Introduction

Recent research conducted in many Asian countries, including Northwest India (Ladha et al., 2003; Pathak et al., 2003), has demonstrated the limitations of the current approach of fixed-rate, fixed-time, i.e., blanket fertilizer recommendations for large areas. Such an approach does not take into account the existence of large spatial and temporal variability in soil nutrient supply and crop response to nutrients among farms (Timsina and Connor, 2001). This helps to explain why fertilizer NUE is usually poor, the use of P and K fertilizers is often not balanced with crop requirements and other nutrients, and, as a result, profitability is not optimized (Dobermann et al., 1998; Olk et al., 1999). Because of the shortcomings of blanket fertilizer recommendations, the original concept of site-specific nutrient management (SSNM) to manage among-farm nutrient variability was developed in Asia for rice (Dobermann and White, 1999).

From 2002-05, we conducted a series of on-farm experiments with rice and wheat crops at 56 farmers' fields in Northwest India to test the hypothesis that rice and wheat yields, farmer profit, plant nutrient uptake, and fertilizer efficiencies can be increased significantly through field-specific nutrient management. In this article, we evaluate the performance of SSNM compared to prevailing farmer fertilizer practices (FFP).

Experimental Layout and Conduct

Rice-wheat is the dominant cropping system of Punjab province in Northwest India, wherein rice is grown in the summer months (mid-June to October) followed by wheat in the winter months (November to mid-April) and a small fallow period from mid-April to mid-June. We conducted on-farm experiments from 2002-03 to 2004-05 with irrigated wheat and transplanted rice at 56 sites in six rice-wheat production sites across the three major agro-climatic zones of Punjab. The sites in which on-farm experiments were conducted were Gurdaspur, Hoshiarpur, Ludhiana, Patiala, Faridkot, and Firozpur. The experimental set-up followed a standard protocol at all sites and included nutrient omission plots (0-N, 0-P, 0-K) to estimate indigenous nutrient supplies, a SSNM treatment plot (started from 2003-04 because the data for 2002-03 was used to develop SSNM recommendations for the subsequent year), and farmer fertilizer practice (FFP) plot in each farmer field. Researchers did not intervene in the FFP plots but managed fertilizer application in the SSNM and nutrient omission plots. Farmers were responsible for all other aspects of general crop and pest management and the choice of variety.

An estimate of soil indigenous N, P, and K supply was obtained from omission plots situated in each farmer field. The results from these plots were used as inputs in a model designed to estimate field-specific fertilizer requirements for the rice and wheat crops in the SSNM plots (Khurana et al., 2007; Khurana et al., 2008).

Soil nutrient supplies varied widely, and two- to four-fold ranges were found for each nutrient and site (Tables 1 and 2). Average rice grain yields in nutrient omission plots increased in the order 0-N (3.82), 0-K (5.41) = 0-P (5.45 t/ha), while the corresponding values for wheat were 0-N (3.08) $<$ 0-K (4.35) $\leq$ 0-P (4.55 t/ha). These data confirm that N deficiency is a general feature of irrigated rice-wheat systems in Punjab, whereas P and K supply are equally limiting factors, especially when considering the average rice and wheat yield goals of 7.9 t/ha (Khurana et al., 2007) and 5.8 t/ha (Khurana et al. 2008), respectively, for Punjab.

Performance indicators used for the agronomic evaluation of SSNM and FFP were:

- Recovery efficiency of fertilizer N (REN) is the increase in plant N uptake per unit fertilizer N applied (kg plant N/kg fertilizer N).
- Physiological N efficiency (PEN) is the increase in grain per unit increase in plant N uptake from fertilizer (kg grain/kg plant N).
- Agronomic N use efficiency (AEN) is the product of REN and PEN, expressed as the yield increase per unit fertilizer N applied (kg grain yield/kg fertilizer N).

