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ORIGINAL ARTICLE

Green leaf manuring with prunings of *Leucaena leucocephala* for nitrogen economy and improved productivity of maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system

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Abstract Green leaf manuring with prunings of *Leucaena leucocephala* is regarded as a useful source of N to plants but the actual substitution of N fertilizer, release and recovery of N as well as effects on soil fertility are not adequately studied. The present studies investigated the effect of sole and combined use of *Leucaena* prunings and urea N fertilizer in different proportions on productivity, profitability, N uptake and balance in maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system at New Delhi during 2002–2003 and 2003–2004. Varying quantities of *Leucaena* green leaf biomass containing 3.83–4.25% N (18.2–20.5 C:N ratio) were applied to provide 0, 25, 50, 75 and 100% of recommended N (120 kg ha^{-1}) to both maize and wheat before sowing. In general, direct application of urea N increased the productivity of both crops more than *Leucaena* green leaf manure, but the reverse was true for the residual effect of these sources. The productivity of maize increased progressively with increasing proportions of N through urea fertilizer and was 2.41–2.52 t ha^{-1} with 60 kg N ha^{-1} each applied through *Leucaena* and urea, which was at par with that obtained with 120 kg N ha^{-1} through urea alone (2.56–2.74 t ha^{-1}). Similarly, wheat yield was also near maximum (4.46–5.11 t ha^{-1}) when equal amounts of N were substituted through *Leucaena* and urea. Residual effects were obtained on the following crops and were significant when greater quantity of N (>50%) was substituted through *Leucaena*. Nitrogen uptake and recovery were also maximum with urea N alone, and N recovery was higher in maize (33.4–42.1%) than in wheat (27.3–29.8%). However, recovery of residual N in the following crop was more from *Leucaena* N alone (8.5–10.3%) than from urea fertilizer (1.7–3.8%). Residual soil fertility in terms of organic C and $KMnO_4$ oxidizable N showed improvement with addition of *Leucaena* prunings, which led to a positive N balance at the end of second cropping cycle. Net returns were considerably higher with wheat than with maize, and were comparatively lower with greater proportion of *Leucaena* because of its higher cost. Nonetheless, it was beneficial to apply *Leucaena* and urea on equal N basis for higher productivity and sustainability of this cereal-based cropping system.

Keywords Apparent N balance · C:N ratio · Direct effect · Grain yield · N recovery · Net returns · Residual effect · Soil fertility · Urea N

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Introduction

Vegetative materials have long been used for moisture conservation, nutrient supply and weed control for improving crop productivity under varying soil and climatic conditions. Mulching with twigs and leaves of

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various non-fodder trees and shrubs has been widely investigated for erosion control and moisture conservation in rainfed and hilly areas (Sharma et al. 2005). In irrigated lowland areas, green manuring with annual legumes in situ such as *Sesbania aculeata* and *Crotalaria juncea* was practised for effecting nitrogen economy, improving productivity and soil fertility (Singh et al. 1991; Sharma and Ghosh 2000). Of late, these beneficial practices have shown a gradual decline due to adoption of intensive cropping systems, easy availability of chemical fertilizers, irrigation, herbicides and other inputs. The problem is further aggravated due to non-availability of traditional organic manures, discontinuance of legumes in sole or intercropped cereal-based systems and repetitive tillage with complete removal of residues, leading to deterioration of soil fertility and productivity decline in the long-run. Such effects have been widely experienced in the highly productive lands of the Indo-Gangetic plains where the predominantly cereal-based rice-wheat and maize-wheat systems are followed (Nambiar 1998; Sharma and Behera 2004; Prasad 2005).

Fast-growing leguminous trees and shrubs like *Gliricidia*, *Cassia*, perennial *Sesbania* and *Leucaena* are grown in non-agricultural lands or in alley cropping systems for multiple uses such as fodder, fuel and minor timber as well as nutrient cycling from the pruned biomass. *Leucaena leucocephala* was introduced in India in 1970s, and it was often hailed as a wonder tree with huge potential for production of biomass (20–25 t ha^{-1}) and nitrogen (500 kg ha^{-1}) (Guevarra 1976), and suitability for excessive pruning in alley or hedge-row cropping systems. Use of *Leucaena* prunings as fodder has not found much favour with the farmers due to the presence of mimosine toxin, resulting in various disorders in milk cattle. In many situations, *Leucaena* is now growing in wild form as a weed due to its excessive reproductive and regeneration ability. Its prunings can be used as a green leaf manure because of succulent biomass which is rich in nitrogen (3–5%), with low C:N ratio (Karachi 1998). Incorporation of tender twigs of *Leucaena* has been found beneficial for meeting N requirement and improving productivity of maize (Mafongoya et al. 1997; Pandey et al. 1998; Soltan et al. 2001). Further, there are significant residual effects on soil fertility and productivity of the following crops (Mureithi et al. 1994; Jones et al. 1996; Lehria et al. 2006). In view of the growing energy crisis for production of chemical N fertilizers and non-availability of organic materials for recycling in crop production, it is imperative to use wild-growing vegetative materials such as *Leucaena* to supplement nitrogen needs of cereal crops like maize and wheat. The use of such locally available biomass is also essential for improving nitrogen-use efficiency of applied fertilizers (Akkinifesi et al. 1996; Mafongoya et al. 1997) and building-up of soil fertility (Jones et al. 1996). There is not much information available on utilization of *Leucaena* biomass and urea N fertilization in different proportions in order to achieve the potential productivity of each of the crops of maize and wheat grown in sequence. Therefore, this study was planned to evaluate varying combinations of *Leucaena* and urea fertilizer on nitrogen economy, productivity, profitability and soil fertility in maize-wheat cropping system.

