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Point placement of late vegetative stage nitrogen splits increase the productivity, N-use efficiency and profitability of tropical maize under decade long conservation agriculture

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A R T I C L E I N F O

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A B S T R A C T

The rising economic and environmental costs of mineral fertilizers associated with lower nutrient use efficiency, and the need to respond the limitations of N fertilization under residue retained condition of conservation agriculture (CA) motivate the research for alternative N placement methods. The third principle of CA, *i.e.,* residue retention on the soil surface hinders the right placement of split applied nitrogen (N). To address this issue, we assessed the impact of three N placement methods, *i.e.,* NPM_1: both the N splits were surface band placed, NPM_2: the first split of N was sub-surface point placed and second N split (late vegetative stage) was surface band applied, and NPM_3: both the N splits were sub-surface point placed, under 4-long-term tillage and residue management (+R) options, *i.e.*, permanent raised bed (PB+R), zero-till flat (ZT+R) conventional till flat (CT+R) and first time zero till flat sowing of the crop on last 10-year fallow land (FZT+R), in an on-going long-term study (since 2008) in maize for three consecutive years (2018–2020). Results showed that sub-surface point placement of both the N splits (NPM_3) increased maize grain yield by 4.7, 7.0 and 6.0% (3-years mean basis) compared to NPM_2, under CA-based PB, ZT, and FZT plots, respectively. The peak growth rate in the CA-based PB+R plot was advanced by 4-days with a 9.2% higher growth rate compared to CT+R. Similarly, the peak growth rate in NPM_3 was 20% higher than NPM_1 plots. The changes in soil properties under CA altered the crop growth behavior, while sub-surface point placement of split applied nitrogen (N) increased the grain N content and altered the peak growth rate of maize. The variability in maize grain yield was best described by cob length and number of cobs in long-term tillage and by cob length in N management plots. The cob length and grains per cob were increased by 4.8–8.7 and 8.6–12.8% under CA-based plots compared to CT+R, respectively. The amount of vegetative stage accumulated N remobilized to maize grain was 21.2% higher under PB+R compared to CT+R plots, while the N remobilization in NPM_3 was 22.9% higher compared to NPM_1 plots. Similarly, the contribution of reproductive stage N uptake to grain was 9–12% higher in CA-NPM_3 compared to CT-NPM_1 plots. Further, the early and vigorous growth of maize resulted in a higher accumulation of N and its remobilization to the grains in CA-based and N point placed plots. The sub-surface point placement of N (NPM_3) resulted in a 12.8, 14.5 and 9.2% higher benefit-cost ratio compared to NPM_1 plots in 11th (2018), 12th (2019) and 13th (2020) years of experimentation, respectively. Therefore, the present study visualizes the impact of a decade-long CA and efficient N management on crop growth behavior, N uptake and remobilization and crop productivity and

Abbreviations: AGR, Absolute crop growth rate; CA, Conservation agriculture; CT, Conventional tilled; GR, Gross return; GY, Grain yield; IGP, Indo-Gangetic Plains; NBCR, Net benefit cost ratio; NPM, Nitrogen placement method; NR, Net return; NUE, Nitrogen use efficiency; PB, Permanent raised bed; WUE, Water use efficiency; ZT, Zero tillage flat bed.

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water use efficiency. This study provides evidence to popularize this technology in the CA-systems of Indo-Gangetic Plains and other similar agro-ecologies.

1. Introduction

The parallel progress of Indian agriculture with Indian economy describes their reciprocate mutualism for safeguarding livelihood and food security since the era after the green revolution (Yadav and Anand, 2019). Though in the last few decades, Indian agriculture has made progress to achieve food self-sufficiency, simultaneously, the future sustainability of agricultural production has also been questioned (Jat et al., 2019b; Sidhu et al., 2019). The challenges faced by researchers, farmers, and policy planners for a sustainable increase in food production to meet the future food needs are different and complex compared to those of the pre-green revolution era (before the 1960s). With limited scope for further expansion of agricultural land, rejuvenation of the current form of farming is a must need for future food security. Therefore, it is urgent to optimize land unit productivity (produce more from the same land area), which can be achieved through an increase in inputs use efficiencies and by adopting suitable agronomic practices. Modern agriculture demands the most efficient use of all the applied inputs, and more specifically the fertilizers, *i.e.,* nitrogen.

The commanding Rice-Wheat cropping system of Indo-Gangetic Plains (IGP) provides food security to the major mass of the South Asian population. However, the future sustainability of this system is under threat due to multiple challenges. The major challenges are natural resource degradation (Chauhan et al., 2012), rapid fall in the water table (Jain et al., 2021; Yadvinder-Singh et al., 2014), deteriorating soil quality (Parihar et al., 2016a), and low nutrient use efficiency, more specifically for nitrogen. The N use efficiency (NUE) is low in cereal-based agroecosystems. Cereals take up only 40–60% of the applied nitrogen (Herrera et al., 2016). Among cereals, the least NUE is observed in rice and wheat (< 30–40%) (Herrera et al., 2016; Norton et al., 2015; Taulemesse et al., 2015). Farmers apply more N to compensate for the low N uptake to maintain or enhance grain yield (Elbasyoni et al., 2019; Taulemesse et al., 2015). Most of the time total N losses amount to more than 50% of applied N, leading to adverse environmental and socio-economic impacts including surface and groundwater contamination, and green house gas emissions (Hawkesford, 2017; Huang et al., 2017). The application of 100 kg of N results in emissions of about 1.2 kg of N in the form of N_2O from the soil (Albanito et al., 2017). Therefore, it is urgent to identify economical and environment-friendly N management practices that increase N availability at critical growth stages to increase yield and NUE.

The past research evidence by Parihar et al. (2016a), Jat et al. (2018, 2020a,b), and Gathala et al. (2013) describe conservation agriculture (CA) as a more sustainable form of agriculture in cereal-based cropping systems, in terms of resource use efficiency (water, fertilizers, and energy), profitability, soil quality, and agri-ecosystem resilience to climate change. The CA is based on three principles, *i.e.,* (i) minimum tillage and soil disturbance, (ii) permanent soil cover with crop residues and live mulches and, (iii) crop rotation and intercropping (FAO, 2019). In general, the adoption of CA brings many benefits for soil quality parameters, including increased soil organic matter (Guo et al., 2020; Page et al., 2019; Parihar et al., 2020; Zhao et al., 2014), decreased runoff and soil erosion (Fischer and Hobbs, 2019; Soane et al., 2012), increased water infiltration and reduced evaporation (Li et al., 2019; Patra et al., 2019), and increased soil water storage (Dixit et al., 2019; Ella et al., 2016; Ogle et al., 2019). As per the CA principles, the diversification of rice with maize in the rice-wheat system could help in enhancing crop productivity (Gathala et al., 2013), profitability (Jat et al., 2019b), soil quality (Parihar et al., 2016a), and resources use efficiency, in particular for water and nitrogen (Jat et al., 2019b; Sidhu et al., 2019). Presently maize-wheat cropping system is followed in an area of 1.85 Mha and is the third most important cropping system of India (Parihar et al., 2017).

The success of CA depends on how well the nutrient, water, and weed management strategies are developed to support it. However, little attention has been directed towards investigating nutrient management practices under CA, despite of having a significant effect on crop growth and productivity (Jat et al., 2019b). Several options have been evaluated and proposed to enhance the nutrient use efficiency (NUE) of nitrogenous fertilizer based on 4R Nutrient Stewardship (use of the *right source* at the *right time* and *right dose* with *right placement* method) (Ryan et al., 2012; Roberts, 2007), as the use of leaf color chart in rice and wheat, green seeker-based N recommendations in rice and wheat, use on nutrient expert decision support tool, crop manager based recommendations and chlorophyll meter. However, those options mostly focus on the right dose and right time of N fertilizer application. Along with timing and dose, the right placement of fertilizer (applying the nutrient in the immediate vicinity of rhizosphere) is required to facilitate crop uptake of applied N. The results of a meta-analysis of 40 field studies (considering 15 crops including maize, winter wheat, spring wheat, winter rye, sorghum, rice, soybean, rapeseed, turnip rape, potato, sugar beet, lettuce, cauliflower, chinese cabbage, and mixed grassland grass species) showed that the right placement of fertilizer led to a 3.7% and 11.9% increment in yield and nutrient content in above-ground parts, respectively (Nkebiwe et al., 2016). The horizontal and vertical distribution of the root in the soil under the CA system is better as compared to conventional agriculture, which is associated with improved soil quality as a result of better aggregation, porosity with the predominance of biogenic pores, and low penetration resistance offered under CA (Aggarwal et al., 2017). Further, the broadcasting of split applied N fertilizer at later crop growth stages may result in lower N availability to the crop with reduced NUE. Consequently, the point placement of N-fertilizers near the root zone represents an effective approach for enhancing N use efficiency (Bowen et al., 2004). Suitable machinery for sub-surface placement (10–30 cm below the soil surface) of mineral fertilizers (Kraska et al., 2021; Mallarino and Borges, 2006; Ressler et al., 1998), and poultry litter (Pote et al., 2011) have been developed for crops like rice, legumes, and pastures where the crop is of short height. However, in South Asia more specifically in India, Bangladesh, and Nepal, the machinery with high clearance (to suit for maize) to work under residue retained condition is not yet popularized, and so as the sub-surface placement of split applied N in residue retained CA plots. It is widely accepted that sub-surface placement of fertilizers increases nutrients use efficiency (Barbieri et al., 2014; Hansel et al., 2017; Kraska et al., 2021; Mallarino and Borges, 2006; Ressler et al., 1998). In Bangladesh, Alam et al. (2018) found that fertilizer banding improves phosphorus acquisition and grain yield of maize. In the recent past, research-based evidence showed higher NUE in paddy with application of N using sub-surface irrigation (Jat et al., 2020a,b, 2019a; Parihar et al., 2019; Sidhu et al., 2019). However, the feasibility and economics of the sub-surface N application method under CA practices are yet to be explored in wide-spaced crops like maize.

