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Identifying viable nutrient management interventions at the farm level: The case of smallholder organic Basmati rice production in Uttarakhand, India

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ABSTRACT

Smallholder farmers may gain notable livelihood benefits by participating in organic value chains. However, whether there are enough resources available to maintain organic production sustainably on smallholder farms in resource-poor regions is of concern. If not balanced by sufficient inputs, continual nutrient export via commodity crops will result in nutrient mining, and livelihood improvements gained by participating in profitable value chains could be negated by soil degradation in the long term. The objectives of this study were to test an integrated approach for understanding the farm-level impacts of subsystem nutrient management actions and to identify locally viable interventions for increased nutrient supply and recycling. We employ a systems analysis methodology to address the nutrient gaps on smallholder farms in Uttarakhand, India producing organic Basmati rice for an international value chain. Farmers here rely on few livestock (three to five head of cattle ha^{-1}) to supply nutrient inputs and are achieving smaller than potential Basmati yields. We surveyed 42 small farms (< 3.5 ha, average annual income around \$1000 year^{-1}) and analyzed available manure stocks for nutrient contents in order to trace the farm-level flow of manure nutrients, identify vectors of avoidable nutrient loss, and systematically identify locally relevant and feasible improvements. The interventions identified as viable were reducing nutrient losses through simple and relatively cheap manure management modifications (i.e. using straw bedding to capture livestock urine, covering farmyard manure stockpiles with plastic sheeting, enclosed biogas slurry storage, and using biogas slurry for improved compost production), in situ green manuring, and purchasing farmyard manure. Cost–benefit analyses predicted that proposed interventions could increase farmers' net profit by up to 40% while also addressing problematic nutrient gaps. While our results pertain specifically to Uttarakhand, we found that our integrated research approach worked well to address the problem of nutrient gaps on resource-poor smallholder organic farms, and believe that the strategy could be used with equal success to address similar problems in other regions.

1. Introduction

The state of Uttarakhand is on the forefront of promoting organic agriculture in India (Panneerselvam et al., 2012) and is one of the few places in the world where Basmati rice (*Oryza sativa* 'Basmati') is grown. Situated along the Western Himalayan foothills, Uttarakhand's major cropping system is a rice–wheat rotation, where coarse-grain paddy rice is grown in the rainy *kharif* season (approximately June–October) and wheat in the dry *rabi* season (approximately November–March). The number of farmers adopting high-value Basmati in place of coarse-grain paddy has notably increased, and India's export of Basmati grew by 56% between 2010 and 2015 (APEDA, 2016; Jena and Grote, 2012).

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Intercooperation in collaboration with Intercooperation Social Development India (ICSD) targets smallholders in Uttarakhand's Nainital District with potential for joining an organic and fair-trade Basmati value chain, aiming to improve smallholder livelihoods through sale of the in-demand product (Eyhorn, 2017). Participants receive extension support in the transition to grow organic Basmati, and gain access to a reliable marketing scheme. Farmers in the project are generally solely dependent on farming for income and rely on their few livestock (three to five head of cattle ha^{-1}) to supply the bulk of the nutrient inputs used in their organic systems. As in other resource-poor regions of the world, a concern is whether there are enough resources available on smallholder farms to maintain profitable organic production sustainably. A willingness to adopt organic practices does not necessarily imply that farmers are able to employ best organic management, as many are constrained by the availability of essential resources, namely water and organic soil amendments. If not balanced by sufficient inputs, continual nutrient export via commodity crops will result in nutrient mining, and livelihood improvements gained by participating in a profitable value chain could be negated by soil degradation in the long term.

Many farmers in the region achieve lower than potential yields, for various reasons. To achieve sustainable intensification of these systems and thereby magnify the social and economic benefits of farmers' involvement in the organic and fair-trade scheme, the issue of insufficient nutrient supply must be addressed. Since livestock manure is the primary source of nutrient inputs to crop fields, manure management is an essential focus for identifying potential improvements to farm-level nutrient management that are within reach of resource-poor farmers. How manure is managed after excretion and during collection, storage, and field application can result in varying degrees of nutrient losses; these directly affect both the quantity and composition of manure, which in turn affect soil quality and crop yield.

Farmers in the Uttarakhand hills use two primary methods of manure management: farmyard manure (FYM), the practice of collecting animal manures and other organic farm wastes in minimally managed stockpiles, and vermicomposting (VC), the practice of using earthworms to compost animal manures and organic wastes. Some farmers have installed biogas plants, which produce combustible gas (principally CH_4) through anaerobic digestion of animal manures. Biogas is harvested for household use, and spent manure slurry is released from the digestion tank as liquid effluent. Farmers with biogas plants utilize this effluent (biogas slurry, BGS) as a fertilizer. We hypothesize that across all three management practices there is potential for system improvements that are economically, socially, and environmentally acceptable. In addition, there are farmers who have adopted in situ green manuring (GM) with *Sesbania aculeata* between *rabi* and *kharif* seasons, and we hypothesize that this practice improves farm nutrient status.

Smallholder farms may be viewed as composed of multiple intertwined subsystems, the management of which influence whole-farm performance. To investigate adequately the farm-level impacts of different subsystem management actions, an integrated systems approach is needed (Alvarez et al., 2014; Fonte et al., 2012); we adopt such an approach in this study. Furthermore, while useful knowledge can be gained by testing interventions at experiment station field trials, farm-level realities and trade-offs are not always accounted for in the development of management solutions. Diversity among smallholder farmers' production systems and socio-economic constraints necessitates a site-specific approach to ensure that unique and complex interplays of social and ecological factors inform the development of system improvements (Giller et al., 2011). For this reason, we applied our research approach to a case study.