Materials and methods

Field experiments were conducted during 2002–2004 at the research farm of Indian Agricultural Research Institute, New Delhi located at 28.4°N, 77.1°E and 228 m above mean sea level. The soil of the experimental site (0–15 cm depth) was sandy loam with pH 7.7, 0.47% organic C, 221 kg ha^{-1} $KMnO_4$ oxidizable N, 10 kg ha^{-1} 0.5 N $NaHCO_3$ extractable P, and 261 kg ha^{-1} 1.0 N NH_4OAc exchangeable K. The study was made in fixed plots beginning with maize in 2002 and all the subsequent crops of wheat and maize over two cropping cycles were grown in same plots without changing the layout. Initially, there were six treatments to first crop of maize: no N ($L_0 + U_0$), 120 kg N ha^{-1} through *Leucaena* ($L_{120} + U_0$), 90 kg N through *Leucaena* + 30 kg N ha^{-1} through urea ($L_{90} + U_{30}$), 60 kg N through *Leucaena* + 60 kg N ha^{-1} through urea ($L_{60} + U_{60}$), 30 kg N through *Leucaena* + 90 kg N ha^{-1} through urea ($L_{30} + U_{90}$), and 120 kg N ha^{-1} through urea ($L_0 + U_{120}$) (Table 1). After maize harvest, the main plot was divided into 6 sub-plots to accommodate the following fertilization schedules to wheat, viz. no N ($L_0 + U_0$), 120 kg N ha^{-1} through *Leucaena* (($L_{120} + U_0$), 90 kg N through *Leucaena* + 30 kg N ha^{-1} through urea (L_{90} + U_{30}), 60 kg N through *Leucaena* + 60 kg N ha^{-1} through urea ($L_{60} + U_{60}$), 30 kg N through

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Leucaena + 90 kg N ha^{-1} through urea ($L_{30} + U_{90}$), and 120 kg N ha^{-1} through urea ($L_0 + U_{120}$). Thus, there were 36 treatment combinations for wheat, involving six fertilization schedules applied to previous maize (residual effect), and six treatments applied directly to wheat (direct effect). In the second cropping cycle (2003–2004), maize was grown without changing the layout with direct application of *Leucaena* and urea fertilizer as given during 2002, considering the residual effect of treatments given to previous wheat. Similarly, the subsequent crop of wheat was also grown under the residual effect of treatments applied to maize as well as direct application of *Leucaena* + urea N as given during 2002–2003. Accordingly, there were six treatments in the first crop of maize arranged in a randomized block design, and 36 treatment combinations in all the subsequent crops of wheat and maize arranged in a split-plot design with treatments applied to maize in main plot and treatments to wheat in subplots. Four replications were followed uniformly throughout.

The field was ploughed cross–cross with a disc harrow followed by cultivator and planking in May. In 2002, long and narrow main plots of 23.0 × 4.2 m were made and fresh tender twigs of *Leucaena* after chopping (4–6 cm) were spread on soil surface at varying rates in mid-June as per treatment. These were incorporated with disc harrow followed by cultivator. Sowing of maize cv 'Ganga Safed 2' (85 days) was done by end of June at 65 cm row spacing, applying a common basal dose of 26.2 kg P + 33.3 kg K ha^{-1}, along with 50% N through urea as band placement in the respective treatments. The remaining N was top-dressed at 20 and 35 days after sowing through hill placement. After harvest of maize in the beginning of October, main plot was sub-divided into six sub-plots of 4.2 × 3.0 m for wheat sowing. *Leucaena* biomass was again applied as per treatment and incorporated with a disc harrow. Wheat cv 'HD 2329' (150 days) was sown by mid-November with a seed drill and fertilized basally with 26.2 kg P + 33.3 kg K ha^{-1} and 50% N through urea as per treatment. The remaining N to wheat was top-dressed at 30 days of growth after first irrigation through broadcasting. Both crops were raised under irrigated conditions and recommended package of practices were followed.

Table 1 Details of treatments applied to maize and wheat crops

	Leucaena (kg ha^{-1})[a]			Urea (kg ha^{-1})	
	Fresh weight	Dry weight	N	Fertilizer	N
To maize					
$L_0 + U_0$	0	0	0	0	0
$L_{120} + U_0$	8,370	2,960	120	0	0
$L_{90} + U_{30}$	6,280	2,220	90	65.2	30
$L_{60} + U_{60}$	4,190	1,470	60	130.4	60
$L_{30} + U_{90}$	2,090	740	30	195.7	90
$L_0 + U_{120}$	0	0	0	260.9	120
To wheat					
$L_0 + U_0$	0	0	0	0	0
$L_{120} + U_0$	7,690	3,120	120	0	0
$L_{90} + U_{30}$	5,800	2,340	90	65.2	30
$L_{60} + U_{60}$	3,870	1,560	60	130.4	60
$L_{30} + U_{90}$	1,930	780	30	195.7	90
$L_0 + U_{120}$	0	0	0	260.9	120

[a] Nitrogen content and C:N ratio of *Leucaena* applied to maize and wheat was 4.25% and 18.2:1, and 3.83% and 20.5:1 respectively

Observations were recorded on growth and yield performance of crops. Nitrogen content in *Leucaena* twigs was estimated by Kjeldahl method (Prasad et al. 2006). Accordingly, varying quantities of *Leucaena* biomass from the nearby wild-growing shrubs were applied. Nitrogen content was also estimated in the grain and stover of maize and wheat at harvest to work out N uptake and recovery of N from *Leucaena* and urea by difference method. Apparent N balance was determined based on the total N inputs (initial soil N + N added through fertilizer + N added through *Leucaena* prunings) and total N outputs (post-harvest soil N + N uptake by maize + N uptake by wheat) for the two cropping cycles.

Soil samples were taken from all the plots (two places in each plot at 0–15 cm depth) after termination of the study in April 2004. These samples from the four replications were composited for each treatment. Thus, 36 samples were analysed (in duplicate) for determination of organic C and $KMnO_4$ oxidizable N by following standard procedures (Prasad et al. 2006). The actual change in $KMnO_4$-N over the initial status was worked out.

Economic analysis of the data was done based on the prevailing cost of inputs/operations and price of produce. The cost of cultivation for growing crops involved the expenditure towards land preparation, seed and sowing, fertilizers and their application, pest

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control, irrigation, harvesting and threshing, and rental value of land (Table 2). The cost of fertilizer nutrients was: Rs 11 kg^{-1} N, Rs 41 kg^{-1} P, Rs 8.4 kg^{-1} K; while cost of N from *Leucaena* was Rs 20 kg^{-1} N (Indian Rs 50 ≃ 1 US $). Gross returns were worked out based on the price of main produce (grain) and byproduct (stover) of the crop. The price of produce $tonne^{-1}$ was : maize grain, Rs 5,000, maize stover, Rs 1,000; wheat grain Rs 8,000, wheat stover Rs 2,000. Net returns were estimated by deducting total cost of cultivation from gross returns, and the net returns per Re invested by dividing the net returns with the cost of cultivation.