Economic calculations were made using U.S. dollars as standard currency:

$$TFC = P_N F_N + P_P F_P + P_K F_K$$

$$GRF = P_R Y_R - TFC \text{ (for rice) and } GRF = P_W Y_W - TFC \text{ (for wheat)}$$

where TFC = total fertilizer cost ($/ha); P_N = price of N fertilizer ($0.32/kg N); F_N = amount of N applied (kg N/ha); P_P = price of P fertilizer ($1.81/kg P); F_P = amount of P applied (kg P/ha); P_K = price of K fertilizer ($0.50/kg K); F_K = amount of K applied (kg K/ha); GRF = gross returns above fertilizer cost ($/ha); P_R = price of rice ($0.12/kg paddy); P_W = price of wheat grain ($0.14/kg); and Y_R and Y_W = rice and wheat yields (kg/ha), respectively. The prices used were minimum procurement prices for the Government of India for rice and wheat grains and average retail prices for different fertilizers in Punjab for the year 2005. As the data on land rental costs were not easily available and because of the difficulties in imputing costs to family labor, it was not possible to calculate the absolute level of profit with and without SSNM. This is not a major drawback, since the absolute level of profits is less important than the change in profits due to adoption of the technology. The incremental profitability of SSNM (ΔGRF, $/ha) was therefore measured as the difference in GRFs due to different grain yields for SSNM and FFP minus the change in total fertilizer costs due to different fertilizer usage in the two treatments:

$$\Delta GRF = GRF_{SSNM} - GRF_{FFP}$$

PROC GLM of SAS (SAS Institute, 1988) was used to perform ANOVA on the differences between SSNM and FFP (Δ = SSNM - FFP) measured at each farm for each crop grown during 2003-04 and 2004-05 using the following model: Site df = 5; Farm within site df = 50; Crop year df = 1; Site x crop year df = 5; Residual df = 51. A fixed-effects model was used to analyze the on-farm data because the sampling locations were not selected in a truly random manner. For variables with missing observations, the denominator mean square was adjusted using the Satterthwaite approximation (Satterthwaite, 1946). All effects, except site, were tested against the residual. Site effect was tested against site within site as error term. Since the crop year effect was non-significant for all parameters in our study, we tabulated the average data for 3 years (2002-03, 2003-04, and 2004-05) for grain yield and plant nutrient (N, P, and K) accumulation in nutrient omission plots and average data for 2 years (2003–04 and 2004–05) for differences between SSNM and FFP treatments for grain yield, fertilizer N applied, NUE, TFC, and GRF. The level of significance used was 5% ($P = 0.05$).

Results and Discussion

Compared with FFP, SSNM significantly increased grain yield at all sites in the two wheat and rice crops (Figure 1). But there was no significant difference between the two years of experimentation, which helped us pool the year-wise data for grain yield for each site. On average, SSNM generated a yield gain of at least 0.9 (17%) and 0.5 t/ha (12%) in rice and wheat crops, respectively, compared with FFP in approximately 48% of the sites studied. At 21 of the total 56 farms studied, rice grain yield increases were ≥1 t/ha with SSNM compared with FFP, while at 24 of the total 56 farms studied, wheat grain yield increases were ≥0.8 t/ha, showing the potential of the SSNM approach used. Another interesting fact observed was that the maximum increases in rice and wheat grain yields were obtained at sites with low fertility soils, while the sites with high fertility soils had minimum though significant increases in grain yields of rice and wheat crops. This corroborates our hypothesis that blanket fertilizer recommendations, as is the current norm in Punjab, are of limited use in tackling site-specific soil fertility problems and that the adoption of site-specific strategies can give some impetus to the productivity growth of rice and wheat crops.

Average fertilizer N applied to the rice and wheat crops in FFP at all sites in Punjab (148 and 143 kg N/ha, respectively) was relatively higher than the fertilizer N applied in other parts of India (Dobermann et al., 2002; Pathak et al., 2003). However, most farmers had no means of adjusting their fertilizer rates according to the actual soil fertility status. Correlation between N rate and indigenous nitrogen supply (INS) in wheat was -0.16, clearly outlining why despite higher N use under FFP (Figure 2), grain yield and N accumulation were low as compared with that under SSNM. Like N, P rates were also not significantly correlated with indigenous phosphorus supply (IPS) ($r = -0.05$ and $= 0.01$ for wheat and rice, respectively). On the other hand, fertilizer K application in FFP was not much in Punjab probably because of substantial contribution of K (6 to 51 kg K/ha with an average of 29 kg K/ha) from irrigation water.

On average, SSNM saved a significant amount (8 and 10% for rice and wheat, respectively) of fertilizer N compared with FFP (Figure 2), clearly bringing out the positive effect of site-specific N management practiced in SSNM. In contrast, average fertilizer P application significantly increased in rice and remained the same in wheat in both SSNM and FFP treatments, while fertilizer K application was significantly increased with SSNM compared with FFP for both rice and wheat crops. This might be due to the fact that 10 and 30 kg/ha P and K, respectively, were set as the minimum amounts to be applied to replenish net removal of these nutrients from a site and minimize risk of any macronutrient deficiency.