The objectives of this study were: (i) to test the effectiveness of an integrated research approach for assessing the farm-level impacts of subsystem nutrient management actions on smallholder mixed crop–livestock farms; and (ii) to systematically identify locally relevant and feasible solutions to increase nutrient supply and recycling at the farm level in the case study context.

2. Materials & methods

2.1. The study area

The research was conducted in the Nainital District in the hilly southeast region of Uttarakhand, India. Average annual rainfall and temperature here are 1648 mm and 18 °C, respectively. Soils are loamy and shallow to medium-deep with poor water-holding capacity (Srivastava and Singh, 2009). The Nainital District hosts a primarily agriculture-based economy, with $>$ 70% of landholdings $<$ 1 ha (Tuteja, 2013). Commonly cultivated crops include paddy rice, soya, wheat, pulses, tomato, onion, and ginger, as well as a wide variety of herbs and vegetables grown for home consumption. Farmers raise nondescript local hill breeds of cattle and buffalo for milk, manure, and draught power. Farm households typically rely on an average annual income of 69,700 INR (approximately $1065) (Eyhorn et al., 2018). The farms targeted for this study were located in the Patkote, Kotabagh, and Betalghat village areas, and were already participating in the aforementioned organic Basmati development project. A common cropping sequence on these farms was Basmati, coarse-grain paddy, and soya in *kharif*, followed by wheat, tomato, and pulses in *rabi*.

In a field trial at the nearby Govind Ballabh Pant University of Agriculture and Technology (GBPUAT) in Pantnagar, the impact of a suite of organic management practices on the yield performance of Basmati rice is being tested. Data from the experiment station field trial, both published and unpublished, were used to calculate several parameters in our study (see Table 1). For a description of the field trial, see Singh et al. (2016).

2.2. Methods

The research followed the four-phase DEED methodology described by Giller et al. (2011) and inspired by Kolb's experiential learning cycle (Kolb, 1984), in which the research phases are named (1) Describe, (2) Explain, (3) Explore, and (4) Design (Fig. 1). The cyclical nature of the methodology facilitates an iterative approach where knowledge gained from the research can lead to positive action relevant to the actual conditions and concerns of the stakeholders involved. A description of the objectives and methods employed in each research phase follows.

2.2.1. Describe

In the first research phase, we described farmers' actual manure management and GM practices, manure availability, manure application rates, and Basmati crop performance. Data collection activities were organized around a conceptualization of manure management in mixed crop–livestock systems described by Rufino et al. (2006). In this conceptual model (Fig. 2), whole-farm manure nutrient availability and losses are understood as the products of management activities in four farm subsystems: 1. Livestock; 2. Manure collection and handling; 3. Manure storage and composting; and 4. Soil nutrient availability, crop capture, and crop conversion (Rufino et al., 2006).

2.2.1.1. On-farm surveys. Forty-two farmers were surveyed in February–April 2016. The survey was designed to understand farmers' practices in each of the four management subsystems described in Fig. 2, and covered farm size, livestock holding, manure production and collection, allocation of manure to different storage and processing methods, green manuring practices, manure application rates, and Basmati yield. Respondents were purposively selected using stratified sampling to achieve representation of farmers practicing each of four nutrient management practices: FYM, VC, BGS, and GM. At the end of each survey, farmers were asked to describe qualitatively what they perceived as the advantages and disadvantages of their nutrient

Table 1
Literature values used in calculating nutrient inputs, outputs, and balances, and the data source.

Parameter description	Parameter	Value	Source	Notes
Nutrients input via atmospheric deposition	AD_N AD_P AD_K	1.527 kg ha^{-1} 0.036 kg ha^{-1} 1.051 kg ha^{-1}	Pathak et al. (2010)	Data were unavailable for Uttarakhand, so values were taken for Himachal Pradesh, the state most closely resembling the geography of Uttarakhand for which data were available
N input via fixation by in situ green manure crop	IN_{GM}	82 kg ha^{-1}	Toomsan et al. (2000)	Mean value for a low-density planting of *Sesbania aculeata*
Harvest index for Basmati rice	HI	0.36	Singh et al. (2012)	Mean from Basmati yield data
Nutrient contents of Basmati grain	G_N G_P G_K	12.86 g kg^{-1} 2.44 g kg^{-1} 2.43 g kg^{-1}	GBPUAT field trial results (2015, unpublished data)	Means across all organic treatments
Nutrient contents of Basmati straw	S_N S_P S_K	4.80 g kg^{-1} 1.27 g kg^{-1} 12.14 g kg^{-1}	GBPUAT field trial results (2015, unpublished data)	Means across all organic treatments
N leaching loss ($NH_4^+ + NO_3$) as fraction N applied	L_N	$IN_N * 0.03$	Bandyopadhyay and Sarkar (2005); Cao et al. (2014); Tan et al. (2012); Tian et al. (2007)	Mean leaching ($NH_4^+ + NO_3$) emission factor for rice
N volatilization loss (NH_3) as fraction N applied	V_N	$IN_N * 0.132$	Bandyopadhyay and Sarkar (2005); Banerjee et al. (2002)	Mean NH_3 volatilization emission factor for rice

management practice(s). Responses to qualitative survey questions were analyzed using open, inductive coding (Gibbs, 2007).

2.2.1.2. Manure products sampling. Farmers' manure products were sampled in June 2016 directly prior to field application for the Basmati crop and analyzed for dry matter (DM%) and nitrogen (N), phosphorus (P), and potassium (K) contents (%, dry weight basis). Seven FYM samples and five each of VC and BGS were collected. Sample sites were chosen randomly from the pool of farmers previously surveyed. At each site, three random samples were taken from the manure stockpile and mixed thoroughly to form a composite. Samples were then transported directly to the lab at GBPUAT where N (Subbiah and Asija, 1956), P (Olsen et al., 1954), and K (Hanway and Heidel, 1952) were measured.