The positive effect of point placement of N fertilizers on crop yields, NUE, and soil quality is rich-established, however, no information is available, how the add–on of subsurface point placement of split applied N (a step toward improving NUE) under long-term CA will affect the crop growth behavior, productivity, profitability, N remobilization, N and water use efficiency. The present study investigates the room for improvement in crop productivity while synchronizing the two-resource conservation technologies, *i.e.,* CA and point placement. The objective of this study was to evaluate the effect of different N application methods on growth, productivity and NUE of tropical maize under a long-term CA. In the present study, we hypothesized that sub-surface point placement of split applied N under long-term CA will enhance the crop performance, N-uptake, crop productivity, water use efficiency, and farm profitability of tropical maize in South Asia. In particular, we investigated how the point placement of N interacts with the decade-long CA and CT to alter the crop growth behavior, N uptake, and remobilization pattern and established the relationship between crop yield and yield attributing characters.

2. Materials and methods

2.1. Experimental site and climatic condition

A field experiment was conducted in an ongoing long−term field experiment (from 2008 till continuing) with a set of tillage and crop establishment techniques in maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and mungbean (*Vigna radiata* L.) cropping system. The experiment was undertaken at the research farm of the Indian Council of Agricultural Research (ICAR)-Indian Agricultural Research Institute (IARI), New Delhi, situated at 28°38'15″ N latitude, 77°09′10″ E longitude and 228.6 m above mean sea level. During 11th (2018), 12th (2019), and 13th (2020) years of experimentation, the daily maximum and minimum temperature varied between 10.5–39.2 °C, 14.0–44.8 °C, and 10.8–41 °C, respectively (Supplementary Fig. 1). The experimental area falls under the semi-arid region having annual average rainfall of 708 mm with hot-dry summer and cold winter seasons (70–75% of rainfall is received between July to September months). The total precipitation during the rainy seasons of 2018, 2019, and 2020 was 854.2, 569.5, and 615.3 mm, respectively (Supplementary Table 1). Details of the weather parameters were obtained from the meteorological observatory of ICAR-IARI located adjacent to the experimental site. The soil of the experimental site is well-drained, very deep (> 3 m), non-saline, slightly alkaline and sandy loam in texture. The analysis of the representative initial soil sample reveals that the available N ($KMnO_4$ oxidizable) content (0–30 cm soil depth) was 169.1, 168.3, 159.3 and 169.7 kg ha^{-1} in permeant bed plots (PB), zero-till plots (ZT), conventional till plots (CT), and first-time ZT on last 10-year (FZT+R), respectively, in which crop residue were retained/incorporated in all plots.

2.2. Experimental details

The experiment was laid out in a split-plot design with 12 treatment combinations replicated thrice (Table 1). There were 4-main plot factors (Tillage practices; PB+R, ZT+R, CT+R, and FZT+R) and 3-sub plot factors (N placement methods; NPM_1, NPM_2 and NPM_3), with an additional control treatment, where neither N was applied, nor crop residue were retained (CT-R) outside the split-plot design layout. In the N placement treatments, N fertilizers were point placed at ~7.5–10 cm below the soil surface as per the treatment description given in Table 1. In our experimental layout +R indicates residue retention/incorporation, whereas –R indicates residue removal. The plot size was 17.0 m^2. The details of the treatments are given in Table 1.

Table 1
Detailed description of imposed treatments.

S. No.	Notations
A. **Main-plot:** *Tillage and crop establishment techniques **(04)***	
1. Zero till permanent raised bed with residue retention	PB + R
2. Zero till flat with residue retention	ZT + R
3. First time zero till flat sowing of crops on last 10-year fallow land with residue retention	FZT+ R
4. Conventional till flat with residue incorporation	CT+ R
B. **Sub-plot:** *Nutrient management options **(03)***	
1. Surface band placement of 1/3 N fertilizer as basal + Surface band placement of 1/3 N fertilizer along crop rows (at V_6 stage) + Surface band placement of remaining 1/3 N fertilizer along crop rows (at pre-tasseling stage).	NPM_1
2. Surface band placement of 1/3 N fertilizer as basal + Sub-surface-point placement (7.5–10 cm below the soil surface) of 1/3 N fertilizer (at V_6 stage) + Surface band placement of remaining 1/3 N fertilizer along crop rows (at pre-tasseling stage).	NPM_2
3. Surface band placement of 1/3 N fertilizer as basal + Sub-surface point placement (7.5–10 cm below the soil surface) of 1/3 N fertilizer (at V_6 stage) + Sub-surface point placement (7.5–10 cm below the soil surface) of remaining 1/3 N fertilizer at pre-tasseling stage).	NPM_3
C. **Additional Treatment-Control**	CT-R
1. Conventional tillage without residue and N application	

2.3. Maize based agro-techniques

2.3.1. Sowing of crop, cultivar and crop geometry

The CT+R and CT-R treatments were imposed with one plowing with the help of disc harrow followed by a spring-tine cultivator. In FZT+R and ZT+R plots, the crop was drilled directly using a ZT multi-crop planter. The fresh raised beds were formed during the first year (July 2008) and in subsequent years they were left as permanent beds (PB). The beds had a flat top of 37 cm wide. Further, the bed width (mid-furrow to mid-furrow) and furrow depth were 67 cm, and 15 cm, respectively. At the end of each annual cropping cycle, the permanent beds were reshaped simultaneously in one go while planting with raised bed multi-crop planter. During the present experimentation (2018–2020), 100% of mung-bean residues (2.60–3.73 Mg ha^{-1}, dry weight basis) were retained in PB+R, ZT+R, FZT+R plots while the same quantities of residues were incorporated in CT+R plots. On the other hand, a maize crop was raised in CT-R (control) plots without residue retention and N application. During the 3-years, the PMH1 (maize hybrid) was sown with a seed rate of 20 kg ha^{-1} (7.46 seeds m^{-2}) during the first week of July in the rainy season and was harvested in the second week of October. In ZT+R, CT+R, FZT+R, and CT-R plots maize planting was done at 67 cm row to row spacing and a plant spacing of 20 cm, while in PB+R plots a single row of maize was planted on top of the raised beds (67 cm apart and a plant spacing of 20 cm) keeping a seed density of 7.46 seeds m^{-2} across all the treatments.

2.3.2. Fertilizer and water application and weed management

A fertilizer dose of 150 kg N + 60 kg P_2O_5 + 40 kg K_2O + 25 kg $ZnSO_4$ ha^{-1} were applied. One-third of N and entire P_2O_5, K_2O, and $ZnSO_4$ were applied as basal at the time of sowing, while the rest two-thirds of N was top-dressed through the application of urea fertilizer at different growth phases as per the N placement protocols of different treatments (detail about treatments is given in Table 1). From the precipitation data, the effective rainfall (ER) was computed using the USDA SCS method (Cropwat 8.0). Irrigation was applied at critical stages as per crop water requirement for each treatment and in the dry spells or periods without rainfall. With the similar number of irrigations, the amount of water applied varied between the tillage practices, while in the case of N placement methods total water applied was same in all the treatments. The water application, measurement, and water use efficiency computations were done as described by Parihar et al. (2017). As for weed management, glyphosate @ 1.0 kg active ingredient (a.i.) ha^{-1} was applied in the ZT+R, PB+R, and FZT+R plots two days before sowing. However, in the case of CT+R and CT-R plots, Atrazine @ 0.75 kg a.i. ha^{-1} + Pendimethalin @ 750 ml a.i. ha^{-1} as pre-emergence (PE) was applied. In addition, 2, 4-D ester was applied @ 750 ml a.i. ha^{-1} in all the plots at 23–25 days after sowing (DAS), while the CT+R and CT-R plots were hand weeded once during 30–35 DAS.