Statistical analysis of the data was done using ANOVA technique following MSTAT-C software for a randomized block design (maize 2002) or split-plot design (maize 2003 and wheat in both years). The treatment means were compared at $P < 0.05$ level of probability using student *t*-test and working out LSD values.

Results

Biomass and N addition through *Leucaena*

Tender twigs of *Leucaena* contained variable amounts of moisture and N when applied before sowing of maize (June) and wheat (October) (Table 1). Accordingly, different amounts of the biomass were applied to supply the needed quantity of N under different treatments. The amounts increased proportionately with increasing rates of N through *Leucaena*. Moisture as well as N content was relatively more in *Leucaena* applied to maize than to wheat. Therefore, the amount of fresh weight of *Leucaena* prunings applied to maize was comparatively more but the dry weight was less than that applied to wheat. The C:N ratio of the *Leucaena* biomass was comparatively less in June (18.2:1) than in October (20.5:1).

Table 2 Common cost of cultivation of maize and wheat crops (Rs ha^{-1} basis) (Rs 50 ≃ I US $)

Input/field operation	Maize	Wheat
Land preparation	1,500	1,500
Seed	800	1,600
Sowing	400	400
Fertilizers (P and K)[a]	1,600	1,600
Thinning	300	0
Irrigations	1,000	2,000
Herbicides/weeding	800	500
Insecticides	600	0
Pesticide application	1,000	400
Harvesting, threshing etc.	1,400	1,600
Rental value of land	4,000	4,000
Total	13,400	13,600

[a] Common dose of 26.2 kg P and 33.3 kg K ha^{-1} was applied to all the plots. Nitrogen was applied through *Leucaena* and urea fertilizer at different rates; accordingly its cost varied in different treatments

Crop productivity

Productivity of maize and wheat varied significantly due to different combinations of *Leucaena* + urea fertilizer (Table 3). In the first cropping cycle (2002–2003), the response of maize to 120 kg N ha^{-1} was considerably higher when applied through urea fertilizer than *Leucaena* green leaf manuring. In fact, the yield increased by 160% through sole use of urea N compared with only 79% through *Leucaena* N over no N application. Evidently, the prunings of *Leucaena* alone could not provide the maize crop with adequate N supply. The yield of grain and stover of maize increased more with urea N but to a smaller extent with *Leucaena* N. The highest grain yield was obtained at 120 kg N ha^{-1} through urea fertilizer, which was on par with application of 60 kg N ha^{-1} each through urea and *Leucaena*. However, applying less than half of recommended N through urea reduced the yield of maize drastically compared with higher proportions of N through urea. Stover production was similar with 120 kg N ha^{-1} through urea alone and 30 kg N through *Leucaena* + 90 kg N ha^{-1} through urea, but reducing the proportion of urea N further resulted in significantly lower yields. Maize being a short-duration and vigorously growing crop, required ample supply of easily available N which was apparently more from urea fertilizer than from *Leucaena* biomass. Non-significant effect on grain yield when 25–50% of N fertilizer was supplemented through *Leucaena* indicated that it (*Leucaena*) also contributed substantially towards meeting the N requirement of the maize crop.

Wheat yields showed significant differences due to the residual effect of *Leucaena* + urea N combinations (Table 3). There was no greater change in grain

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Table 3 Effect of green leaf manuring with *Leucaena* and urea N fertilizer on productivity (t ha^{-1}) of maize–wheat cropping system

Treatment (*Leucaena* + urea N, kg ha^{-1})	First cropping cycle (2002–2003)				Second cropping cycle (2003–2004)			
	Maize grain	Maize stover	Wheat grain	Wheat straw	Maize grain	Maize stover	Wheat grain	Wheat straw
To maize								
$L_0 + U_0$	1.02a	3.00a	3.76a	4.86a	1.30a	3.68a	4.66a	5.81a
$L_{120} + U_0$	1.83b	4.97b	4.10bc	5.76d	2.00b	4.99b	5.10b	6.32b
$L_{90} + U_{30}$	2.02b	5.38bc	4.15c	5.55cd	2.40c	5.93c	4.76a	6.23b
$L_{60} + U_{60}$	2.41c	6.18cd	4.05bc	5.62cd	2.52cd	6.51d	4.69a	6.21b
$L_{30} + U_{90}$	2.51c	7.00de	3.90abc	5.25bc	2.62cd	6.54d	4.72a	6.17b
$L_0 + U_{120}$	2.65c	7.30e	3.88ab	4.88ab	2.74d	6.30cd	4.71a	6.17b
SEM±	0.098	0.307	0.084	0.125	0.072	0.178	0.091	0.116
LSD (0.05)	0.295	0.925	0.253	0.376	0.217	0.536	0.274	0.349
To wheat								
$L_0 + U_0$			3.31a	4.24a	2.07a	5.06a	4.54a	5.59a
$L_{120} + U_0$			3.42ab	4.61b	2.58c	6.05b	4.50a	5.73a
$L_{90} + U_{30}$			3.98c	5.43c	2.34b	5.86b	4.90b	6.07b
$L_{60} + U_{60}$			4.30d	6.05d	2.25b	5.91b	5.11c	6.50c
$L_{30} + U_{90}$			4.37d	5.81d	2.27b	5.95b	4.80b	6.49c
$L_0 + U_{120}$			4.46d	5.79d	2.07a	5.21a	4.79b	6.53c
SEM±			0.060	0.102	0.053	0.103	0.062	0.094
LSD (0.05)			0.168	0.286	0.149	0.289	0.174	0.264

Means of treatments to maize or wheat with same alphabets are at par as per LSD (0.05)

yield when urea N alone or along with small amounts of *Leucaena* (30 kg N ha^{-1}) was applied to maize compared with no N at all. However, there was 7.7–10.4% increase in grain yield of wheat when 50–100% of N was substituted through *Leucaena*. A greater residual effect on wheat straw yield was also observed and there was 14.2–18.5% increase in yield compared with little or no change (0.5–8.0%) when 75–100% of N was supplied through urea fertilizer. On the other hand, direct application of *Leucaena* + urea N brought about significant increase in yield of grain as well as straw of wheat. The response to urea N was much higher than to *Leucaena* N, as the increase in yield with sole urea N was 34.7–36.6% compared with only 3.3–8.7% with *Leucaena* N alone. Significant increase in wheat yield was observed when 60 kg N ha^{-1} was applied each through *Leucaena* and urea fertilizer. The grain yield increased marginally when 75–100% of N was substituted through urea compared with 50% substitution through each source. The yield of straw rather showed some decline at higher proportion of urea N and lower addition of *Leucaena* biomass.

