z

Chopra P. and Angiras N.N. (2008). Effect of tillage and weed management on productivity and nutrient uptake of maize (*Zea mays*). *Indian Journal of Agronomy* **53**, 66–69.

CSISA (2014). *Cereal Systems Initiative for South Asia (CSISA)-Annual Report 2014*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT). Available at https://csisa.org/annual-reports/

CSISA (2015). *Cereal Systems Initiative for South Asia (CSISA)-Phase-II Annual Report 2015*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT). Available at http://csisa.org/annual-reports/

CSISA (2016). *Cereal Systems Initiative for South Asia (CSISA)-Annual Report*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT).

CSISA (2017). *Cereal Systems Initiative for South Asia (CSISA)-Annual Report*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT).

CSISA (2018). *Cereal Systems Initiative for South Asia (CSISA)-Annual Report*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT).

CSISA (2019). *Cereal Systems Initiative for South Asia (CSISA)-Annual Report*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT).

CSISA (2020). *Cereal Systems Initiative for South Asia (CSISA)-Annual Report*. New Delhi, India: International Maize and Wheat Improvement Center (CIMMYT).

DeBruin J.L., Schussler J.F., Mo H. and Cooper M. (2017). Grain yield and nitrogen accumulation in maize hybrids released during 1934 to 2013 in the US Midwest. *Crop Science* **57**, 1431–1446. doi: 10.2135/cropsci2016.08.0704

Derpsch R. (2011). *No-Tillage, Sustainable Agriculture in the New Millennium*. Available at http://www.rolf-derpsch.com

Devkota K.P., McDonald A.J., Khadka A., Khadka L., Paudel G. and Devkota M. (2015). Decomposing maize yield gaps differentiates entry points for intensification in the rainfed mid-hills of Nepal. *Field Crops Research* **179**, 81–94. doi: 10.1016/j.fcr.2015.04.013

Devkota K.P., McDonald A.J., Khadka L., Khadka A., Paudel G. and Devkota M. (2016). Fertilizers, hybrids, and the sustainable intensification of maize systems in the rainfed mid-hills of Nepal. *European Journal of Agronomy* **80**, 154–167. doi: 10.1016/j.eja.2016.08.003

Dobermann A. (2007). Nutrient use efficiency—measurement and management. In Krauss A. (ed), *Fertilizer Best Management Practice: General Principles, Strategy for Their Adoption and Voluntary Initiatives Vs Regulations*. IFA Int. Worksh. on Fertilizer Best Management Practices, Brussels, Belgium, 7–9. Paris, France: International Fertilizer Industry Association, pp. 1–28.

Erenstein O. and Laxmi V. (2008). Zero tillage impacts in India's rice-wheat systems: a review. *Soil and Tillage Research* **100**, 1–14. doi: 10.1016/j.still.2008.05.001

FAO (2018). *FAOSTAT Database*. Rome: FAO. Available at http://www.fao.org/faostat/en/#data/QC (accessed 30 April. 2019).

Giller K.E., Witter E., Corbeels M. and Tittonell P. (2009). Conservation agriculture and smallholder farming in Africa: the heretics' review. *Field Crops Research* **114**, 23–34. doi: 10.1016/j.fcr.2009.06.017

Govaerts B., Sayre K.D. and Deckers J. (2005). Stable high yields with zero tillage and permanent bed planting? *Field Crops Research* **94**, 33–42. doi: 10.1016/j.fcr.2004.11.003

Haarhoff S.J. and Swanepoel P.A. (2018). Plant population and maize grain yield: a global systematic review of rainfed trials. *Crop Science* **58**, 1819–1829. doi: 10.2135/cropsci2018.01.0003

Hobbs P. and Gupta R.K. (2003). Rice-wheat cropping systems in the Indo-Gangetic Plains: issues of water productivity. I. Relation to new resource-conserving technologies. In Kijne J.W., Barker R. and Molden D. (eds), *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. Wallingford, UK: CABI Publishing, pp. 239–253.