2.4. Data recording and measurement of yields

Accumulated dry matter was measured at 15 days interval by uprooting the plants with proper sampling protocol. The collected plant samples were oven-dried at 60 °C for 2 days till a constant weight was obtained and the dry weight was expressed as g plant^{-1}. Absolute crop growth rate (AGR) was calculated based on the accumulated dry matter within a time span (AGR; g $plant^{-1}$) = $\frac{\Delta W}{\Delta T}$, where $\frac{\Delta W}{\Delta T}$ is the change in dry matter per unit change in time. The yield attributes, *viz.* the number of cobs per hectare, cob length (cm), cob girth (cm), the number of grain rows per cob, the number of grains per row, and 100-grains weight were estimated as per the procedure described by Parihar et al. (2018b). The data of grain and stover yields were estimated from harvested net plots [after excluding the 2-border rows from both directions and 0.5 m in perpendicular direction]. After separating the stover and removing the husk and silk, all the cobs were sun-dried and threshed. The grain yield (GY) was calculated at 15% moisture content and expressed as kg ha^{-1}. The maize stover was cut from ground level and weighed after sun drying. The weight of total harvested produce (cob + stover) from the net plot was recorded after sun drying and was expressed as biological yield (kg ha^{-1}).

2.5. Growth analysis of maize

To describe the biomass accumulation pattern, non linear crop growth models, *viz.* logistic, Gompertz, and quadratic equations were fitted with the observed biomass at a 15-days periodic interval. The best fitted model was used to describe the maize growth behaviour subsequently.

$$y = \frac{c}{(1 + \exp(-a \times (DAP - b)))} (Logistic \quad equation)$$

The parameters a, b, c were estimated by the nls function.

The models were evaluated using the root mean square error (RMSE) values. The RMSE of a certain variable *i* indicates the differences between measured and fitted values. The lower RMSE indicates a better fit for the data.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X - Y)^2}{n}}$$

where X and Y are the measured and fitted values, respectively and n is the number of data points.

2.6. Plant nitrogen analysis, nitrogen uptake and N remobilization

Plant samples were collected at different stages and air-dried. After that, these samples were oven-dried at 60 °C till a constant moisture was obtained and were grounded by Retsch mixer mill MM 400 for N analysis. The N content in grains and stover was determined by CHNS analyzer (Euro EA). N uptake was computed using the following equations:

N uptake (kg ha^{-1}) in grain/stover = [% N in grain/stover × grain/stover yield (kg ha^{-1})].

Total N uptake (kg ha^{-1}) = N uptake in grain + N uptake in stover

The N remobilization and reproductive stage N uptake were calculated by balance method (Ciampitti and Vyn, 2013).

Remobilized N = N accumulated till the end of the vegetative stage – Stover N uptake at harvest

Grain N = Reproductive N + Remobilized N

Where, grain N: total N accumulation in the grain; reproductive N: the N uptake by the plant during the reproductive stage which mostly accumulates in the maize grain; and remobilized N: the fraction of N accumulated in grain contributed by the vegetative parts of the plant. Agronomic N use efficiency was computed as unit increase in grain yield per unit application of N over to control plot.

2.7. Economic analysis

The economic analysis in terms of gross and net return and net benefit-cost ratio (net returns per rupee invested) was computed based on the rate of inputs and output during the study period. The cost of human labor was computed based on the minimum wage rate according to the Indian Labour Law on a person-day basis for a hectare of land, considering 8 h to be equal to one person-day (Minimum Wages Act, 1948). Similarly, a tractor-drawn machine/implement time (h) necessary to complete a field operation was noted and expressed as hr per hectare. The cost for different operations was computed using the time required to complete the specific operation, diesel consumption for completion of each field operation and market price of diesel. Input cost was summed up to calculate the total variable cost (TVC). The gross return (GR) was computed by multiplying the economic outputs (grain and stover yields) with their respective prices. The net returns (NR) were calculated by deducting the TVC from GR (NR = GR-TVC). Indian rupees (INR) were changed into USD by considering the average exchange rate 71.0 in 2018, 70.6 in 2019 and 74.2 in 2020.

2.8. Statistical analysis

The sp.plot function of the package agricolae (Mendiburu, 2021), in R 3.6 (R Core Team, 2018) was used for the analysis of all the data in a split-plot design. When the ANOVA was found significant for main-plot, sub-plot, or interactions, the least significant difference test (using LSD. test function) was used to compare the means. To compare the replication-wise data of split-plot design with the control plot, Welch two-sample *t*-test was done using the t.test function. Correlation between yield attributing character and grain yield was done using the GGally package in R. Step-wise regression was performed between the maize grain yield and yield attributing characters. The linear model with a lower AIC value was used to find the important yield attributing characters describing the variation in maize grain yield. The overall significance of the regression was tested by the lm function and its summary.

3. Results

3.1. Maize growth behavior

The logistic equation best described the maize growth behavior with least observed RMSE value. Among the tillage practices, the accumulated dry-matter followed the trend FZT > PB > ZT > CT (Fig. 1a) (data not shown for FZT and ZT), while for the N placement methods, the trend for dry-matter accumulation was $NPM_3 > NPM_2 > NPM_1$ (Fig. 1b). The highest absolute crop growth rate (AGR) of maize was observed in PB plots (3.79 g $plant^{-1}$ d^{-1}) during 51 DAS, whereas the lowest peak AGR of maize was recorded in CT plots (3.47 g $plant^{-1}$ d^{-1}) at 55 DAS. In FZT and ZT plots, the peak AGR was 3.67 and 3.57 g $plant^{-1}$ d^{-1}, which were observed during 52 and 53 DAS, respectively (Fig. 2a and b).

Maize dry-matter accumulation, till achieving maximum AGR, was higher in the FZT plots (116 g $plant^{-1}$) than PB, ZT, and CT plots (103–108 g $plant^{-1}$) (Fig. 2a). The dry matter accumulation under PB plots was higher at the end of the vegetative stage than FZT, ZT, and CT plots. Interestingly, the fitted AGR under CT plots was slightly higher than the CA-based PB and ZT plots beyond 66–69 DAS. During the week preceding the attainment of physiological maturity, the biomass accumulation in the CT plots was 9.6 g $plant^{-1}$, whereas in the PB plots it was 6.9 g $plant^{-1}$, indicating a forced maturity in CT plots. While in PB plots a slower accumulation and remobilization of carbohydrates might have favored a better cob and grain development. The attainment of physiological maturity was delayed by 2–3 days in PB plots, while silking and pollination was almost completed on the same day in both CA and CT plots.

In all the N placement method plots, the peak AGR was observed during 52 DAS, however, the amount of dry matter accumulation was different. At the time of peak AGR, the maize crop under NPM_3 and NPM_2 had higher dry-matter accumulation than NPM_1 by 13.8 and 9.8 g per plant, respectively. The maximum AGR in NPM_3 was 4 g d^{-1}, whereas, in NPM_1 and NPM_2, the peak AGR amounted to 3.32 and

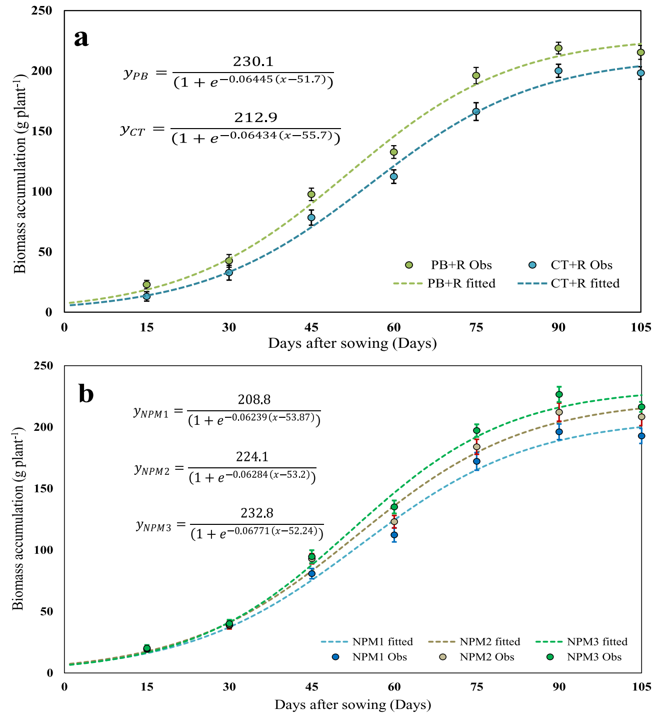

Fig. 1. Biomass accumulation of maize as affected by long-term tillage (a) and nitrogen placement options (b). PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed.