2.2.1.3. Manure availability. Total raw manure available for use in the *kharif* season (M_{kharif}, kg fresh weight) was calculated as:

$$M_{kharif} = M_{excreted} * m * d + MP \qquad (1)$$

where $M_{excreted}$ is the total fresh manure (kg) collected on-farm per day, m is the number of months manure is collected and saved for use as compost product(s) in *kharif*, d = 30 (days per month), and MP is manure purchased off-farm (kg, fresh weight).

2.2.1.4. Nutrient input rates. NPK doses supplied to Basmati crops via manure products were calculated with the reference values for DM% and NPK contents of FYM, VC, and BGS derived from the on-farm sampling (Table 3). NPK application rates to Basmati crops were calculated per farm (kg ha^{-1}) as:

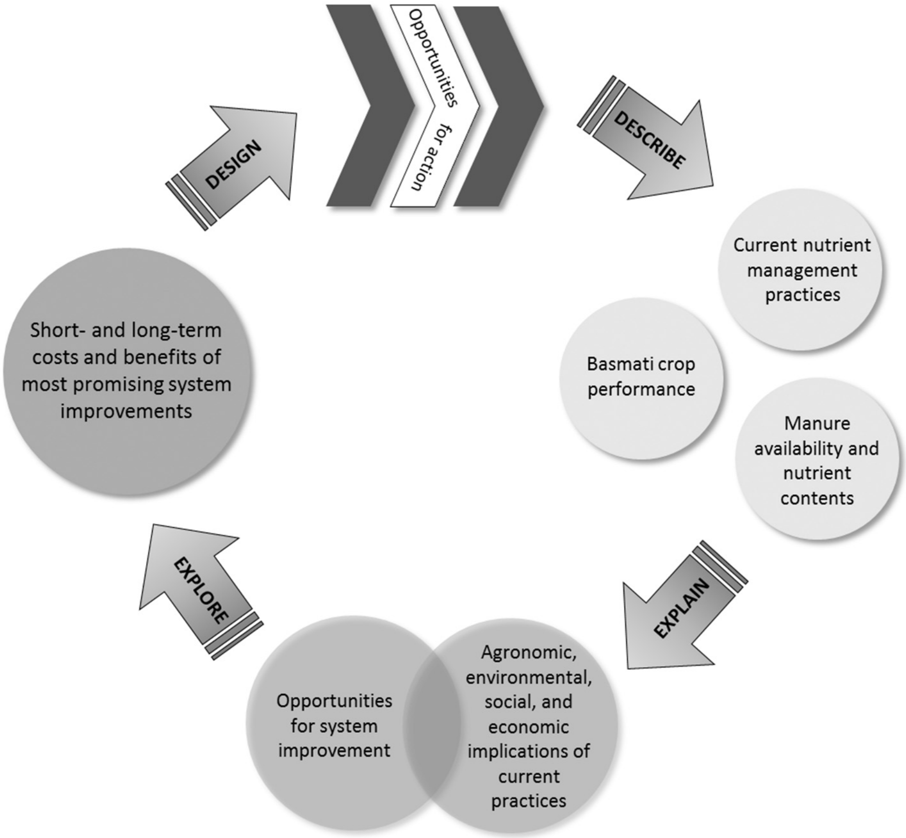

Fig. 1. The four-phase research framework, inspired by the DEED cycle (Giller et al., 2011) and Kolb's experiential learning cycle (Kolb, 1984).

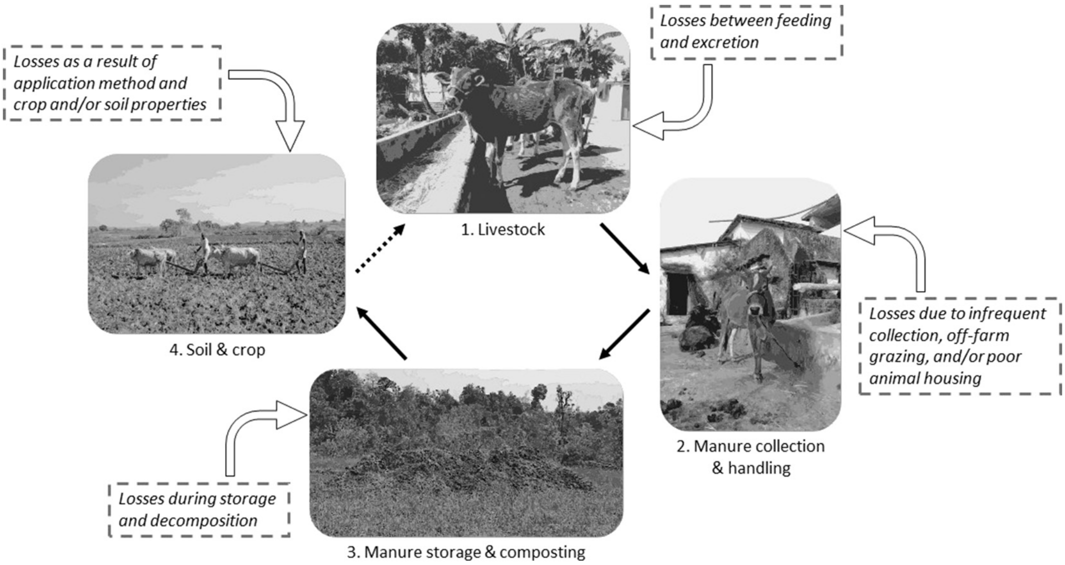

Fig. 2. Conceptualization inspired by Rufino et al. (2006) of farm-level manure nutrient availability and losses in mixed crop–livestock systems as the products of four manure management subsystems.

$$IN_{NPK} = (IN_{FYM}*DM_{FYM}*NPK_{FYM}) + (IN_{VC}*DM_{VC}*NPK_{VC}) + (IN_{BGS}*DM_{BGS}*NPK_{BGS}) + IN_{GM} \quad (2)$$

where $IN_{FYM,VC,BGS}$ is the amount of manure product(s) applied to the Basmati crop (kg ha^{-1}, fresh weight), $DM_{FYM,VC,BGS}$ is the fraction dry matter of the manure product, $NPK_{FYM,VC,BGS}$ is the nutrient concentration of each manure product, and IN_{GM} is the reference value for N fixed by an average *Sesbania* GM crop (Table 1).