Hussain A., Islam M.T., Islam M.S., Ahmed S., Sarker K.K. and Gathala M.K. (2019). Chemical weed management in maize (Zea mays L.) under conservation agricultural systems: an outlook of the Eastern Gangetic Plains in South-Asia. In *Maize-Production and Use*. IntechOpen. Available at https://repository.cimmyt.org/bitstream/handle/10883/20223/60936.pdf?sequence=1

Islam S., Timsina J., Salim M., Majumdar K. and Gathala M.K. (2018). Potassium supplying capacity of diverse soils and K-use efficiency of maize in South Asia. *Agronomy* **8**, 121. doi: 10.3390/agronomy8070121

Kumar D., Devakumar C., Kumar R., Das A., Panneerselvam P. and Shivay Y.S. (2010). Effect of neem-oil coated prilled urea with varying thickness of neem-oil coating and nitrogen rates on productivity and nitrogen-use efficiency of lowland irrigated rice under Indo-Gangetic plains. *Journal of Plant Nutrition* **33**, 1939–1959. doi: 10.1080/01904167.2010.512053

Kumar R., Srinivas K. and Sivaramane N. (2013). *Assessment of the Maize Situation, Outlook and Investment Opportunities in India*. Hyderabad, India: Country Report–Regional Assessment Asia (MAIZE-CRP), National Academy of Agricultural Research Management, p. 133.

Leathers H.D. and Smale M. (1991). A Bayesian approach to explaining sequential adoption of components of a technological package. *American Journal of Agricultural Economics* **73**, 734–742.

Mekky M.S., Nassar A.N. and Attalla S.I. (2002). Effect of weed control treatments on weeds, growth, chlorophyll, crude protein and yield of maize (Zea mays L.). *Egyptian Journal of Basic and Applied Science* **17**: 219–240.

Modak D.P., Behera B., Jena S.N., Roul P.K. and Behera S.D. (2019). Nutrient uptake and yield of maize (Zea mays L.) in rice-maize system under tillage and weed management and impact on soil health. *IJCS* **7**, 1786–1791.

Nandan R., Singh V., Singh S.S., Kumar V., Hazra K.K., Nath C.P., Poonia S., Malik R.K., Bhattacharyya R. and McDonald A. (2019). Impact of conservation tillage in rice–based cropping systems on soil aggregation, carbon pools and nutrients. *Geoderma* **340**, 104–114. doi: 10.1016/j.geoderma.2019.01.001

Page E.R., Cerrudo D., Westra P., Loux M., Smith K., Foresman C., Wright H. and Swanton C.J. (2012). Why early season weed control is important in maize. *Weed Science* **60**, 423–430. doi: 10.1614/WS-D-11-00183.1

Pampolino M.F., Witt C., Pasuquin J.M., Johnston A. and Fisher M.J. (2012). Development approach and evaluation of the Nutrient Expert software for nutrient management in cereal crops. *Computer Electronic Agriculture* **88**, 103–110. doi: 10.1016/j.compag.2012.07.007

Panneerselvam P., Kumar V., Banik N.C., Kumar V., Parida N., Wasim I., Das A., Pattnaik S., Roul P.K., Sarangi D.R., Sagwal P.K., Craufurd P., Singh B., Yadav A., Malik R.K., Singh S., and McDonald A.J. (2020). Transforming labor requirement, crop yield, and profitability with precision dry-direct seeding of rice and integrated weed management in Eastern India. *Field Crops Research* **259**, 107961. doi: 10.1016/j.fcr.2020.107961

Paul J., Surim V.K., Sandal S.K. and Choudhary A.K. (2011). Evaluation of targeted yield precision model for soybean and toria crops on farmers' fields under sub-humid sub-tropical north-western Himalayas. *Communication Soil Science and Plant Analysis* **42**, 2452–2460. doi: 10.1080/00103624.2011.609254

Piha M.I. (1993). Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. *Experimental Agriculture* **29**, 405–415. doi: 10.1017/S0014479700021128

Pradhan A., Idol T., Roul P.K. (2016). Conservation agriculture practices in rainfed uplands of India improve maize-based system productivity and profitability. *Frontiers in Plant Science* **7**, 1008. doi: 10.3389/fpls.2016.01008

Ray M., Patro H. and Mishra N. (2016). Temporal rainfall distribution characteristics at Mayurbhanj, Odisha, India. *Plant Archives* **16**, 413–418.