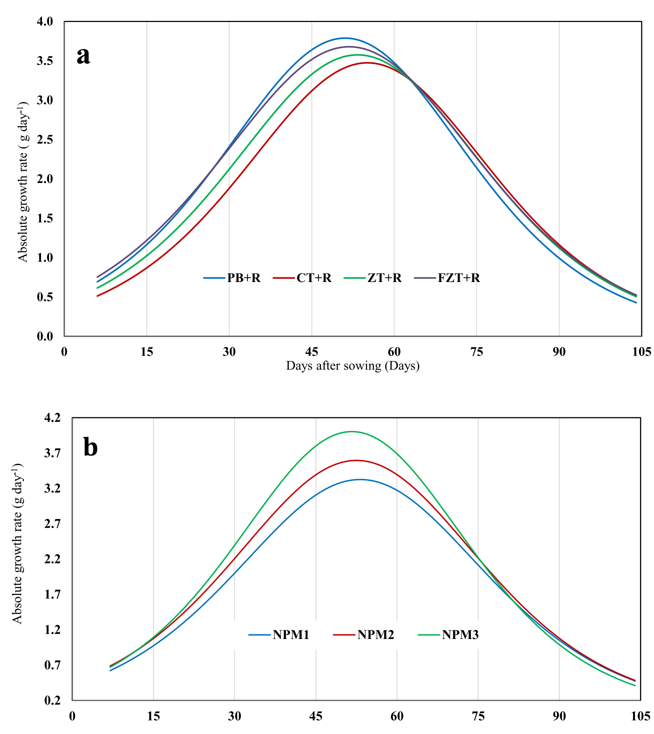

Fig. 2. Absolute growth rate of maize as affected by long-term tillage (a) and nitrogen placement options (b). For treatment detail please see caption of Fig. 1 and Table 1.

3.59 g d^{-1}, respectively. The peak AGR of maize under NPM_1 and NPM_2 plots was similar to the AGR of maize in NPM_3 plots during 65 and 61 DAS, respectively (Fig. 2b). The maximum difference in AGR between NPM_2 and NPM_3 was observed at 49 DAS. Thus, the effect of point placement of N fertilizer on increasing AGR is evident.

3.2. Maize yield attributing characters

Cob length was significantly ($P < 0.01$) affected by both tillage and N placement methods across the years. The interaction effect of tillage and N placement methods was non-significant (data not presented). On average, the cob length in the FZT plots was significantly ($P < 0.01$) higher than CA-based PB and ZT by 2.5% and 3.5%, respectively (Table 2a and b), whereas the least cob length was observed in CT plots (lower than FZT-based plots by 8.5%). Among the N placement methods, NPM_3 had highest cob length, which was 2.3 cm (12.4%) longer than that of NPM_1 (18.5 cm) (Table 2a and b). The parameters cob girth, grain rows per cob and test weight did not vary with respect to tillage, N management methods and their interaction (Table 2a and b). The number of grains per row and number of grains per cob were significantly affected by tillage and N placement methods ($P < 0.05$), whereas the interaction effect was non-significant. The CA-based PB, ZT and FZT plots had a similar number of grains per row (31.4–31.7), which were significantly higher as compared to CT plots (29.1) by 8.4%. Among the N placement methods, NPM_3 had significantly higher grains per row than NPM_1 (by 9.2%), but was at par with NPM_2 (Table 2a and b). NPM_2 and NPM_3 had similar grains per row. CA-based PB, ZT and FZT plots had similar grains numbers per cob, but significantly higher as compared to CT plots. On average, there were 36–53 (8.7–12.9%) more grains per cob in the CA-based plots compared to CT plots (Table 2a and b). Among the N placement methods, NPM_3 had 45 more grains per cob than NPM_1. The number of cobs per hectare were similar among the tillage and N placement methods, as the plant population was maintained similarly in all the treatments.

3.3. Relation between yield attributing characters and yield

The correlation analysis between yield attributing characters and grain yield (GY) showed that the GY was significantly and positively correlated with cob length, number of grains per row and number of cobs per hectare (Supplementary Fig. 2). When the overall correlation was faceted by long-term tillage and N placement methods, the correlation between the GY and cob length was significant only in NPM_3 ($r = 0.512$, $P < 0.01$) and NPM_2 ($r = 0.434$, $P < 0.01$), but not in NPM_1. For all the three N placement methods, the number of grains per row was significantly correlated with GY. Similar results were also confirmed from the step-wise regression. Among the tillage practices, in CT plots, the cob length and number of grains per row were significantly and positively correlated with the GY, whereas, in CA-based PB plots along with the cob length and grain per row, test weight had significant correlation with GY. The number of cobs per hectare was significantly correlated with GY in FZT plots only ($r = 0.565$, $P < 0.01$).

3.4. Nitrogen content and accumulation in grain and stover

Across the three years of the study, N concentration in grains was significantly affected by N placement methods, whereas the effect of tillage and interaction between tillage and N placement methods was non-significant (Table 3). The N content in grain was 3.5% higher in NPM_3 as compared to NPM_1, while NPM_2 and NPM_3 showed a similar N content. The lowest grain N content of ZT-NPM_1 treatment (1.66%) was at par with the grain N content (1.76%) of CT-NPM_3 treatment. The stover N content was not significantly affected by tillage, N placement methods and their interaction (Table 3).

The grain N uptake was significantly affected by the tillage ($P < 0.05$) and N placement methods ($P < 0.001$) (Table 4). Among the tillage

Table 2
Effect of long-term tillage and nitrogen (N) placement methods on yield attributing characters of maize.

a.

Treatments	Cobs ('000 ha^{-1})				Cob length (cm)				Cob girth (cm)			
	2018	2019	2020	Mean	2018	2019	2020	Mean	2018	2019	2020	Mean
Tillage & crop establishment techniques												
PB+R	81.9^{a}	81.0^{a}	82.3^{a}	81.7^{a}	20.0^{b}	19.9^{b}	20.2^{b}	20.0^{b}	14.0^{a}	13.9^{a}	14.1^{a}	14.1
ZT+R	78.8^{a}	78.9^{a}	80.3^{a}	79.3^{a}	19.8^{b}	19.6^{b}	19.9^{b}	19.8^{b}	14.1^{a}	14.0^{a}	14.2^{a}	14.2
FZT+R	81.8^{a}	80.5^{a}	81.9^{a}	81.4^{a}	20.5^{a}	20.4^{a}	20.7^{a}	20.5^{a}	14.2^{a}	14.1^{a}	14.3^{a}	14.2
CT+R	76.3^{a}	77.3^{a}	78.7^{a}	77.4^{a}	18.9^{c}	18.7^{c}	19.0^{c}	18.9^{c}	14.1^{a}	14.0^{a}	14.2^{a}	14.1
Nitrogen placement options												
NPM_1	78.7^{a}	78.4^{a}	79.7^{a}	79.0^{a}	18.5^{c}	18.4^{c}	18.6^{c}	18.5^{c}	14.1^{a}	14.0^{a}	14.2^{a}	14.1
NPM_2	80.1^{a}	79.4^{a}	80.8^{a}	80.1^{a}	20.1^{b}	19.9^{b}	20.2^{b}	20.1^{b}	14.1^{a}	14.0^{a}	14.2^{a}	14.1
NPM_3	80.3^{a}	80.5^{a}	81.8^{a}	80.9^{a}	20.8^{a}	20.7^{a}	21.0^{a}	20.8^{a}	14.2^{a}	14.1^{a}	14.3^{a}	14.2
Interaction (*P* value)	0.079	1.00	1.00	0.83	0.26	0.27	0.25	0.26	0.99	0.99	0.99	0.99
Control (CT-R) mean	55.2	55.2	56.4	55.6	14.5	14.4	14.6	14.5	12.1	12.0	12.2	12.1

b.