Farmers' NPK inputs were compared with recommendations stated in a locally distributed organic Basmati extension manual (Srivastava et al., 2014) and provided by local rice agronomists to quantify potential nutrient gaps. The recommended fertilization rate for organic Basmati of the varieties grown by farmers in the study region (Dehraduni/Type 3 and Taraori) is NPK 70:30:30 (kg ha^{-1}), which agronomists equate with a dry weight FYM input rate of 10 Mg ha^{-1} (Srivastava et al., 2014).

2.2.1.5. Nutrient balances. Simple Basmati field level nutrient balances (kg nutrient ha^{-1}) were calculated for each N, P, and K as the difference between nutrient inputs and outputs. Inputs were atmospheric deposition, N fixation by in situ GM, and nutrients in applied manure products. Outputs were nutrients in harvested Basmati rice grain and straw, NH_4^+ and NO_3^- leaching, and NH_3 volatilization. Input and output parameter values taken from the literature are described in Table 1. Nutrient balances were calculated as follows:

$$BAL_{NPK} = (AD_{NPK} + GM_N + M_{NPK}) - (B_{NPK} + L_N + V_N) \quad (3)$$

where AD_{NPK} is the nutrients delivered via atmospheric deposition, GM_N is the N fixed by in situ *Sesbania* GM, M_{NPK} is the nutrients applied with manure products, B_{NPK} is the nutrients removed in harvested Basmati rice grain and straw, L_N is the N ($NH_4^+ + NO_3$) lost by leaching and V_N is the N (NH_3) lost by volatilization (Table 1).

The nutrients removed in harvested Basmati rice grain and straw (B_{NPK}) were calculated as:

$$B_{NPK} = (Y*G_{NPK}/1000) + ((Y/HI - Y)*S_{NPK}/1000) \quad (4)$$

where Y is a farmer's reported average Basmati grain yield (kg ha^{-1}) from 2013 to 2015, G_{NPK} is the reference NPK uptake of rice grain (g nutrient per kg grain), HI is the reference Harvest Index of Basmati, and S_{NPK} is the reference NPK uptake by rice straw (g nutrient per kg straw) (Table 1).

The method we used to calculate nutrient balances did not take into account inputs delivered via biological fixation by free-living microbes, N fixation by previous legume crops, or native soil banks, nor outputs occurring through denitrification or erosion. We acknowledge the omission of these factors as a limitation of our method, and nutrient balances presented here should therefore be considered as partial and simplified.

2.2.1.6. Statistical analysis. The effect of the use of GM on NPK balances was assessed using one-way ANOVA in R (Version 3.2.1). Differences between farmer groups using GM and not using GM were considered significant at $p < 0.05$. Shapiro–Wilk and Bartlett's tests were conducted to confirm that the assumptions of normal distribution and homogeneity of variance, respectively, were met.

2.2.2. *Explain*

In the second phase, we synthesized the results of the *Describe* phase to build an agronomic, ecological, and socio-economic understanding of the implications of manure management and green manuring for farm-scale nutrient supply and Basmati crop performance. Farmers' practices were systematically examined in each subsystem (Fig. 2) to identify incidences where management actions (or lack thereof) likely lead to nutrient loss. The magnitudes of these losses were estimated by comparing actual farmers' practices with best practice recommendations in the literature. By pairing points of probable nutrient loss with potential management modifications, we identified a pool of options to improve farm-level nutrient availability and recycling.

2.2.3. *Explore*

In the third phase, we narrowed down the pool of potential management interventions by crosschecking the applicability of modifications within the constraints identified in the *Describe* phase and developed a suite of proposed interventions. The viability of each intervention was explored by conducting a cost–benefit analysis and evaluating the trade-offs of projected short- and long-term impacts. To predict the yield benefit of different management interventions we employed a regression model describing the grain yield response of Basmati rice to N input rate. The model was derived from Basmati yield data and the respective N input rates as found in the literature (Mannan et al., 2010; Manzoor et al., 2006; Pandey et al., 1999; Singh et al., 2012, 2016). We fit a linear, quadratic, and loglinear model, and selected the quadratic model as the best fit to predict yields, based on the Akaike information criterion (for details see Appendix, Fig. A.1 and

Table 2
Parameter values used in cost–benefit analyses, and the data source.

Parameter	Value	Source
Baseline cost of cultivating organic Basmati rice[a]	8654 INR ha^{-1}	GBPUAT field trial (2015, unpublished data)
Baseline cost of cultivating conventional Basmati rice[a]	15,652 INR ha^{-1}	GBPUAT field trial (2015, unpublished data)
Cost of *Sesbania aculeata* seed	48 INR kg^{-1}	Farm survey
Cost of N as FYM	404 INR kg^{-1}	Farm survey
Cost of N as synthetic fertilizer (NPK 10:26:26)	206 INR kg^{-1}	Indian Farmers' Fertilizer Collective, price reported in October 2016
Cost of rice straw	1.5 INR kg^{-1}	Farm survey
Cost of plastic sheeting	30–60 INR m^{-2}	Farm survey
Cost of installing a plastic biogas slurry collection tank	4000 INR	Reported by ICSD advisory staff
Sale price of organic Basmati rice	29.5 INR kg^{-1}	Mean for 2014–2015 (ICSD, unpublished data)
Sale price of conventional Basmati rice	23 INR kg^{-1}	Mean for 2014–2015 (ICSD, unpublished data)

[a] This value accounts for external material input costs associated with rice production (e.g. seeds, pest control agents, equipment) and the cost of labor (hired labor and/or household labor). It does not include the value of existing on-farm resources (such as nutrients input via manures) nor the cost of manure or fertilizer.