In the second cropping cycle (2003–2004), maize yields increased progressively with successively higher proportions of urea N (Table 3). The highest grain yield was obtained when full N was applied through urea but it was on par with application of 60 kg N ha^{-1} each through *Leucaena* + urea. There was also no significant change in stover yield when the proportion of urea N was increased beyond 50%. Nonetheless, sole application of urea N caused a much higher increase in yield of grain (+1.34 t ha^{-1}) and stover (+2.62 t ha^{-1}) over no N compared with sole *Leucaena* (0.70 and 1.31 t ha^{-1}, respectively). These yield increases were relatively lower than in the first cropping cycle probably due to enhanced residual fertility of previously applied *Leucaena* to wheat.

Residual effect of *Leucaena* + urea N applied to wheat was evident on maize productivity. Contrary to the direct effect of increasing proportions of urea N, the yield of maize increased due to residual effect of greater proportions of *Leucaena* N. The highest yield of grain and stover of maize was obtained under the residual effect of entire amount of N applied through

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Leucaena to wheat. Evidently, the residual effects of *Leucaena* N were far greater than urea N due to its very quick mineralization and greater losses of N from the fertilizer source. In fact, there was hardly any noticeable residual effect of sole application of urea N compared with no N.

Wheat yields increased progressively when greater proportion of *Leucaena* N was applied to previous maize, the highest being when entire N was applied through *Leucaena* (Table 3). The wheat yields were not much different under the residual effect of 25–75% N substituted through *Leucaena* or urea, and were on par with full dose of N through urea and no N treatments to maize. As observed in the first cropping cycle, there was no beneficial effect of sole *Leucaena* applied directly to wheat but along with urea N, productivity improved significantly. The wheat yields were near maximum when 50% N was applied directly through *Leucaena* and urea, and further increase in proportion of urea N did not prove beneficial. The magnitide of increase in yields under different *Leucaena* + urea N treatments was much lower than in the first cropping cycle. This might be due to fertility build-up due to repeated applications of even smaller quantities of *Leucaena* over the two-year period.

Nitrogen uptake and recovery

Chemical analysis of wheat grain showed much higher mean N content (1.87%) than of maize grain (1.41%) (Table 4). On the other hand, the stover N content was more in case of maize (0.47%) than straw N of wheat (0.33%). Nitrogen content in grain and stover of maize improved with direct application of *Leucaena* as well as urea N, the increase being more pronounced with the latter. Similarly, the direct effect of urea N was more conspicuous on grain and straw N content of wheat than of *Leucaena* N. Residual effects of both *Leucaena* and urea N on N content of following crops were small.

Maize N uptake increased significantly with each successive increase in proportion of urea N (Table 4). Maximum N uptake was when full N was applied through urea fertilizer and it was on par with 30 kg N through *Leucaena* + 90 kg N ha^{-1} through urea, but significantly more than all other treatments. The increase in N uptake over no N application was much higher with sole N through urea (+40.1 to 50.6 kg ha^{-1}) than with *Leucaena* N alone (+17.3 to 21.5 kg ha^{-1}). The N uptake remained even significantly lower when equal amount of N was supplied through *Leucaena* + urea compared with 100% N through urea alone. The residual effect of *Leucaena* + urea N applied to wheat on maize N uptake in the second cycle was significant compared with no N or urea N alone. The maximum residual effect on N uptake was observed when entire N to wheat was applied through *Leucaena* and decreased with lower amounts of *Leucaena* N and increasing amounts of urea N.

Beneficial residual effect of *Leucaena* applied to first crop of maize was also observed on N uptake of succeeding wheat (Table 4). When full N to maize was applied through *Leucaena*, the magnitude of increase in N uptake of wheat was 10.2–11.1 kg ha^{-1} compared with 4.6–4.9 kg ha^{-1} when urea alone was applied to maize crop. This indicates that application of *Leucaena* N to maize was also effective in increasing N uptake of following wheat. Further, the magnitude of increase in N uptake of wheat due to residual effect of sole *Leucaena* N was about half compared with its direct effect on maize. Direct application of N to wheat through different combinations of *Leucaena* + urea N increased N uptake significantly. The wheat N uptake was maximum when full N was applied through urea, which was however, on par with application of 30 kg N through *Leucaena* + 90 kg N ha^{-1} through urea. Sole urea application increased N uptake by 32.7–35.8 kg ha^{-1} while the effect of sole *Leucaena* was only from 3.7–6.1 kg ha^{-1}. This magnitude of increase in N uptake of wheat due to direct N application was relatively lower than for maize N uptake. In other words, there was greater response of maize to direct as well as residual N through *Leucaena* + urea N than of wheat.

Apparent N recovery under different combinations of *Leucaena* + urea N showed interesting trends in maize and wheat crops (Fig. 1). In general, the N recovery was higher in maize than in wheat; and increased with increasing proportions of N through urea in both crops. Maximum N was recovered in maize with 120 kg N ha^{-1} through urea (33.4–42.1%) and lowest with *Leucaena* (14.4–17.9%). The N recovery in wheat was 27.8–29.8% with 120 kg N ha^{-1} through urea and only 3.1–5.1% with *Leucaena*. The lower N recovery in wheat than in maize might be because of lower temperatures and

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Table 4 Effect of green leaf manuring with *Leucaena* and urea N fertilization on nitrogen uptake (kg ha^{-1}) in maize–wheat cropping system (data in parentheses are N content, %)