Treatments	Number of grains row^{-1}				Number of grains cob^{-1}				100- grain weight (g)			
	2018	2019	2020	Mean	2018	2019	2020	Mean	2018	2019	2020	Mean
Tillage & crop establishment techniques												
PB+R	30.5^{a}	31.5^{a}	32.6^{a}	31.5^{a}	429.6^{a}	442.0^{a}	462.7^{a}	444.7^{a}	28.2^{a}	28.9^{a}	29.0^{a}	28.7^{a}
ZT+R	30.4^{a}	31.3^{a}	32.4^{a}	31.4^{a}	425.1^{a}	437.5^{a}	457.6^{a}	440.1^{a}	28.5^{a}	29.2^{a}	29.3^{a}	29.0^{a}
FZT+R	30.7^{a}	31.6^{a}	32.8^{a}	31.7^{a}	441.4^{a}	453.9^{a}	475.8^{a}	457.0^{a}	28.6^{a}	29.3^{a}	29.4^{a}	29.1^{a}
CT+R	28.2^{b}	29.1^{b}	30.1^{b}	29.1^{b}	390.7^{b}	402.8^{b}	421.4^{b}	404.9^{b}	28.7^{a}	29.3^{a}	29.4^{a}	29.1^{a}
Nitrogen placement options												
NPM_1	28.5^{b}	29.4^{b}	30.4^{b}	29.5^{b}	400.6^{b}	412.4^{b}	431.1^{b}	414.7^{b}	28.1^{a}	28.7^{a}	28.8^{a}	28.6^{a}
NPM_2	30.1^{ab}	31.1^{ab}	32.2^{a}	31.1^{ab}	421.0^{ab}	433.5^{ab}	453.8^{ab}	436.0^{ab}	28.3^{a}	29.0^{a}	29.1^{a}	28.8^{a}
NPM_3	31.2^{a}	32.2^{a}	33.3^{a}	32.2^{a}	443.6^{a}	456.3^{a}	478.1^{a}	459.3^{a}	29.1^{a}	29.8^{a}	29.9^{a}	29.6^{a}
Interaction (*P* value)	0.99	0.99	0.99	0.99	0.94	0.93	0.91	0.92	0.43	0.42	0.42	0.42
Control (CT-R) mean	19.7	20.5	21.2	20.4	237.9	247.4	258.1	247.8	27.8	28.3	28.4	28.1

PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed.

Table 3
Nitrogen content in maize as affected by long-term tillage and N placement methods.

Treatments	N content (%)					
	Grains			Stover		
	2018	2019	2020	2018	2019	2020
Tillage & crop establishment techniques						
PB+R	1.727^{a}	1.690^{a}	1.671^{a}	0.566^{a}	0.558^{a}	0.548^{a}
ZT+R	1.701^{a}	1.665^{a}	1.647^{a}	0.554^{a}	0.549^{a}	0.538^{a}
FZT+R	1.752^{a}	1.716^{a}	1.696^{a}	0.563^{a}	0.557^{a}	0.548^{a}
CT+R	1.728^{a}	1.694^{a}	1.672^{a}	0.533^{a}	0.525^{a}	0.515^{a}
Nitrogen placement options						
NPM_1	1.691^{b}	1.656^{b}	1.637^{b}	0.551^{a}	0.542^{a}	0.534^{a}
NPM_2	1.737^{a}	1.702^{a}	1.682^{a}	0.555^{a}	0.550^{a}	0.540^{a}
NPM_3	1.753^{a}	1.717^{a}	1.696^{a}	0.557^{a}	0.549^{a}	0.539^{a}
Interaction (*P* value)	0.934	0.921	0.916	0.998	0.995	0.996
Control (CT-R) mean	1.545	1.517	1.502	0.453	0.445	0.441

PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed.

treatments, the highest N uptake was observed in FZT and PB plots. The 3-year mean N uptake in PB and ZT plots were 13.5% and 8.9% higher than CT plots, respectively (Table 4). Similarly, across the years, NPM_3 plots had significantly higher N uptake by 14.6–19.6% compared to NPM_1 plots. Among tillage and N placement methods, the N uptake varied between 82.8-83.7 kg ha^{-1} in CT-NPM_1 to 115 kg ha^{-1} in FZT-NPM_3 and 115.5 kg ha^{-1} in PB-NPM_3 (data not presented). Across the years, total N accumulation in maize stover was significantly different among the tillage practices and N placement methods ($P < 0.05$), whereas the interaction effect was non-significant. The N accumulation in the stover was similar in PB, ZT, and FZT plots (46.1–49.5 kg ha^{-1}), which was significantly higher than CT-plots. The largest stover N uptake was observed in NPM_3 plots, and smallest in the NPM_1 plots, which was at par with NPM_2. Overall, the stover N accumulation in NPM_3 treatment plots was 14.5% higher than the NPM_1 plots.

3.5. Nitrogen remobilization and reproductive stage N uptake

The N remobilization was significantly affected by the tillage ($P < 0.05$) and N placement methods ($P < 0.001$), whereas the interaction effect was non-significant (Fig. 3). Although the N content during initial reproductive stage of maize was similar in all the tillage treatments, the CA-based PB, ZT, and FZT plots had higher N remobilization (by 16.2–21.1%) compared to CT plots (Fig. 3). Across the years, the amount of vegetative N remobilized to maize grain was significantly different among N placement methods. The N remobilized in the NPM_3 and NPM_2 treatments was 22.9% and 10.8% higher than the NPM_1 treatment, respectively (Fig. 3). Among the tillage practices and N placement methods, the percentage of vegetative stage accumulated N remobilized to grain was not significantly different (Table 4). The percentage of vegetative stage accumulated N remobilized to maize grain ranged between 46.1% in CT to 49.4% in FZT among tillage treatments and 47.5% in NPM_1 to 48.9% in NPM_3 among N placement treatments.

The N uptake during reproductive stage was significantly affected by tillage practices ($P < 0.05$), N placement methods ($P < 0.001$) and interaction between tillage and N placement methods ($P < 0.05$). The CA-based PB and ZT plots had 12% and 9% higher N uptake during the reproductive stage compared to CT plots, respectively (Fig. 3). Among the N placement methods, NPM_2 and NPM_3 treatments had 9–13% higher N uptake during the reproductive stage as compared with NPM_1 (Fig. 3), while both NPM_2 and NPM_3 treatments had similar N uptake. Among the interaction effects (tillage × N placement methods), the highest reproductive stage N uptake was observed in PB-NPM_3, ZT-NPM_3, and FZT-NPM_3 plots (data not presented). Interestingly, unlike CA-based plots, the sub-surface point placement of the third split of N

Table 4
Nitrogen uptake in grain and stover and 3-year mean % of vegetative N remobilized in maize as affected by long-term tillage and N placement methods.

Treatments	N uptake (kg ha^{-1})								% of Vegetative N remobilized
	Grain				Stover				
	2018	2019	2020	Mean	2018	2019	2020	Mean	
Tillage & crop establishment techniques									
PB+R	101.9^{a}	104.4^{a}	106.4^{a}	103.7^{a}	47.2^{a}	49.5^{a}	48.6^{a}	43.1^{a}	47.6^{a}
ZT+R	98.8^{ab}	101.5^{a}	101.3^{ab}	99.6^{a}	45.1^{a}	46.3^{a}	45.5^{a}	40.6^{a}	48.9^{a}
FZT+R	102.4^{a}	101.5^{a}	104.0^{a}	102.9^{a}	46.3^{a}	46.1^{a}	46.7^{a}	42.7^{a}	49.5^{a}
CT+R	91.3^{b}	89.9^{b}	92.0^{b}	91.4^{b}	40.1^{b}	39.7^{b}	39.2^{b}	35.4^{b}	46.2^{a}
Nitrogen placement options									
NPM_1	89.4^{c}	91.3^{c}	93.8^{b}	91.1^{c}	41.1^{b}	43.7^{b}	43.2^{a}	37.8^{c}	47.5^{a}
NPM_2	99.5^{b}	99.9^{b}	101.5^{ab}	100.1^{b}	45.3^{ab}	45.3^{ab}	45.3^{ab}	40.2^{b}	47.6^{a}
NPM_3	106.9^{a}	106.9^{a}	107.5^{a}	107.0^{a}	47.7^{a}	47.3^{a}	46.6^{a}	43.3^{a}	48.9^{a}
Interaction (*P* value)	0.25	0.99	0.85	0.73	0.91	0.92	1.00	0.11	0.76
Control (CT-R) mean	37.3	38.4	38.1	38.0	24.3	23.6	23.3	22.3	–

PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed.