Table A.1). The model is as follows:

$$y = -4E^{-5}x^2 + 0.0173x + 1.6433 \quad (5)$$

where y is the model-predicted Basmati grain yield (Mg ha^{-1}) and x is the N input rate (kg ha^{-1}). The model applies to input rates between 0 and 200 kg N ha^{-1}.

We then estimated the projected net profit resulting from each intervention. Net profit (INR ha^{-1}) was calculated as the difference between the profit gained by the projected yield and the cost of production. Production costs were calculated as the sum of the baseline cost of cultivating Basmati rice and the cost of the intervention. Parameter values used in cost–benefit analyses are listed in Table 2.

2.2.4. Design

In the final research phase, proposed management interventions were validated by an expert panel. The panel included a local rice agronomist from GBPUAT, a leader from the organic and fair-trade Basmati rice development project, a farmer advocate and agricultural advisor, and several project scientists. We identified the potential challenges and constraints to advisory efforts targeted at implementing the proposed interventions, and identified which farmers would likely benefit most from each intervention.

3. Results & discussion

3.1. Describe

3.1.1. Farm structure, livestock, and Basmati crop performance

Farms ranged in size from 0.3 to 3.3 ha (average 1.1 ha). Livestock holdings ranged from 1.4 to 7.8 livestock units[1] (LU) with an average of 4.5 LU, equivalent to four cows or buffaloes and one calf. The average stocking rate was 5.4 LU ha^{-1}. When asked if they had enough fodder available to feed more livestock, 73% of farmers said yes and, on average, estimated they could feed two additional LU. Why farmers did not have these additional livestock was not addressed in the survey, but responses implied that factors other than feed availability (e.g., labor and cost of animal purchase) were limiting farmers' ability or desire to own more animals.

Basmati yields reported for 2013–2015 ranged from 600 to 3600 kg ha^{-1} with an average of 1816 kg ha^{-1}, which is 37% less than the average of 2871 kg ha^{-1} reported at the GBPUAT field trials (Singh et al., 2016). Average organic Basmati yields have been reported from another study in the same region as 2079 kg ha^{-1} (Eyhorn et al., 2018). Reasons for differences in average farmer yields between the current and the latter study could be stratified versus random sampling and reliance on farmer recall versus measured yields. Nevertheless, in both studies there is a substantial yield gap of 28–37% between average farmer-reported yields and those on the experiment station, which might be reduced by improved farm management and especially efficient use of available on-farm inputs. Other factors that probably contributed to the yield gap are that the GBPUAT trials are located in the plains with deep fertile soils, higher temperatures due to the lower altitude, reliable irrigation, and optimal weed management.

3.1.2. Manure collection and handling

Farmers in the study region mostly kept animals on-farm in open yards during the day and in enclosed sheds at night. Yards were uncovered, and animals stood without bedding on bare soil or stones. We observed that few farmers employed gutters to collect urine. Only one respondent reported off-farm grazing; farmers explained that proximity to the neighboring Jim Corbett National Park posed too much risk of livestock being harmed by large predators. Keeping animals exclusively on the farm allows for frequent and thorough manure collection. All farmers reported collecting manure daily. On average, they then allocated 98% of collected manure to FYM, VC, or BGS, and only 2% to other household uses. Regardless of which manure processing method farmers cited as primary, all farmers reported also storing some FYM, on average 30% of available manure.

We estimated that there was, on average, just over 10 Mg fresh manure available per farm for fertilizing *kharif* crops. This value is < 1/3 of the recommended fresh weight per hectare application rate for Basmati. Assuming degradation losses during storage, the average farmer lacked the raw manure resources to meet agronomic recommendations for Basmati fertilization.

3.1.3. Manure storage and composting

The results of on-farm sampling and analysis (Table 3) show that the nutrient contents of manure products generally fell in the mid to lower range of what is reported in the literature, indicating that there is potential for management interventions to improve manure quality.

The most common storage practice for FYM was to pile materials in a heap on bare soil (88% of farmers making FYM did this) and use no form of cover (47% reported this). All VC farmers reported keeping the material enclosed in a cemented pit, which was usually located under the shade of a tree. 100% of BGS farmers kept the slurry in an uncovered heap or shallow pit on bare soil.

Farmers reported taking minimal measures to actively compost manure stockpiles. Most farmers making FYM or VC (87%) did report supplementing manure with additional organic materials, but few mentioned using an intentional layering technique when adding biomass. Supplementary materials included wasted animal feed, animal bedding, cow urine, crop residues, weeds, tree leaves, and kitchen scraps. Feed waste, composed primarily of straw, most often provided the largest bulk contribution, averaging around 750 kg per season. Only 10% of farmers reported collecting urine for addition to stockpiles. In total, N-rich materials formed a smaller fraction of non-manure

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[1] We define livestock unit (LU) in Indian terms as an adult cow or buffalo (300 kg LW) of a nondescript local hill breed.

Table 3
Average DM, N, P, and K contents of manure products sampled on-farm. Values in parentheses are ranges found in the literature.

	Nutrient content (%)			
	DM	N	P	K
Farmyard manure	43.64	0.52 (0.27–0.95)	0.50 (0.15–1.00)	0.52 (0.30–1.31)
Vermicompost	36.80	0.71 (0.98–2.00)	0.67 (0.20–1.90)	0.68 (0.24–1.21)
Biogas slurry	23.10	0.54 (0.44–2.12)	0.30 (0.16–1.60)	0.45 (0.30–1.09)

Table 4
Average Basmati field-level N, P, and K balances for farmers growing GM, not growing GM, and all farmers surveyed.