Treatment (*Leucaena* + urea N, kg ha^{-1})	First cropping cycle (2002–2003)						Second cropping cycle (2003–2004)					
	Maize			Wheat			Maize			Wheat		
	Grain	Stover	Total	Grain	Straw	Total	Grain	Stover	Total	Grain	Straw	Total
To maize												
$L_0 + U_0$	13.3a	12.9a	26.2a	68.9a	15.4a	84.3a	17.8a	15.0a	32.8a	86.3a	19.5a	105.8a
	(1.31)	(0.43)		(1.83)	(0.32)		(1.37)	(0.41)		(1.85)	(0.34)	
$L_{120} + U_0$	25.4b	22.3b	47.7b	75.9bc	18.8d	94.6cd	28.1b	21.9b	50.1b	95.2b	21.8b	116.9b
	(1.39)	(0.45)		(1.85)	(0.33)		(1.41)	(0.44)		(1.87)	(0.35)	
$L_{90} + U_{30}$	28.7b	24.4bc	53.1b	76.9c	17.9cd	94.8d	33.8c	27.2c	61.0c	89.1a	21.2b	110.3ab
	(1.42)	(0.45)		(1.85)	(0.32)		(1.41)	(0.46)		(1.87)	(0.34)	
$L_{60} + U_{60}$	34.9c	27.9c	62.9c	75.2bc	18.7d	93.9bcd	35.7cd	30.3d	66.0d	89.2a	20.5ab	109.7ab
	(1.45)	(0.45)		(1.86)	(0.33)		(1.42)	(0.47)		(1.90)	(0.33)	
$L_{30} + U_{90}$	36.1c	35.5d	71.6cd	72.3a	17.0bc	89.3bc	37.7de	33.3e	70.9e	89.2a	20.3a	109.5ab
	(1.44)	(0.51)		(1.85)	(0.32)		(1.44)	(0.51)		(1.89)	(0.33)	
$L_0 + U_{120}$	38.8c	37.9d	76.8d	72.4ab	16.5ab	88.9ab	39.8e	33.1e	72.9e	89.3a	21.5b	110.8ab
	(1.47)	(0.52)		(1.87)	(0.34)		(1.45)	(0.53)		(1.90)	(0.35)	
SEM±	1.32	1.47	2.96	1.21	0.39	1.76	0.79	0.76	1.55	1.83	0.51	2.84
LSD (0.05)	3.98	4.43	8.91	3.64	1.17	5.31	2.38	2.29	4.67	5.51	1.54	8.56
To wheat												
$L_0 + U_0$				58.5a	12.5a	71.0a	28.9a	22.6a	51.5a	73.5a	16.9a	90.5a
				(1.77)	(0.29)		(1.39)	(0.45)		(1.62)	(0.30)	
$L_{120} + U_0$				62.7b	14.5b	77.2b	36.7d	27.1b	63.8c	75.4a	18.9b	94.3a
				(1.83)	(0.32)		(1.42)	(0.45)		(1.68)	(0.33)	
$L_{90} + U_{30}$				73.8c	18.1c	91.8c	33.0c	29.8c	62.8bc	90.5b	20.4c	110.8b
				(1.85)	(0.33)		(1.42)	(0.51)		(1.85)	(0.34)	
$L_{60} + U_{60}$				80.5d	20.2d	100.7d	32.1bc	29.5c	61.6bc	97.0c	20.4c	117.4c
				(1.87)	(0.33)		(1.43)	(0.50)		(1.90)	(0.34)	
$L_{30} + U_{90}$				83.0de	18.4c	101.4d	31.8bc	28.7c	60.5b	100.5c	23.2d	123.7d
				(1.90)	(0.33)		(1.41)	(0.48)		(2.10)	(0.36)	
$L_0 + U_{120}$				83.1e	20.7d	103.8d	30.5ab	22.9a	53.5a	101.4c	24.9e	126.3d
				(1.87)	(0.36)		(1.41)	(0.44)		(2.12)	(0.38)	
SEM±				0.90	0.28	1.21	0.72	0.49	0.89	1.83	0.34	1.92
LSD (0.05)				2.53	0.79	3.39	2.02	1.38	2.51	5.14	0.95	5.38

Means of treatments to maize or wheat with same alphabets are at par as per LSD (0.05)

drier soil conditions prevailing during the wheat-growing season. On the other hand, a greater amount of residual N from *Leucaena* applied to maize was recovered in wheat than from urea N. In fact, there was a decreasing trend in residual N recovery in wheat with increasing proportions of urea N to maize. Recovery of residual N in wheat ranged from 8.5–9.2% when entire N was given through *Leucaena* compared with only 3.8–4.1% through sole urea. Conversely, the recovery of residual N in maize during the second cropping cycle was 10.3% with sole *Leucaena* and only 1.7% with urea. These results suggest that direct effects of *Leucaena* N may be small but the residual effects are more pronounced than of urea. Evidently, combined use of *Leucaena* + urea N on equal N basis may be appropriate for efficient utilization of N and enhancing total N recovery in maize–wheat cropping system.

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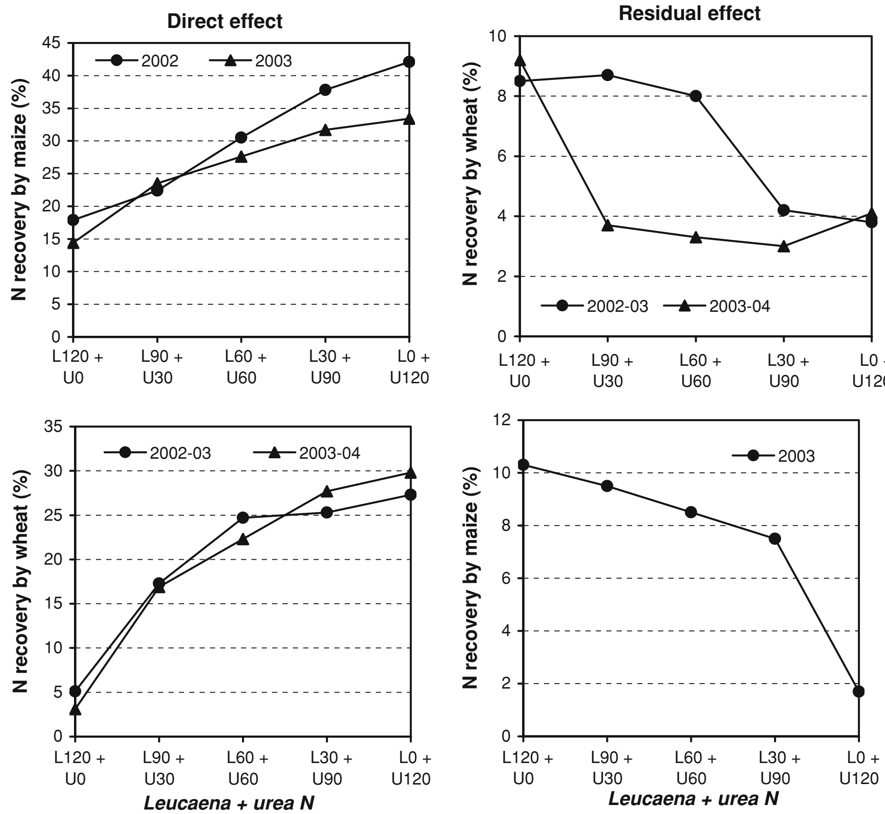