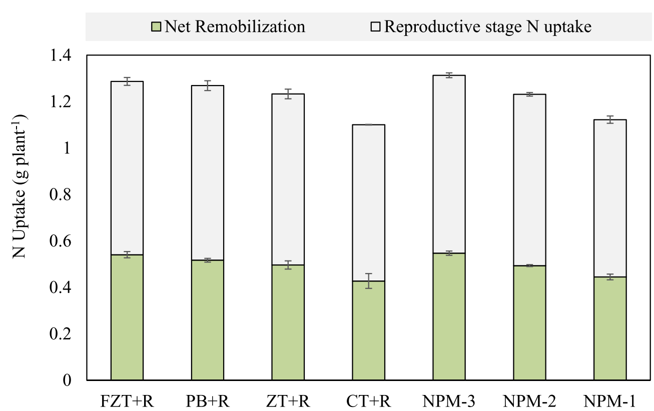

Fig. 3. Contribution of remobilized N and reproductive stage N uptake to grain N uptake under long-term tillage and N placement options. Values are the mean ± standard error. For treatment detail please see caption of Fig. 1 and Table 1.

fertilizer (NPM_3) did not increase the reproductive stage N uptake in the CT plots (data not presented).

3.6. Yield and agronomic nitrogen use efficiency

Maize grain yield (GY) was significantly affected by tillage ($P <$ 0.05), N placement methods ($P < 0.001$), and their interaction ($P <$ 0.05). Across the years, CA-based ZT, PB, and FZT plots had similar GY, which was significantly higher than CT plots by 9.9–15.7% (Table 5). As for N placement methods, adoption of NPM_2 and NPM_3 increased the GY by 6.9–13.2% (3-year mean basis) compared to NPM_1 plots, respectively. Among tillage × N placement methods, the highest GY was observed in the NPM_3 plots of FZT, PB, and ZT. The NPM_3 plots of CA-based PB, ZT, and FZT had significantly ($P < 0.05$) higher GY as compared to their respective NPM_2 plots by 4.7%, 7.0% and 6.0% (Fig. 4). On the contrary, the GY was not affected by N placement methods under CT. Sub-surface N point placement of both first and second splits (NPM_3) in CA-based PB and ZT practices gave a prominent yield increment up to 284–413 kg ha^{-1} compared to sub-surface point placement of only the first N split (NPM_2), whereas no such increment was observed in CT plots between NPM_2 and NPM_3 (Fig. 4). The highest GY observed in the CT plots (observed in CT−NPM_3 plots) was similar to the GY in NPM_1 of CA-based plots.

The stover yield was significantly ($P < 0.05$) affected by tillage and N placement methods, whereas the interaction (tillage × N placement methods) was non-significant. Across the years, the CA-based ZT, PB, and FZT plots showed similar stover yield, which was 8.4–17.4% higher than CT (Table 5). Similarly, the stover yield in NPM_3 and NPM_2 plots were higher than the NPM_1 by 6.9–14.5% and 3.3–9.3%, respectively (Table 5).

The effect of tillage, N placement methods and their interactions were significant on agronomic N use efficiency (ANUE) (Table 6). Across

Table 5
Effect of long-term tillage and N placement methods on maize grain, stover and biological yields.

Treatments	Grain yield (kg ha^{-1})				Stover yield (kg ha^{-1})				Biological yield (kg ha^{-1})			
	2018	2019	2020	Mean	2018	2019	2020	Mean	2018	2019	2020	Mean
Tillage & crop establishment techniques												
PB+R	5896^{a}	6078^{a}	6355^{a}	6110^{a}	8334^{a}	8891^{a}	8882^{a}	8702^{a}	15,707^{a}	16,630^{a}	17,170^{a}	16,502^{a}
ZT+R	5803^{a}	5923^{a}	6146^{a}	5958^{a}	8150^{a}	8478^{a}	8454^{a}	8361^{a}	15,331^{a}	16,094^{a}	16,318^{a}	15,914^{a}
FZT+R	5839^{a}	5952^{a}	6133^{a}	5975^{a}	8207^{a}	8313^{ab}	8527^{a}	8349^{a}	15,553^{a}	15,728^{a}	16,623^{a}	15,968^{a}
CT+R	5279^{b}	5372^{b}	5494^{b}	5381^{b}	7518^{b}	7572^{b}	7602^{b}	7564^{b}	14,283^{b}	14,407^{b}	14,656^{b}	14,449^{b}
Nitrogen placement options												
NPM_1	5292^{c}	5438^{c}	5736^{c}	5489^{c}	7462^{b}	8035^{b}	8079^{b}	7859^{c}	14,189^{c}	15,081^{b}	15,483^{b}	14,918^{c}
NPM_2	5724^{b}	5845^{b}	6029^{b}	5866^{b}	8153^{a}	8303^{ab}	8381^{ab}	8279^{b}	15,341^{b}	15,691^{ab}	16,267^{a}	15,767^{b}
NPM_3	6097^{a}	6211^{a}	6331^{a}	6213^{a}	8541^{a}	8602^{a}	8637^{a}	8593^{a}	16,125^{a}	16,372^{a}	16,825^{a}	16,441^{a}
Interaction (*P* value)	0.021	0.04	0.15	0.021	0.59	0.86	1.00	0.29	0.40	0.83	1.00	0.20
Control (CT-R) mean	2411	2529	2546	2495	5381	5315	5339	5345	10,027	9622	9687	9779

PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed.

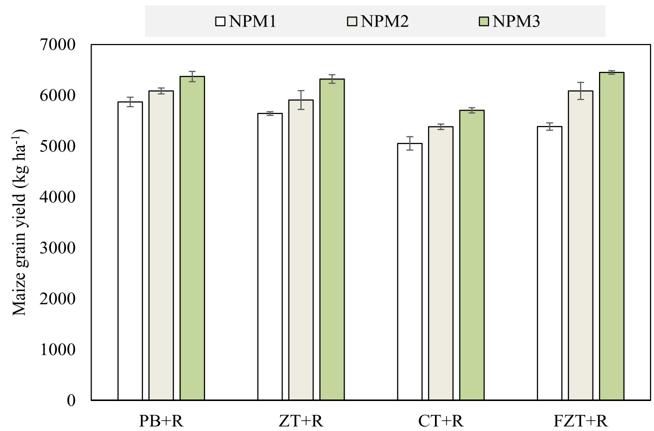

Fig. 4. Maize grain yield (3-year mean basis) as affected by interactive effect of long-term tillage and N placement options. Values are the mean ± standard error. For treatment detail please see caption of Fig. 1 and Table 1.

the 3-years of experimentation, the ANUE was increased by 18.3–28.9% in the CA-based plots than CT. The CA-based plots, *i.e.,* PB, ZT, and FZT were acting equally and had similar ANUE. The point placement of both the N split (NPM_3) gave an additional 4.8 kg of grains per kg of applied N than surface application (NPM_1) amounting to an increase in ANUE by 24%. The interaction effect between tillage and N placement for ANUE followed similar trends as of GY, with the largest ANUE of 26.4 and 25.8 kg grain increase kg^{-1} N applied being observed in the FZT-NPM_3 and PB-NPM_3, while the lowest value was observed under CT-NPM_1 (17.1 kg grain increase kg^{-1} N applied) on a 3-years mean basis (Table 6).

3.7. Economics

The cost of cultivation (COC) in CT plot was significantly higher as compared to CA-based PB, ZT, and FZT plots, by 10.0–11.6% (3-years mean basis) (Table 6). The CA-based PB plots had USD 6.6 more cultivation cost than ZT, while the cultivation cost in ZT and FZT plots were similar across the years (USD 398–459 ha^{-1}; 3-years mean basis). Among the N placement methods, NPM_3 and NPM_2 had 3.3–5.7% and 1.7–2.0% higher cultivation cost compared to NPM_1 (402, 425, and 458 USD ha^{-1} in 2018, 2019, and 2020), respectively (Table 6). Tillage ($P < 0.01$), N placement ($P < 0.001$), and their interaction ($P < 0.05$) had a significant impact on net returns (NR). NR in theCA-based plots varied between USD 1109 to 1248 ha^{-1} (Table 6) across the study years. During all the 3-years, the least NR (USD 918–979 ha^{-1}) was observed in the CT plots. Among the N placement methods, NPM_3 and NPM_2 had significantly higher NR by USD 141–186 ha^{-1} and 70–106 ha^{-1} than NPM_1, respectively. Among the interaction effects, the lowest NR (USD 836–901 ha^{-1}) was observed in the CT-NPM_1 and the highest was observed in FZT-NPM_3 (USD 1280 ha^{-1}) in 2018, FZT-NPM_3 (USD 1261 ha^{-1}) in 2019 and PB-NPM_3 (USD 1284 ha^{-1}) in 2020. Tillage, N placement methods and their interaction significantly affected the net benefit-cost ratio (NBCR). Across the study years, the highest NBCR was observed under CA-plots (2.42–2.81) compared to CT-plots (1.82–2.05) and in NPM_3 and NPM_2 (2.29–2.74) than NPM_1 plots (2.13–2.43). Among the interaction effects, the lowest and highest NBCR was observed under CT-NPM_1 and CA-based practices with NPM_3 practices (PB-NPM_3, FZT-NPM_3, and ZT-NPM_3), respectively. The lowest NBCR ratio in the CA-based plots was 24% higher as compared to CT's maximum NBCR (Table 6).