	Nutrient balance (kg ha^{-1})		
	N	P	K
With GM[a]	62.18	20.66	− 8.05
Without GM[b]	− 15.23	15.44	− 17.29
All farmers[c]	14.26	17.43	− 13.77

[a] $n = 16$.
[b] $n = 26$.
[c] $n = 42$.

contributions to stockpiles than carbon-rich materials.

3.1.4. Soil nutrient availability, crop capture, and crop conversion

After processing manure into FYM, VC, or BGS, all respondents reported preferentially allocating it to Basmati, despite the fact that Basmati occupied < 1/3 of total cultivated land. On average 73% was applied to Basmati fields, 14% was applied to other *kharif* crops, and 13% was applied to kitchen gardens. This implies that farmers perceive the economic importance of Basmati as high relative to other *kharif* crops, and that there is a net flow of nutrients from other parts of the farm (e.g. where livestock feed is grown) to Basmati fields. All farmers reported ploughing in manures at the time of field preparation. Few farmers applied manure products as a top dressing to the standing crop. One farmer said he mixed wet BGS with irrigation water during the growing season.

Farmers were almost exclusively unable to supply the nutrient needs of Basmati crops and maintain positive nutrient balances by applying manure alone. Few of the farmers surveyed used the recommended rates, which was unsurprising given the generally small initial amounts of fresh manure available. On a nutrient basis, farmers growing in situ GM prior to Basmati were able to meet (and in most cases exceeded) the recommended N input rates, while farmers not growing GM were, on average, only able to supply 43% of the recommended N dose. For P the average input gap was 14% (a 4 kg ha^{-1} deficit), while for K the average farmer was able to meet the recommendation of 30 kg ha^{-1}. Of the farmers not growing GM, only one was able to meet the recommended NPK input rates by applying solely livestock manure. Fig. 3 shows the range and frequency of farmers' NPK inputs compared to the recommended rates.

Farmers growing GM had significantly higher field-level N balances than those not growing it ($p \leq 0.001$) (Table 4). K appeared to be the nutrient subjected the most to mining (71% of farmers had negative K balances). P was the nutrient farmers had the least problem with in terms of negative balances; 83% of the farmers even maintained positive P balances. The fact that NPK input gaps relative to input recommendations do not align with calculated nutrient balances indicates that the input recommendations for Basmati rice might need adjustment. In particular, the result that farmers who applied the recommended K input rates also had negative K balances calls for a reevaluation of the K input recommendation. For the 55% of farmers whose N balances were positive, a yield gap of 6–79% was still observed. This implies that there could be factors other than N limiting the relatively small rice yields. Therefore, applying manure at recommended rates may not fully address the problem.

3.1.5. Perceived advantages and disadvantages

Overall, farmers appeared satisfied with their manure management practices; all farmers mentioned at least one advantage of the method they used. Improvement in soil quality was the most frequently noted advantage. Among FYM farmers, the next most cited advantages were positive implications for human health and crop growth. VC farmers reported positive impact on crop growth and ease of use. BGS farmers frequently mentioned that the process created two useful products, gas for cooking and slurry for fertilizing crops. They also discussed positive implications for human health: smoke-producing cooking fuel is replaced with smokeless biogas, and household members can spend less time collecting firewood in the forest, an activity perceived as dangerous. All GM farmers talked about improvements in soil quality; the second most frequently mentioned advantages were positive impact on crop yield and low cost compared to synthetic fertilizer.

Few farmers discussed disadvantages. Issues noted by farmers making FYM were not having enough FYM to satisfy crop needs, the

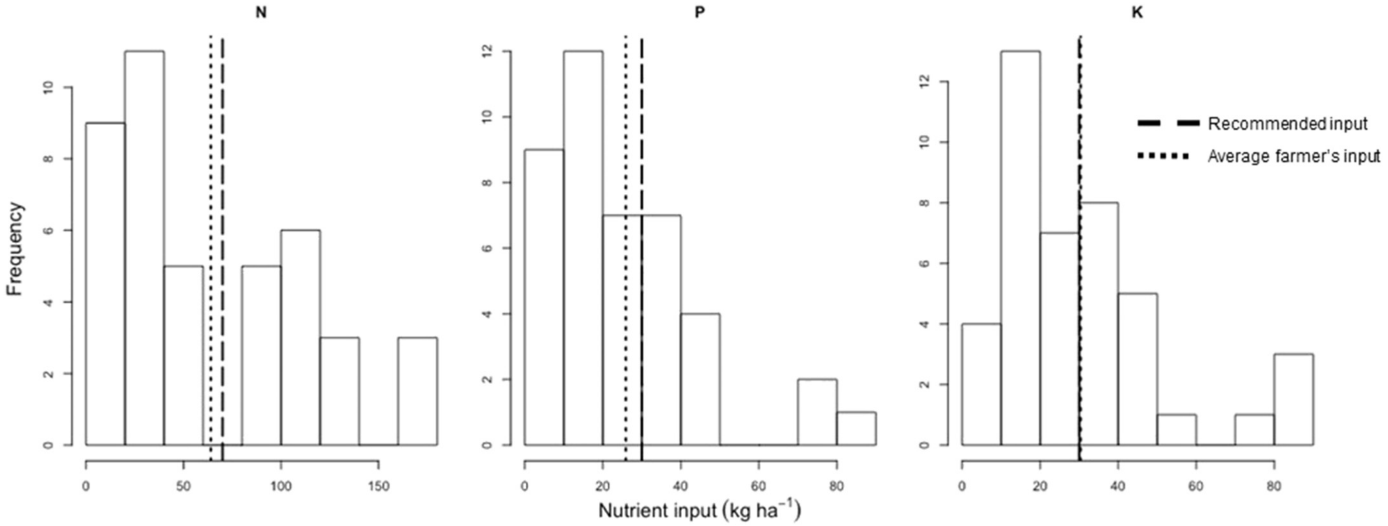

Fig. 3. Range and frequency of NPK inputs by all farmers surveyed compared to recommended input rates.