Significant increases in N use efficiency were achieved in rice and wheat through the field-specific N management practiced in the SSNM treatment (Figure 3). In general, compared with the FFP, less fertilizer N was applied (Figure 2), and AEN, REN, and PEN were significantly increased with SSNM. On average, AEN was increased by 7.3 kg/kg (83%) and 5.3 kg/kg (63%), REN by 0.10 kg/kg (50%) and 0.10 kg/kg (59%), and PEN by 9.5 kg/kg (27%) and 7.7 kg/kg (26%) in rice and wheat crops, respectively. This increase was attributed to (a) more uniform N applications among sites under SSNM as compared to under FFP, (b) more even spreading of N applications through the growing season, and (c) avoiding heavy single applications at early growth stages of rice and wheat crops when compared with FFP (Figure 4).

Site-specific nutrient management led to a small increase in the average fertilizer cost ($8.60/ha/crop [12%] in wheat and $27.30/ha/crop [52%] in rice) but comparatively a larger increase in GRF ($67.70/ha/crop [13%] in wheat and $79.30/ha/crop [14%] in rice) compared with FFP (Figure 5). Increase in the average fertilizer cost under SSNM was mainly attributed to an increase in K fertilizer use – an important input from the balanced crop nutrition point of view but one that is generally skipped by farmers in Punjab.

Conclusions

Site-specific management of macronutrients increased yields of rice and wheat crops by 17 and 12% and profitability by 14 and 13%, respectively, in Northwest India. Results suggest that further increases in yield can only be expected when farmers exploit the synergy that occurs when all aspects of crop, nutrient, and pest management are improved simultaneously. Increased nutrient uptake and N use efficiency across a wide range of rice growing environments with diverse climatic conditions were related to the effects of improved N management and balanced nutrition. A major challenge is to simplify the approach for wider scale dissemination without sacrificing components that are crucial to its success. The underlying principles of SSNM need to be carefully identified and evaluated for each macronutrient. Approaches to further dissemination must be related to prevailing site-specific conditions.

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Table 1 Variability of grain yield and plant nutrient accumulation in nutrient omission plots across 56 irrigated, transplanted rice farms in Punjab, India. Descriptive statistics are based on three rice crops sampled at each farm from 2002 to 2004.

Measurement†	Mean	SD	Min.	Max.	CV among sites in each site‡, %
Grain yield in 0-N plot, t/ha	3.82	0.99	1.8	5.6	16 (12-25)
Grain yield in 0-P plot, t/ha	5.45	1.24	2.7	7.6	10 (6-16)
Grain yield in 0-K plot, t/ha	5.41	1.01	3.1	7.7	10 (7-13)
Plant N in 0-N plot, kg/ha	51.1	15.3	19.8	86.6	18 (12-27)
Plant P in 0-P plot, kg/ha	15.7	4.18	7.8	25.1	18 (13-28)
Plant K in 0-K plot, kg/ha	83.6	21.4	48.4	124	12 (9-14)

† 0-N: N omission plot; 0-P: P omission plot; 0-K: K omission plot.

‡ Coefficient of variation (CV) computed from site-specific average values for three rice crops each sampled in 2002, 2003, and 2004 at each site. Values shown are the mean CV within a site and its range at the six sites (in parenthesis). For each crop, measurements of two replications at each site were combined into a site average. Site averages were then used to compute within-site CV for each crop at each site. These CV values were then used to calculate the average CV for each site across all crops sampled.

Table 2 Variability of grain yield and plant nutrient accumulation in nutrient omission plots across 56 irrigated wheat farms in Punjab, India. Descriptive statistics are based on three wheat crops sampled at each farm from 2003 to 2005.

Measurement†	Mean	SD	Min.	Max.	CV among sites in each site‡, %
Grain yield in 0-N plot, t/ha	3.08	0.85	1.1	4.4	21 (13-35)
Grain yield in 0-P plot, t/ha	4.55	1.02	2.1	6.1	12 (7-19)
Grain yield in 0-K plot, t/ha	4.35	0.81	2.3	6.0	12 (8-19)
Plant N in 0-N plot, kg/ha	66.3	15.7	26.1	94.8	15 (11-23)
Plant P in 0-P plot, kg/ha	15.5	4.09	7.5	23.8	19 (13-26)
Plant K in 0-K plot, kg/ha	79.1	18.8	35.9	115	13 (10-17)

† 0-N: N omission plot; 0-P: P omission plot; 0-K: K omission plot.