3.8. Water use and water use efficiency of maize

Across the years, water use was significantly affected by tillage practices, but not by N placement methods. Among the tillage practices, PB and ZT plots required 15–45 and 10–30 mm less water as compared to CT plots, respectively (Table 7). The water use in all the three N placement method plots was similar across the years (Table 7). Water use efficiency (WUE) was significantly affected by the tillage ($P < 0.05$), N placement methods ($P < 0.001$) and their interactions ($P < 0.05$). The CA-based PB, ZT, and FZT plots had similar WUE, which was higher than WUE of CT plots by 11.9–26.4%. Among the N placement methods, the lowest WUE (10.3–11.7 kg ha^{-1} mm^{-1}) was observed in the NPM_1 treatment (Table 7). The WUE of NPM_3 treatment was 13.4% (3-year mean basis) higher than the NPM_1 treatment. The WUE among the tillage × N placement methods interaction varied between 9.41 and 10.5 kg ha^{-1} mm^{-1} in CT-NPM_1 to 12.2–14.2 kg ha^{-1} mm^{-1} in FZT-NPM_3 and PB-NPM_3 across the years (data not presented). During the 11th, 12th, and 13th years of experimentation, the WUE in NPM_3 of PB and ZT was significantly higher by 0.6–7.2% and 4.6–8.6% than their respective NPM_2 treatment.

4. Discussion

4.1. Yield attributing characters and maize grain yield

The step-wise regression showed that overall variation in the maize GY was described by cob length and number of cobs per hectare. The equation for overall maize GY under CA-based practices and N point placement methods (NPM) is.

GY in overall = 219.94 × Cob length + 0.01719 × Number of Cobs per hectare (Adj. $R^2 = 0.9965$)

GY in CA = 228.85 × Cob length + 0.01607 × Number of Cobs per hectare (Adj. $R^2 = 0.9981$)

Table 6
Economics of maize as affected by long-term tillage and N placement methods.

Treatments	Cost of cultivation (USD ha^{-1})				Net return (USD ha^{-1})				Net BC ratio				ANUE (kg grain increase kg^{-1} N applied)			
	2018	2019	2020	Mean	2018	2019	2020	Mean	2018	2019	2020	Mean	2018	2019	2020	Mean
Tillage & crop establishment techniques																
PB+R	405^{b}	427^{b}	459^{b}	430^{b}	1128^{a}	1149^{a}	1248^{a}	1175^{a}	2.79^{a}	2.47^{a}	2.72^{a}	2.66^{a}	23.2^{a}	23.7^{a}	25.4^{a}	24.1^{a}
ZT+R	398^{c}	421^{c}	453^{c}	424^{c}	1109^{a}	1111^{a}	1197^{a}	1139^{a}	2.79^{a}	2.42^{a}	2.64^{a}	2.62^{a}	22.6^{a}	22.6^{a}	24.0^{a}	23.0^{a}
FZT+R	398^{c}	421^{c}	453^{c}	424^{c}	1119^{a}	1115^{a}	1195^{a}	1143^{a}	2.81^{a}	2.43^{a}	2.64^{a}	2.63^{a}	22.9^{a}	22.8^{a}	23.9^{a}	23.2^{a}
CT+R	450^{a}	473^{a}	497^{a}	473^{a}	923^{b}	918^{b}	979^{b}	940^{b}	2.05^{b}	1.82^{b}	1.97^{b}	1.95^{b}	19.1^{b}	19.0^{b}	19.7^{b}	19.2^{b}
Nitrogen placement options																
NPM_1	402^{c}	425^{c}	458^{c}	428^{c}	972^{c}	981^{b}	1084^{b}	1013^{c}	2.43^{b}	2.13^{b}	2.38^{b}	2.31^{c}	19.2^{c}	19.4^{c}	21.3^{b}	20.0^{c}
NPM_2	410^{b}	433^{b}	466^{b}	436^{b}	1078^{b}	1076^{a}	1154^{a}	1103^{b}	2.64^{a}	2.29^{ab}	2.49^{ab}	2.48^{b}	22.1^{b}	22.1^{b}	23.2^{ab}	22.5^{b}
NPM_3	425^{a}	448^{a}	473^{a}	449^{a}	1158^{a}	1162^{a}	1225^{a}	1182^{a}	2.74^{a}	2.44^{a}	2.60^{a}	2.59^{a}	24.6^{a}	24.5^{a}	25.2^{a}	24.8^{a}
Interaction (*P* value)	–	–	–	–	0.016	0.05	0.18	0.027	0.014	0.04	0.23	0.014	0.021	0.04	0.15	0.021
Control (CT-R) mean	400.6	423.3	450.5	424.8	254.4	286.3	258.3	266.3	0.64	0.68	0.57	0.63	–	–	–	–

PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed.

Table 7
Agronomic nitrogen use efficiency (ANUE), water use and water use efficiency (WUE) of maize as affected by long-term tillage and N placement methods.

Treatments	Total water applied (*ER + irrigation-mm)				WUE (kg $ha^{-1}mm$)			
	2018	2019	2020	Mean	2018	2019	2020	Mean
Tillage & crop establishment techniques								
PB+R	508.7^{c}	453.4^{c}	473.1^{c}	478.4^{c}	11.6^{a}	13.4^{a}	13.4^{a}	12.8^{a}
ZT+R	513.7^{b}	463.4^{b}	488.1^{b}	488.4^{b}	11.3^{a}	12.8^{a}	12.6^{a}	12.2^{b}
FZT+R	513.7^{b}	463.4^{b}	488.1^{b}	488.4^{b}	11.4^{a}	12.8^{a}	12.6^{a}	12.3^{b}
CT+R	523.7^{a}	483.4^{a}	518.1^{a}	508.4^{a}	10.1^{b}	11.1^{b}	10.6^{b}	10.6^{c}
Nitrogen placement options								
NPM_1	515.0^{a}	465.9^{a}	491.9^{a}	490.9^{a}	10.3^{c}	11.7^{c}	11.7^{c}	11.2^{c}
NPM_2	515.0^{a}	465.9^{a}	491.9^{a}	490.9^{a}	11.1^{b}	12.6^{b}	12.3^{b}	12.0^{b}
NPM_3	515.0^{a}	465.9^{a}	491.9^{a}	490.9^{a}	11.8^{a}	13.4^{a}	12.9^{a}	12.7^{a}
Interaction (*P* value)	–	–	–	–	0.021	0.04	0.22	0.022
Control (CT-R) mean	523.7	483.4	518.1	508.4	4.60	5.23	4.91	4.92

PB+R: Zero till permanent raised bed; ZT+R: Zero till flat; CT+R: Conventional till flat; FZT+R: First time zero till flat sowing of crops on last 10-year fallow land; +R indicates residue retention/incorporation; CT-R: Conventional tillage without residue and N application; NPM_1: both the N splits were surface band placed; NPM_2: only 1st split of N was point placed and 2nd split of N was surface band applied: NPM_3: both the N splits were point placed. *Effective rainfall was 458.7 mm in 2018, 353.4 mm in 2019 and 323.1 mm in 2020.

GY in NPM = 289.137 × Cob length (Adj. R^2 = 0.997)

The estimate of the partial regression coefficient for cob length was significant in all the above equations, whereas the estimate for the number of cobs was non-significant. The partial regression coefficient for cob length was higher in CA-based practices, indicating that GY was influenced more by cob length in CA compared to all other system including CT. The larger cob facilitates greater number of grains per row under CA-based plots, *i.e.,* PB, ZT, and FZT plots. In contrary to the tillage practices, among the N point placed treatments, only the cob length remained as an explanatory variable to the GY. Similar results of higher cob length and number of cobs per hectare and their positive correlation to GY under CA were also observed by Jat et al. (2018) and Parihar et al. (2018b).

4.2. Crop yield

In the present study, CA-based practices and point placement of both the N splits (NPM_3) resulted in higher biomass and N-accumulation, which could explain the higher GY in CA and NPM_3 plots. Maize GY had been improved with increase in total biomass production (Lorenz et al., 2010). The enhanced GY with higher biomass and N-accumulation under CA-based systems could be explained by an efficient growing microclimate with better soil physical properties (Parihar et al., 2016a), soil biochemical properties (Parihar et al., 2018a), higher infiltration and favorable soil moisture dynamics (Govaerts et al., 2007; 2009). Additionally, adoption of right placement of nitrogen fertilizer increases the N availability that flourishes the vegetative growth of the cultivated crops (Barbieri et al., 2014; Hansel et al., 2017; Kraska et al., 2021; Mallarino and Borges, 2006; Ressler et al., 1998). Such increase in the vegetative growth improves the source strength in the crop in terms of higher green leaves and biomass formation (Gungula et al., 2005). The potential for biomass accumulation provides a driving force for mineral nutrient accumulation (Karlen et al., 1988) and higher productivity. Similarly, Nash et al. (2013), Johnson et al. (2017) and Jiang et al. (2018) observed higher GY with point placement of N fertilizer.