high cost of purchasing supplemental cow dung, and problems with crop pests transferred in the manure. One BGS farmer mentioned the labor involved with putting manure into the biogas plant daily, and another noted that the slurry was difficult to carry to the field. Only 14% of VC farmers mentioned disadvantages, and among those respondents, only two issues were mentioned: pest problems and a higher labor requirement. 17% of GM farmers stated that having enough water to grow a good *Sesbania* crop was sometimes a problem, particularly if the monsoon arrived late.

3.2. Explain and explore

3.2.1. Livestock

Manure nutrient supply is inherently limited by animal stocking rate, which in turn is limited by a farmer's economic status and access to feed. An average farmer in the present study would need nine additional livestock and the requisite feed resources to produce enough FYM to fill the nutrient input gap for the Basmati crop, which is far beyond what farmers said they could accommodate. Hence, reducing the nutrient gap significantly will require solutions that do not rely on increasing on-farm manure production.

3.2.2. Manure collection and handling

How and where animals are kept, if and how often they are grazed off-farm, and how frequently manure is collected all impact the quantity of nutrients available in the excreta (Rufino et al., 2006). Most respondents kept livestock exclusively on the farm, so off-farm grazing was not a vector of nutrient gain or loss. Furthermore, all reported collecting manure on a daily basis, suggesting that frequency of collection has little influence on nutrient losses. Animal housing conditions, therefore, are most likely the key factors affecting losses in this subsystem since most farmers used various suboptimal techniques. Practices such as keeping animals on bare soil without cover, not collecting urine, and using bedding only in the rainy season may cause avoidable nutrient losses through leaching and/or volatilization, primarily via urine runoff.

Livestock urine is probably the most underutilized on-farm nutrient resource in the study context. On average, $> 50\%$ of the total N excreted by livestock is contained in urine; the N content of livestock urine may range between 2 and 20 g L^{-1}, depending on feed quality (Rufino et al., 2006). According to regional estimates, Indian cattle excrete an average of 7.7 L urine per LU per day (NPCS, 2008). For the average farmer with 4.5 LU and no urine collection, this equates to a current loss of 10–104 kg N per farm each season. Increased urine capture is a first step towards improved recycling of nutrients.

As farmers save manure for *kharif* crops during the dry season, they could keep animals on bedding materials during *rabi* whenever surplus crop residues are available. A farmer might need to purchase straw and then incur an additional cost of up to 2025 INR per season, a 23% cost increase over the baseline that could give a substantial net input of N to the farm system per *kharif* season. Achieving maximum potential N retention would imply that livestock are given feed of optimal quality, but an average farmer would not need to achieve maximum N savings for the intervention to be profitable: by collecting enough urine to meet the recommended N input rate, a farmer could achieve a net profit gain of up to 31% over the baseline.

3.2.3. Manure storage and composting

On the surveyed farms, FYM and BGS storage practices showed the most room for improvement, as farmers making VC largely already followed best practice recommendations. Research shows that up to 50% of the N in manure can be lost during storage (Shah et al., 2012), and that covered FYM piles retain more nutrients than piles exposed to the open air (Shah et al., 2013; Tittonell et al., 2010). Few farmers said they took measures to cover FYM stockpiles, suggesting large nutrient losses from this management subsystem. Evaluated against the alternatives of building a roof or plastering piles with mud, plastic sheeting presents a low-cost and low-labor method of keeping FYM covered that can reduce N losses by up to 21% compared to leaving a pile uncovered (Shah et al., 2012). In the local context, this reduction translates to a potential increase in the N content of FYM from 0.52% to 0.63%. Plastic sheeting would add a yearly cost of 300–600 INR, depending on plastic quality and the size of the FYM pile. This cost, however, would potentially be offset by improved yields. At maximum N loss reduction, the average farmer's N input from FYM could increase from 30 to 36 kg N ha^{-1} with a subsequent 4% increase in net profit.

Improving the storage and composting of BGS is an important point of focus since biogas production has notable social and economic benefits for smallholder farmers (Surendra et al., 2014) and is promoted by local development organizations. The value of BGS as something more than a useful byproduct seems to not be fully recognized by farmers, as the technology is relatively new to the region and the impetus to make biogas is mainly its value as a source of energy. Upon immediate release from the digester tank, wet BGS contains a high concentration of ammonia-N which is lost when the slurry is dried in the sun (Jaiswal et al., 1971). While the best way to reduce N losses during storage would be to keep slurry in enclosed tanks, this technology would require farmers to buy or build additional infrastructure and the materials and labor costs might be prohibitive to many. Alternatively, farmers could line and cover BGS pits with durable plastic sheeting at a cost slightly higher than that predicted for covering FYM piles, or use BGS as a component in layered compost heaps. Sealed storage could potentially more than double the current N concentration of farmers' BGS and improve the transfer of nutrients to the crop, but it is especially difficult to quantify the gains of this intervention because numerous factors besides storage practice affect the nutrient composition of BGS, so we do not attempt to make profit predictions.

3.2.4. Soil nutrient availability, crop capture, and crop conversion

The response of a Basmati crop to manure depends not only on its input rate and nutrient content, but also on other quality factors, whether the manure is applied before or during the growing period, the crop variety, and environmental conditions (Rufino et al., 2006). Due to the complexity of the processes and variables involved, we do not attempt to quantify losses resulting from farmers' management actions nor their effects on crop capture and conversion. Scenarios for increasing nutrients available in the soil, however, can be explored with our foresight approach. Two opportunities to improve nutrient availability in this subsystem emerge as possibilities in the case study context: preceding the Basmati crop with a GM sown between *rabi* and *kharif* seasons, and importing nutrients across the farm gate via purchased FYM.