Fig. 1 Apparent recovery of applied N by maize and wheat grown in sequence

Residual soil fertility and N balance

There was an increase in soil organic C and $KMnO_4$ oxidizable N in treatments where *Leucaena* was applied, and the increase was more conspicuous when 120 kg N ha^{-1} was applied through *Leucaena* alone (Table 5). This was understandable because in these plots, more than 12 t ha^{-1} of *Leuceana* prunings (on dry-weight basis) were applied over the two years period. There was either no change or a slight decrease was observed in these parameters of soil fertility over the initial status when only urea N or no N was applied. Combined application of *Leucaena* + urea on equal N basis had a better effect than urea alone but lower than that with sole *Leucaena*.

Apparent N balance was negative in all treatments where no N was applied to maize or wheat. The balance remained negative even when one crop in the sequence was fertilized with urea and/or *Leucaena* N but the second crop was grown without any fertilizer application. On the other hand, the apparent N balance showed a positive improvement in all treatments where N was applied through different combinations of *Leucaena* and/or urea N to both the crops. The positive N balance was maximum with 120 kg N ha^{-1} through *Leucaena* alone to both maize and wheat. There was no greater difference in apparent N balance when urea N alone or *Leucaena* + urea N were applied to both the crops in the sequence.

The actual change in $KMnO_4$-N over the initial status was negative when no N was given to both the crops. Further, the $KMnO_4$-N content also showed decrease when one crop in the sequence was not fertilized and the second crop was grown with urea N alone. As observed for apparent N balance, the improvement in $KMnO_4$-N was the highest when 120 kg N ha^{-1} was applied through *Leucaena* to both the crops. This was followed by *Leucaena* + urea N and urea N alone to both the crops or either crop in the sequence. The total recovery of N applied to maize via direct and residual effects was 23.6–26.4% with sole *Leucaena* as compared to 37.3–46.0% with sole urea; while in case of N applied to wheat, the values were 15.4 and 31.5%, respectively. Evidently, much less N from *Leucaena*

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Table 5 Residual soil fertility and apparent N balance in maize–wheat cropping system over 2-year period

Treatment[a]		Residual soil fertility		N added (kg ha^{-1})			Total N inputs (kg ha^{-1}) [Initial soil N + D = E]	Total N uptake (kg ha^{-1}) [F]	Total N outputs (kg ha^{-1}) [A + F = G]	Apparent N balance (kg ha^{-1}) [E − G]	Actual change in $KMnO_4$-N (kg ha^{-1}) [A − Initial]
Maize	Wheat	Organic C (%)	$KMnO_4$-N (kg ha^{-1}) [A]	*Leucaena* [B]	Urea [C]	Total [B + C = D]					
$L_0 + U_0$	$L_0 + U_0$	0.442	213	0	0	0	221	206	419	−198	−8
	$L_{120} + U_0$	0.531	235	240	0	240	461	233	468	−7	14
	$L_{60} + U_{60}$	0.469	210	120	120	240	461	264	474	−13	−11
	$L_0 + U_{120}$	0.463	202	0	240	240	461	272	474	−13	−19
$L_{120} + U_0$	$L_0 + U_0$	0.509	250	240	0	240	461	257	507	−46	29
	$L_{120} + U_0$	0.552	284	480	0	480	701	282	566	135	63
	$L_{60} + U_{60}$	0.539	279	360	120	480	701	333	612	89	58
	$L_0 + U_{120}$	0.501	258	240	240	480	701	338	596	105	37
$L_{60} + U_{60}$	$L_0 + U_0$	0.466	236	120	120	240	461	289	525	−64	15
	$L_{120} + U_0$	0.516	271	360	120	480	701	303	574	127	50
	$L_{60} + U_{60}$	0.481	257	240	240	480	701	351	608	93	36
	$L_0 + U_{120}$	0.470	247	120	360	480	701	362	609	92	26
$L_0 + U_{120}$	$L_0 + U_0$	0.439	210	0	240	240	461	300	510	−49	−11
	$L_{120} + U_0$	0.485	246	240	240	480	701	323	569	132	25
	$L_{60} + U_{60}$	0.479	243	120	360	480	701	374	617	84	22
	$L_0 + U_{120}$	0.477	238	0	480	480	701	370	608	93	17

[a] Data are presented for selected treatments only

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was recovered by the crops in a single cropping system than from urea. Accordingly, there was greater retention of N in soil from *Leucaena*, which improved the fertility status and may help in sustainability of the system in the long-run.

Economics

Total cost of cultivation of maize and wheat varied under different treatments due to variable cost of N applied through *Leucaena* and urea (Table 6). The cost was higher when N from *Leucaena* was applied, because the cost of *Leucaena* N was much higher than urea N. Although the total cost of cultivation was not much different for maize and wheat, the gross returns from maize were considerably lower than of wheat. The productivity of maize under these conditions was much lower (2–3 t ha^{-1}) compared with wheat (4–5 t ha^{-1}). Besides the prices of wheat grain and straw were higher than of maize. Accordingly, net returns from wheat were several times more than of maize. There was net loss with maize grown without N or with *Leucaena* N alone, and the highest net returns were obtained with 120 kg N ha^{-1} through urea alone. The total net returns from maize–wheat system increased with successively higher amounts of urea N, and were near maximum when equal amounts of N were supplemented through *Leucaena* and urea N. Similarly, net returns per Rupee (Re) (Indian Rupees 50 $\simeq$ 1 US $) invested in maize and wheat were also higher when more than 50% N was applied through urea. Based on the net returns per Re invested in maize–wheat system, it was inferred that application of *Leucaena* and urea on equal N basis was optimum for higher profitability.