4.3. Nitrogen uptake

The N uptake was higher under CA system and both in NPM_2 and NPM_3 plots, suggesting higher N availability when N was point placed. The higher N uptake could be due to the higher N concentration in the root zone with reduced N volatilization losses. Fengqin et al. (2018) observed higher N uptake under N placement plots and attributed it to direct N application in the effective root zone where the root system grows around the fertilizer placement, while Wang and Zhou (2013) proposed the idea of fertisphere (special nutrient reach zone surrounding root system; Su et al., 2011) overlapping by point placement of applied fertilizer with the active root zone. In a heterogeneous soil environment, the response of plants differ because of differential roots morphological plasticity to forage nutrients (Fengqin et al., 2018). When the roots encounter a nutrient-rich zone or patch, they proliferate and capture the applied fertilizer nutrients. With the deep placement of urea, the tap root diameter increased with proliferation of lateral roots, which increased the ability of the plant to access more rhizosphere volume for nutrient acquisition (Su et al., 2015). Similarly, in the present experiment, a higher total N uptake and reproductive stage N uptake was observed in the N point placed treatments. Likewise, Prasertsak et al. (2002) observed that the crop biomass under subsurface N applied treatment contains significantly more N compared to the corresponding parts in the surface N applied treatment.

4.4. Nitrogen remobilization and reproductive stage N accumulation

The N remobilization was observed higher in the CA and N point placement plots, which could be due to the higher N accumulation through increased biomass with similar N concentration. With higher N accumulation, higher N can be remobilized during the late reproductive stage. Pan et al. (1986) concluded that a balanced contribution from reproductive stage N uptake and remobilized N together contribute to a higher NUE. The percentage of vegetative N remobilized to grain remained similar across the tillage practices and N placement methods. This indicates the similar efficiency of all the systems to remobilize the accumulated N. If the current N uptake is not sufficient because of higher N demand, the remobilization of N is accelerated (Triboi and Triboi-Blondel, 2002), which is followed by leaf senescence. Reduced reproductive stage N uptake in the CT plots could be due to reduced root activity, attributable to poor soil physical properties (Parihar et al., 2016a).

In the present study, across the tillage and N placement treatments, 59.6% of the total N in grain was contributed by the reproductive stage N uptake. The finding of Ciampitti and Vyn (2013) supports our results, in which they found that the contribution of N uptake during the reproductive stage was around 56% to the grain N. Higher mineral N availability (both ammonium and nitrate) in the N point placed plots along with better soil physical environment under CA-based systems delay the leaf senescence. With an active root system, the N uptake during the reproductive stage remained higher in the CA-based plots. In contrast, in CT plots, the root system might not be active for an efficient N uptake during the reproductive stage. Uthuzurum et al. (1998) concluded that moisture and nutrient deficiencies lead to losses of green leaves. Not only the nutrient stress, but also overcrowding at particular nutrient and moisture availability affects the plant behavior (Borrás et al., 2003). Additionally, poor soil physical properties aggravate the negative impacts of moisture and nutrient deficiencies. In our study, in the CT plots, the leaf senescence started earlier which resulted in 2–3 days earlier attainment of physiological maturity as compared with PB plots, suggesting lower moisture and nutrients availability.

4.5. Water use and water use efficiency

The higher WUE in the CA-based plots could be due to the reduction in water use (amount of irrigation water applied) and the proportionately gain in GY. The less water use (Table 7) could be attributed to lesser evaporation from the soil surface due to crop residue retention. Crop residue insulates and shields the soil surface from solar radiation (Busari et al., 2013; Jat et al., 2019b; Parihar et al., 2019; Rasmussen, 1999). A thick layer of crop residue increases the boundary layer resistance and decrease net energy at the soil surface, thus less water evaporates in CA-based plots (Eberbach et al., 2011; Lal, 2008). CA-based practices reduced evaporation by 23–37% than CT plots (Parihar et al., 2019). Additionally, CA-based management practices positively affect water holding capacity of the soil by increasing soil organic matter (SOM) and by altering pores connectivity distribution (Liu et al., 2013; Omara et al., 2019; Patra et al., 2019). Increased soil organic matter in return increase the water holding capacity of the soil due to its hydrophilic properties (Munera-Echeverri et al., 2020; Pareja-Sánchez et al., 2017). As the soil organic matter holds approximately 20 times moisture of their weight, therefore the rapid loss of moisture from CA-based plots are prevented (Reicosky and Wilts, 2005), and resulted in a less frequent moisture deficit. CA not only increases SOM, but also alters pore size distribution (Franzluebbers, 2010; Sun et al., 2020; Williams et al., 2020), which leads to decrease in runoff and increase in soil infiltration capacity, thus increases water storage capacity of the soil. The higher water use efficiency in the N point placed fertilizer treatments could be due to the fact that N increases the growth and GY of the crop (Aulakh and Malhi, 2005).

4.6. Economics

The lesser cultivation cost in the CA-based plots (by USD 38–52 ha^{-1}) could be due to the omission of one discing, two cultivators plowing and one-planking as compared to CT plots. Moreover, next to land management, the additional mechanical weddings in CT-plots increased the cultivation cost. Since the N point placement was done manually, it involves an additional cost of ~20 USD for point placement of both the N splits. The lower grain and stover yields with the additional cultivation cost in CT systems, reduced the Net BC ratio. Similar to our findings, Parihar et al. (2016b), Gathala et al. (2013) and Jat et al. (2018) observed a higher net BC ratio in the CA-based plots mainly attributed to lesser tillage and weeding in established CA-plots.

The lack of suitable machinery for sub-surface application of N in the residue retained soil under CA is a major hurdle. At the same time, a high clearance tractor is required in the case of tall crops like maize, in particular for the late vegetative N splits application. With the availability of machinery, favorable economics can be expected in the majority of the row crops. As per the findings from earlier studies, to achieve higher N use efficiency, a uniform amount of N fertilizer must be point placed at 7.5–10 cm. Maintaining this with the manual application all over the field is not practically feasible as it requires skilled labourers and is time consuming. The availability of a large number of man-days during peak periods is also a daunting task. Placement of N fertilizer with wet hands causes discomfort to the laborers. If the soil is not that wet the holes left after placing the fertilizer will not be filled up automatically.

5. Conclusions

Maize growth rate under CA-based plots remained higher and the peak growth rate was advanced by 4–5 days. Moreover, point placement of N fertilizer increased the maize growth rate, but the growth behavior remained similar. The yield attributing characters, *i.e.,* cob length and the number of cobs per hectare described most of the variability in the GY under CA, whereas the cob length was the only yield attributing character describing the GY variability in N point placed treatments. The higher biomass accumulation till the end of the vegetative stage increased the N uptake in the CA-based and NPM_3 plots, which resulted in higher remobilization of N to the grain during reproductive stage. The proportion of remobilized N to accumulated N remained similar across all the tillage and N placement treatments. The contribution of reproductive stage N uptake to the grain N was higher in the CA-based plots and in NPM_2 and NPM_3 plots. The higher N uptake during reproductive stage and greater contribution of vegetative stage accumulated N to grain as remobilized N in the CA-based and in NPM_2 and NPM_3 plots enhanced maize grain yield and N uptake. The GY was significantly affected by tillage and N placement interactions across the years. The third split N application under CT, either by point placement or surface band placement resulted in a similar GY. However, the point placement of the third N split under CA-based plots significantly increased the GY. Across the three years of the study, agronomic N use efficiency and water use efficiency were higher in CA-based plots and N placement treatments. Consequently, the present study recommends the point placement of N fertilizer under long-term CA to increase the crop productivity, profitability, N uptake and remobilization, and N and water use efficiency in the IGP and other similar agro-ecologies. However, the sub-surface application of N fertilizers has some constraints, which could be overcome once suitable machinery is developed to work under CA.

CRediT authorship contribution statement

HSN, CMP: Conceptualization, design, investigation, and maintainance of experiment, data analysis and writing of manuscript; MLJ, VKS, SLJ, RS: Conceptualization, supervision, funding acquisition and feedback on manuscript draft; BNM: Statistical analysis; KP, SG, JN, AMA: drafting of manuscript, correction at revision stage, writing-review and editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2021.126417.

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