‡ Coefficient of variation (CV) computed from site-specific average values for three wheat crops each sampled in 2003, 2004, and 2005 at each site. Values shown are the mean CV within a site and its range at the six sites (in parenthesis). For each crop, measurements of two replications at each site were combined into a site average. Site averages were then used to compute within-site CV for each crop at each site. These CV values were then used to calculate the average CV for each site across all crops sampled.

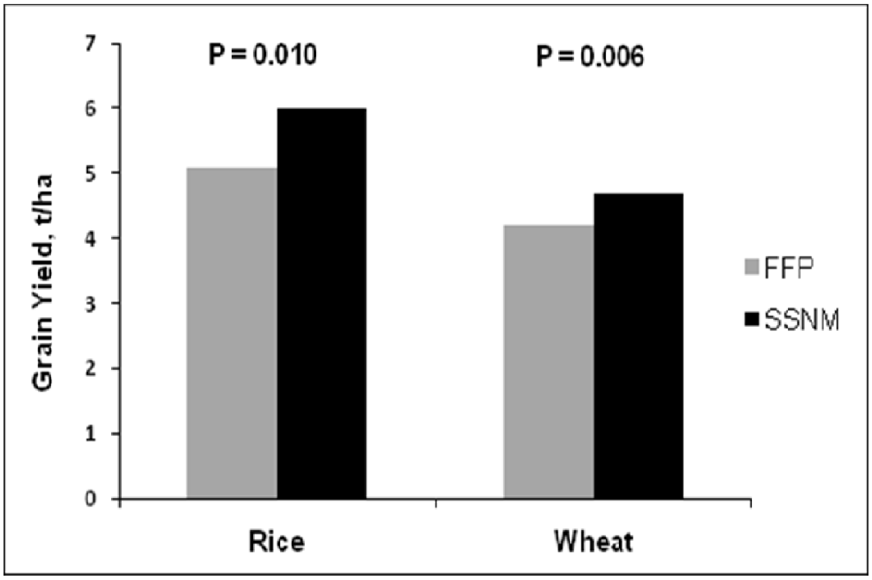

Figure 1. Grain yield of rice and wheat crops in farmer fertilizer practice (FFP) and site-specific nutrient management (SSNM) plots across 56 irrigated rice-wheat farms in Punjab, India averaged for two years (2003-04 and 2004-05). (P values ≤0.05 show significant difference between SSNM and FFP.)

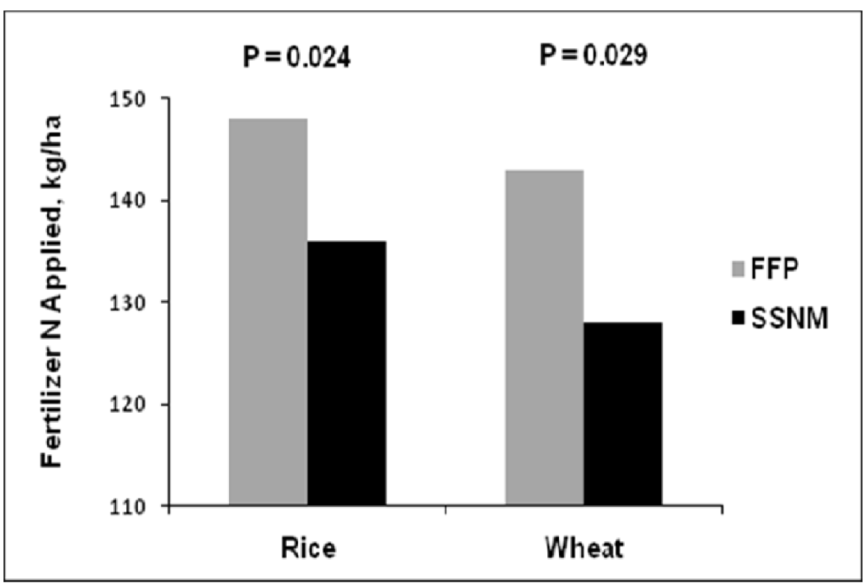

Figure 2. Fertilizer N applied to rice and wheat crops in farmer fertilizer practice (FFP) and site-specific nutrient management (SSNM) plots across 56 irrigated rice-wheat farms in Punjab, India averaged for two years (2003-04 and 2004-05). (P values ≤0.05 show significant difference between SSNM and FFP.)