Discussion

Direct and residual effects of *Leucaena* prunings and urea N fertilizer varied in maize and wheat due to differences in the weather conditions during the two seasons. Maize yields were quite low without N (1.02–1.30 t ha^{-1}), and increased by 2–3 times when 120 kg N ha^{-1} through *Leucaena* and/or urea fertilizer was applied. Direct effect of different combinations of *Leucaena* + urea N showed that yield of maize increased with increasing proportions of N through urea and consequently decreasing proportions of *Leucaena* N. In case of wheat, the yield increased when *Leucaena* and urea N were applied on equal N basis, after which it stabilized. On the other hand, the residual effects of previously applied *Leucaena* were more pronounced on maize

Table 6 Economic analysis of green leaf manuring and urea N fertilization in maize–wheat cropping system (based on mean of 2 years) (Rs 50 $\simeq$ I US $)

Treatment (*Leucaena* + urea N, kg ha^{-1})	Cost of cultivation ($\times10^3$ Rs ha^{-1})		Gross returns ($\times10^3$ Rs ha^{-1})		Net returns ($\times10^3$ Rs ha^{-1})			Net returns per Re invested		
	Maize	Wheat	Maize	Wheat	Maize	Wheat	Total	Maize	Wheat	Mean
To maize										
$L_0 + U_0$	13.4	15.2	9.1	44.4	−4.3	29.2	24.9	−0.32	1.93	0.80
$L_{120} + U_0$	15.8	15.2	14.6	48.9	−1.2	33.7	32.5	−0.08	2.23	1.07
$L_{90} + U_{30}$	15.5	15.2	16.7	47.2	1.2	32.1	33.2	0.08	2.12	1.05
$L_{60} + U_{60}$	15.3	15.2	18.7	46.8	3.4	31.6	35.1	0.22	2.09	1.16
$L_{30} + U_{90}$	15.0	15.2	19.6	45.9	4.6	30.8	35.4	0.31	2.03	1.17
$L_0 + U_{120}$	14.7	15.2	20.3	45.4	5.6	30.3	35.8	0.38	2.00	1.19
To wheat										
$L_0 + U_0$	15.0	13.6	15.4	41.2	0.5	27.6	28.1	0.03	2.03	1.03
$L_{120} + U_0$	15.0	16.0	19.0	42.0	4.0	26.0	30.0	0.27	1.63	0.95
$L_{90} + U_{30}$	15.0	15.7	17.4	47.0	2.4	31.3	33.7	0.16	1.99	1.08
$L_{60} + U_{60}$	15.0	15.5	17.0	50.2	2.0	34.7	36.7	0.13	2.25	1.19
$L_{30} + U_{90}$	15.0	15.2	17.3	49.0	2.4	33.8	36.1	0.16	2.22	1.19
$L_0 + U_{120}$	15.0	14.9	15.9	49.3	0.9	34.4	35.3	0.06	2.31	1.18

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than wheat, and decreased with lower proportions of *Leucaena*. In other words, the direct as well as residual effects of *Leucaena* were higher in maize than in wheat. Maize was a short-duration crop (85 days) and grew more vigorously in the hot and humid summer season compared with wheat which was a long-duration crop (150 days) and grew slowly in the dry winter season. Further, maize being more nutrient exhaustive than wheat, required ample supply of easily available N for its optimum growth which was more from urea fertilizer than from *Leucaena* prunings. Mittal et al. (1992) found that maize yields obtained from 100% *Leucaena* or urea N treatments were similar, and were even more in *Leucaena* plots in the third year. However in our study, prunings from *Leucaena* alone could not provide the maize crop with adequate N supply, despite higher temperatures and ample soil moisture, which were conducive for decomposition of *Leucaena* biomass. The contribution of N from *Leucaena* prunings is usually low (Mulongoy and van der Meersch 1988), and supplementary N fertilizer is needed to maximize maize yields in alley-cropping systems (Kang et al. 1985). The productivity of maize with equal proportion of N through *Leucaena* and urea fertilizer was on par with full dose of N through urea. This was observed in both the cropping cycles, although the residual effects of *Leucaena* applied to wheat on following maize were also considerable in the second cycle. In a pot culture study, Mafongoya et al. (1997) did not find response to N fertilizer when *Leucaena* prunings at 3–6 t ha^{-1} were incorporated, indicating adequate N supply from the prunings. In this study, the dried and ground *Leucaena* prunings were incorporated, which resulted in enhanced mineralization of N. However, in our study, applying less than half of total N through urea decreased the yield of maize significantly probably due to temporary immobilization of N and thereby less N availability in soil at higher proportions of *Leucaena* N. Several workers have reported that 50–75% of N requirement of maize can be substituted through *Leucaena* prunings under varying soil and climatic conditions (Mittal et al. 1992; Palled et al. 2000; Lehria et al. 2006). There are also reports on higher production of maize with combined use of *Leucaena* and N fertilizer than with N fertilizer alone (Mittal et al. 1992; Pandey et al. 1998; Palled et al. 2000; Soltan et al. 2001) probably due to gradual and controlled release of N synchronizing with crop demand at different stages. Residual effects of *Leucaena* applied to wheat on following maize (second cropping cycle) were considerable, particularly at higher rates of its application. However, these were inadequate to meet the N requirement, and direct N application was absolutely necessary to achieve the potential productivity of maize.