Satyanarayana T., Majumdar K. and Biradar D.P. (2011). New approaches and tools for site-specific nutrient management with reference to potassium. *Karnataka Journal of Agricultural Science* **24**, 86–90.

Satyanarayana T., Majumdar K., Pampolino M., Johnston A.M., Jat M.L., Kuchanur P., Sreelatha D., Sekhar J.C., Kumar Y., Maheswaran R. and Karthikeyan R. (2013). Nutrient Expert TM: a tool to optimize nutrient use and improve productivity of maize. *Better Crops-South Asia* **97**, 21–24.

Satyanarayana T., Majumdar K., Shahi V., Kumar A., Pampolino M., Jat M.L., Singh V.K., Gupta N., Singh V., Dwivedi B.S. and Kumar D. (2012). Economics of nitrogen fertilizer application in rice, wheat and maize grown in the indo-gangetic plains. *Indian Journal of Fertilizer* **8**, 62–71.

Shiferaw B.A., Okello J. and Reddy R.V. (2009). Adoption and adaptation of natural resource management innovations in smallholder agriculture: reflections on key lessons and best practices. *Environment, Development and Sustainability* **11**, 601–619. doi: 10.1007/s10668–007–9132-1

Sidhu H.S., Singh M. and Humphreys E. (2007). The Happy Seeder enables direct drilling of wheat into rice stubble. *Australian Journal of Experimental Agriculture* **47**, 844–854.

Singh S.P. (2019). Site specific nutrient management through nutrient decision support tools for sustainable crop production and soil health. In *Soil Fertility Management for Sustainable Development*. Singapore: Springer, pp. 13–23. doi: 10.1007/978-981-13-5904–0_2

Thierfelder C., Mwila M. and Rusinamhodzi L. (2013). Conservation agriculture in eastern and southern provinces of Zambia: long-term effects on soil quality and maize productivity. *Soil Tillage Research* **126**, 246–258. doi: 10.1016/j.still.2012.09.002

Timsina J., Dutta S., Devkota K.P., Chakraborty S., Neupane R.K., Bishta S., Amgain L.P., Singh V.K., Islam S. and Majumdar K. (2021). Improved nutrient management in cereals using Nutrient Expert and machine learning tools: productivity, profitability and nutrient use efficiency. *Agricultural Systems* **192**, 10318. doi: 10.1016/j.agsy.2021.103181

Timsina J., Jat M.L. and Majumdar K. (2010). Nutrient management research priorities in rice-maize systems of South Asia. *BETTER CROPS* **4**, 4–6.

Tittonell P.A., Vanlauwe B., de Ridder N. and Giller K.E. (2007). Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? *Agricultural Systems* **94**, 376−390. doi: 10.1016/j.agsy.2006.10.012

Van Roekel R.J. and Coulter J.A. (2011). Agronomic responses of corn to planting date and plant density. *Agronomy Journal* **103**, 1414−1422. doi: 10.2134/agronj2011.0071

Vanlauwe B., Kihara J., Chivenge P., Pypers P., Coe R. and Six J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* **339**, 35−50. doi: 10.1007/s11104-010-0462-7

Verhulst N., Govaerts B. and Sayre K.D. (2009). Using NDVI and soil quality analysis to assess influence of agronomic management on within-plot spatial variability and factors limiting production. *Plant Soil* **317**, 41–59. doi: 10.1007/s11104-008-9787-x

Zaidi P.H., Jat M.L., Lenka D. and Swain D. (2017). *Package-of-Practices for Profitable Maize Cultivation – A Field Manual.* Hyderabad, India: CIMMYT. Available at https://repository.cimmyt.org/bitstream/handle/10883/19072/58917.pdf?sequence=1

Cite this article: Peramaiyan P, McDonald AJ, Kumar V, Craufurd P, Wasim I, Parida N, Pattnaik S, Singh B, Yadav A, Ajay A, Singh S, and Malik RK. Narrowing maize yield gaps in the rainfed plateau region of Odisha. *Experimental Agriculture*. https://doi.org/10.1017/S0014479722000187