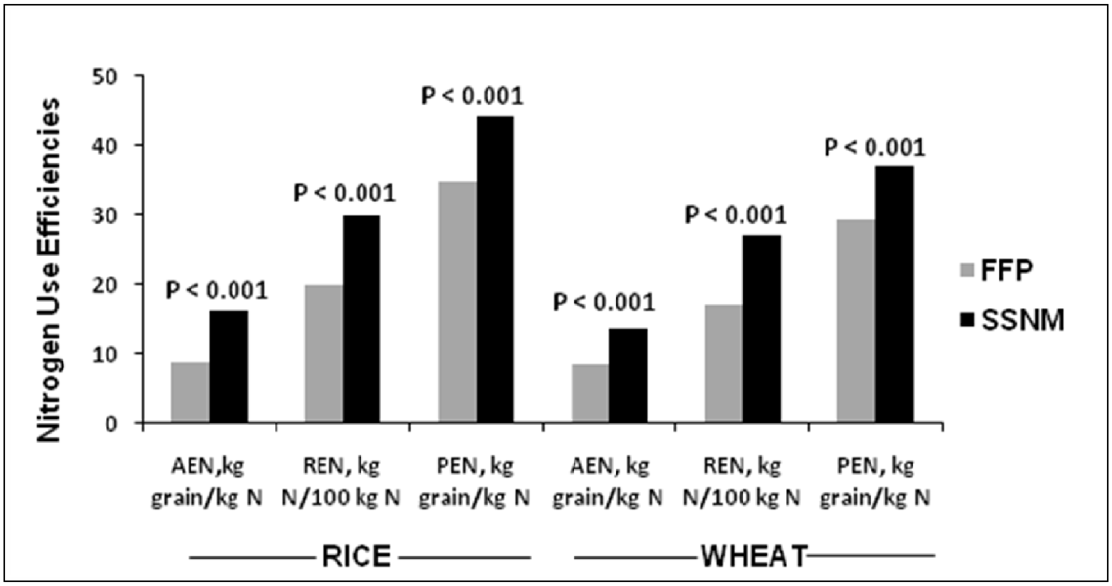

Figure 3. Nitrogen use efficiencies (agronomic N use efficiency [AEN], recovery efficiency of fertilizer N [REN], and physiological N efficiency [PEN]) in rice and wheat crops in farmer fertilizer practice (FFP) and site-specific nutrient management (SSNM) plots across 56 irrigated rice-wheat farms in Punjab, India averaged for two years (2003-04 and 2004-05). (P values ≤0.05 show significant difference between SSNM and FFP.)