Wheat was grown under the residual fertility as well as direct application of *Leucaena* in both cropping cycles; the effects of treatments were in fact cumulative in the fourth cropping season (November 2003 to April 2004) of the experiment. The residual effect of *Leucaena* on wheat yield increased with increasing proportion of its application. Evidently all the *Leucaena* N was not mineralized in the maize-growing season and a part of the temporarily immobilized N became gradually available to the wheat plants. Direct application of *Leucaena* showed much less response on wheat than on maize, which could be explained due to lower temperature particularly during January–February (<10°C) which might have reduced the rate of decomposition and N release from *Leucaena* prunings. While comparing decomposition of different plant residues at room temperature (19–23°C), Tesfaye et al. (2005) reported that *Leucaena* residue resulted in N immobilization initially and mineralization after 30 days of incubation. The disadvantage of reduced N mineralization during the initial period was offset by the enhanced growth duration and increasing temperatures from the end of February onwards. Due to these reasons, the grain yield of wheat increased even when the proportion of urea N was increased beyond 50% due to less availability of *Leucaena* N in the first cropping cycle. However, in the second cycle, when the soil fertility had improved due to the cumulative effects of *Leucaena* application over the past three seasons, the yields stabilized with equal proportions of *Leucaena* and urea N. Shah and Ahmed (2006) reported that the highest yield of wheat was obtained from treatments receiving N from urea and FYM in 75:25 ratio, followed by the 50:50 ratio; and the yields were significantly lower in treatments where N from urea source was below 50%. Significant residual effects of *Leucaena* applied to maize on following wheat have been obtained (Mittal et al. 1992; Nanda et al. 2002; Lehria et al. 2006).

Nitrogen content in grain and stover of maize as well as wheat increased more with urea N than with

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Leucaena N due to ready availability of N from the former source. However, there was significant increase in N uptake of maize over no N (52.7–81.7%) when *Leucaena* alone was applied directly. This indicates that application of *Leucaena* contributed substantially towards the N nutrition of the crop. Soltan et al. (2001) reported increased concentration of N, P and K and thereby higher uptake in maize due to combined use of *Leucaena* and N fertilizer. Less increase in wheat N uptake (4.1–8.6%) was due to slower decomposition of *Leucaena* under lower temperatures. Similarly, higher recovery of N in maize both from urea fertilizer and *Leucaena* was due to quick-growing habit of maize under hot and humid conditions. Nonetheless, the recovery of N from *Leucaena* was only 14.4–17.9% compared with 33.4–42.1% from urea because the organic N in *Leucaena* was not readily available and took some time for release of N to plants. *Leucaena* might have exhibited immobilization of N initially followed by net mineralization later (Jones et al. 1996; Tesfaye et al. 2005). The amount of N mineralized from *Leucaena* peaked after a month of its incorporation (Mugendi et al. 1999). Therefore, addition of urea N along with *Leucaena* improved synchrony by increasing the N supply at the initial stages of immobilization from large applications of *Leucaena*. In a greenhouse experiment, Mafongoya et al. (1997) reported N recovery in maize from *Leucaena* prunings to be 22.2%. Wheat recorded much less recovery from *Leucaena* (3.1–5.1%) than from urea fertilizer (27.8–29.8%), which was due to gradually decreasing temperature after its application in October. Xu et al. (1993) reported N recovery values of 4.0–9.8% from *Leucaena*, while Akkinifesi et al. (1996) and Vanlauwe and Sanginga (1998) reported 8.6–10.0% recovery from ^{15}N labeled *Leucaena* prunings in maize. Evidently, the recovery of N from organic sources like *Leucaena* is determined by the weather conditions, particularly temperature and soil moisture availability, as well as the characteristics of the material used.

While the low recovery of N from urea may be because of losses due to denitrification, volatilization, leaching etc., the *Leucaena* N is retained in soil due to its slow release and held up for a longer period. This was evident from higher recovery of residual N from *Leucaena* in the second crop (8.5–9.3% in wheat and 10.3% in maize) than from urea N (3.8–4.1% in wheat and 1.7% in maize). The recovery of residual N from chemical fertilizers is reported to vary from 2 to 5%, depending on crop, season, rate and method of application, residue management etc. (Ladha et al. 2005). The combined use of *Leucaena* + urea resulted in lower total N recovery than from urea N alone. This did not mean loss of N with integrated application of the two sources but its greater retention in soil due to temporary immobilization for gradual availability to the subsequent crops. Combining organics with inorganic fertilizer increases synchrony and reduces losses by conserving inorganic N into organic forms (Buresh and De Datta 1991; Ladha et al. 2005). It was for these reasons that there was relatively greater increase in soil organic C and $KMnO_4$-N at the termination of study with addition of *Leucaena* prunings. Increased amounts of organic matter and various nutrients including N in *Leucaena* amended soil have been reported by various workers (Jones et al. 1996; Pandey et al. 1998). Accordingly, there was increased positive balance of N with *Leucaena* application, especially when it was applied to both the crops in sequence. These results suggested that application of liberal amounts of *Leucaena* prunings along with urea N not only ensured higher productivity but also greater fertility build-up in soil for sustainable production in the long-run.

Maximum net returns were obtained from direct application of urea alone in maize and from 60 kg N ha^{-1} each through *Leucaena* and urea N in wheat. The overall profitability was lower when *Leucaena* was applied at higher rates than when urea was applied. This was because urea N increased the productivity more than *Leucaena* N and the cost of *Leucaena* N was about twice (Rs 20 kg^{-1} N) more than urea N (Rs 11 kg^{-1} N). Mittal et al. (1992) reported significantly higher net returns when *Leucaena* and urea N were applied in 25:75 proportion in maize-wheat system. In our economic analysis, we considered only the direct cost of N and not the indirect benefits of *Leucaena* green leaf manuring. *Leucaena* prunings also contained other major nutrients such as P (0.2–0.3%) and K (1.5–2.0%) (Karachi 1998), besides large quantity of organic matter which might have brought out favourable improvement in physical and biological properties of soil. It was less economical to apply *Leucaena* directly to wheat because of its poor response but the residual effects were pronounced on following maize. There was also some practical difficulty in sowing of wheat in

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Leucaena amended plots due to interference of undecomposed *Leucaena* prunings with the tines of seed drill. In view of these problems, it was found more practical and economical to apply *Leucaena* prunings to maize when *Leucaena* is available in plenty due to its luxuriant growth and decomposition is also faster in hot and humid conditions. Based on these studies, it was concluded that combined use of green leaf manuring with *Leucaena* prunings and urea fertilizer on equal N basis resulted in higher productivity, profitability and more efficient utilization of N, leading to fertility build-up and thus sustainability of maize–wheat cropping system in the long-run.

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