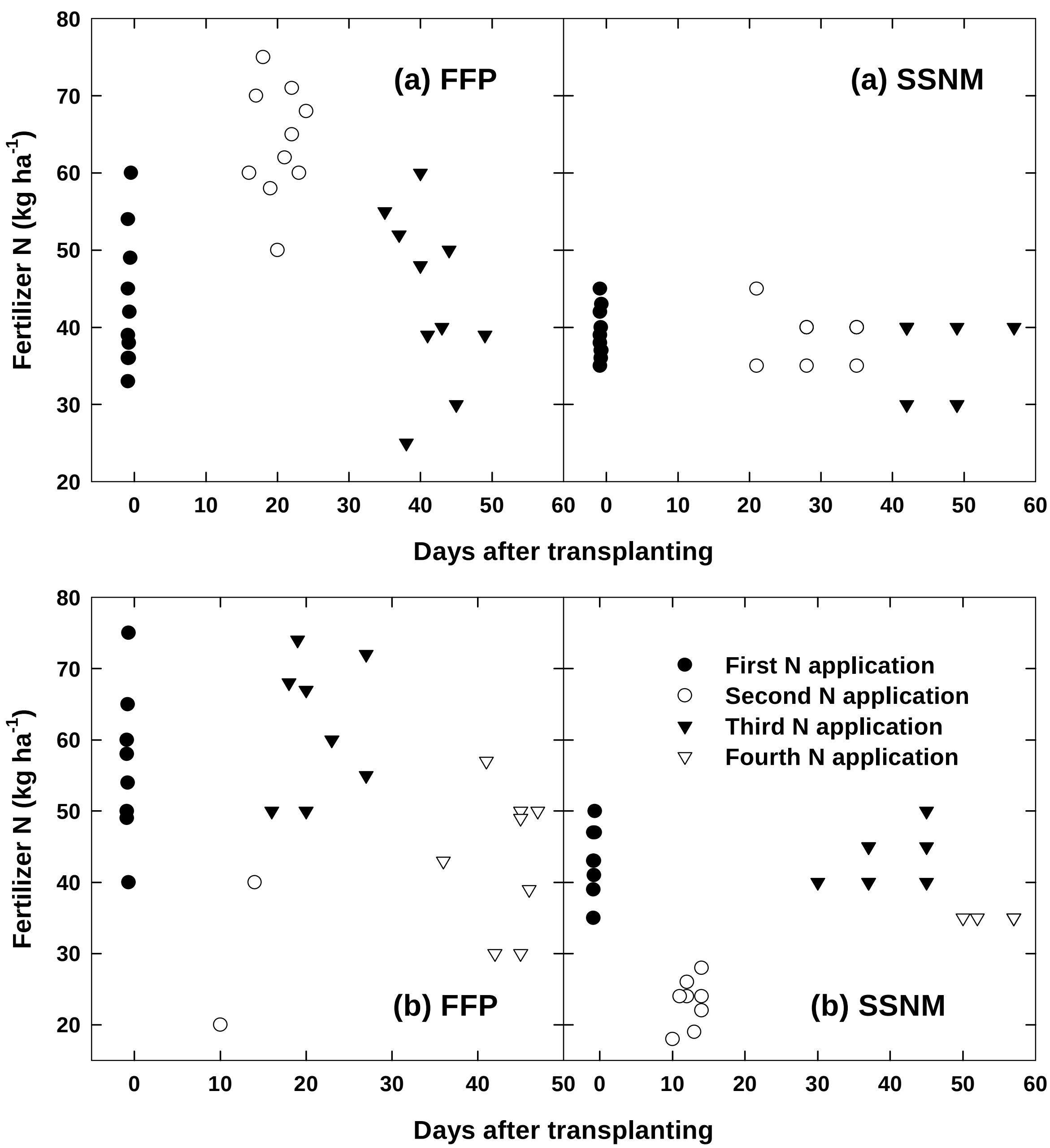

Figure 4. Fertilizer N applications in rice in the farmers' fertilizer practice (FFP) and site-specific nutrient management (SSNM) plots at (a) Gurdaspur (GD) and (b) Firozpur (FP) sites in Punjab.

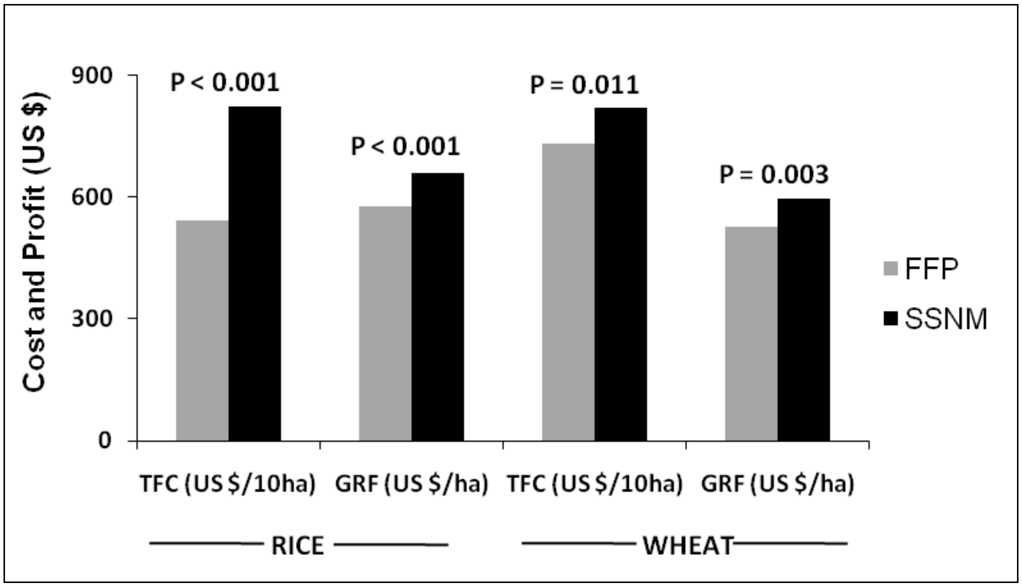

Figure 5. Total fertilizer cost (TFC) and gross returns above fertilizer cost (GRF, profitability) in rice and wheat crops in farmer fertilizer practice (FFP) and site-specific nutrient management (SSNM) plots across 56 irrigated rice-wheat farms in Punjab, India averaged for two years (2003-04 and 2004-05). (P values ≤0.05 show significant difference between SSNM and FFP.)