3.2.4.1. Green manure.

Given the results that farmers growing in situ GM were able to meet and exceed N input recommendations and had few complaints about the method, GM could be a promising solution for filling the N gap in the soil and crop subsystem. Studies show that a productive *Sesbania* crop (8–25 Mg fresh biomass ha^{-1}) can add 60–126 kg N ha^{-1} when turned into the soil (Dahama, 1997; Toomsan et al., 2000), which is equivalent to the N contribution of 3–10 Mg ha^{-1} FYM. However, as well as an additional seed cost, a GM crop would add a substantial labor burden for farmers who currently leave fields fallow between wheat harvest and rice planting. To explore this issue in a cost–benefit analysis, we identified three labor scenarios in which the farmer (1) relies solely on manual labor by household members; (2) hires supplemental manual laborers; and (3) rents a tractor and does the labor mechanically. In all three scenarios, we found the projected net profit to be greater than the current average farmer's practice when the organic premium is paid (Table 5).

The largest increase in net profit (40%) was gained in the scenario where the household alone absorbs the added labor burden, followed by tractor rental and hired manual labor. Without the organic premium,

Table 5
Net profit results of three labor scenarios for implementing in situ GM with *Sesbania aculeata* prior to sowing Basmati. Values in parentheses (%) show the projected percent change over baseline organic net profit.

	Net profit (INR ha^{-1})	
Labor scenario	With organic premium	Without organic premium
Own manual labor	72,438 (+40%)	54,284 (+5%)
Hired manual labor	68,902 (+33%)	50,748 (−2%)
Rented tractor	71,913 (+39%)	53,759 (+4%)

only the hired manual labor scenario showed decreased net profit. These results imply that if a farmer has a large household labor force or access to a tractor, the financial benefit of GM will offset the cost whether or not the organic premium is maintained. In addition to Basmati yield increases, GM could also bring positive long-term effects such as increased soil microbial activity and organic matter content, improved soil aggregate stability, and a net import of exogenous N that could feasibly reduce manure input requirements over time (Mandal et al., 2003). That said, although a GM crop may mobilize P and K already in the soil into plant-available forms, it does not imply a net input of these nutrients.

3.2.4.2. Imported manure. Increasing the nutrients supplied to the Basmati crop could also be achieved with larger manure applications, however, limited on-farm fodder resources probably prevent most farmers from increasing livestock holdings to the size needed for adequate nutrient supply with farm-produced manure. Alternatively, nutrients could be imported via manure purchased off-farm; in order to avoid externalizing negative nutrient balances to other farms, it could be sourced from landless livestock owners. We predicted the economic return on incremental increases in N input for four manure purchase scenarios. In the first scenario, we assume a farmer receives the organic price premium and purchases FYM to fill the N deficit beyond what the average farmer can supply via on-farm resources. Second, we assess the same scenario but without the organic premium. Third, we project that the farmer uses only synthetic fertilizer and does not receive the organic premium. Finally, we evaluate an integrated scenario where N inputs beyond what can be supplied by the average farmer's own manure production are supplied by synthetic fertilizer and, therefore, no organic premium is received. Fig. 4 shows the results of this analysis.

The highest net profit was achieved in the ‘FYM, organic premium’ scenario at an input level of 45 kg N ha^{-1}. To match this input rate, the average farmer would need to buy 6.7 Mg ha^{-1} FYM (fresh weight), and in doing so would theoretically gain a 5% increase over the net profit achieved at the average farmer's N input level. This implies that nutrient gaps that could cause soil degradation in the long run can be reduced while simultaneously providing a marginal profit increase for the farmer. Similar to GM, larger FYM inputs would also imply secondary gains over time, such as increased soil organic matter content (Edmeades, 2003) and improved water infiltration and water-holding capacity, which could in turn positively impact farm performance (Rasool et al., 2007). Unlike GM, purchasing FYM would imply a net import of P and K in addition to N. Given that manure would have to be imported from nearby sources, an expanded boundary of the farm system to include landless neighbors could result in less nutrient loss and improved cycling, as well as better nutrient allocation for productive use within the local farming landscape. However, the long-term sustainability of nutrient sources used by landless neighbors must also be considered when evaluating this intervention.

3.3. Design

The expert panel evaluated the three promising interventions that emerged from the *Explain* and *Explore* phases: improving manure handling and storage methods, implementing GM between *rabi* and *kharif*, and importing manure across the farm gate.

3.3.1. Improved manure management

The panel supported three measures to improve manure management. First, using bedding to capture urine during the dry season would be a good option for farmers who have few animals and surplus straw available; it could also be attractive to farmers with many animals (and therefore large potential gains via urine collection) and the funds to purchase straw. The profit increase gained by collecting urine is in a similar range as what could be achieved by planting GM, and would require considerably less labor. Second, since stockpiling at least some FYM is ubiquitous in the study region, the panel recommended that all farmers should invest in plastic sheeting or be provided subsidies to pay for it. The projected profit gained from this intervention is similar to that of more labor-intensive and costly interventions, and could be particularly attractive to poorer farmers and those who are less receptive to farm-scale changes. Third, the panel agreed that because adoption of biogas plants will likely continue to rise in the study region, improving BGS storage and use to ensure its quality as an organic soil amendment will become increasingly important. They therefore recommended to promote covering effluent pits with plastic sheeting and periodically spreading layers of BGS on compost heaps, as well as further research into developing a low-cost and effective BGS storage tank.

The main obstacle to implementing manure management

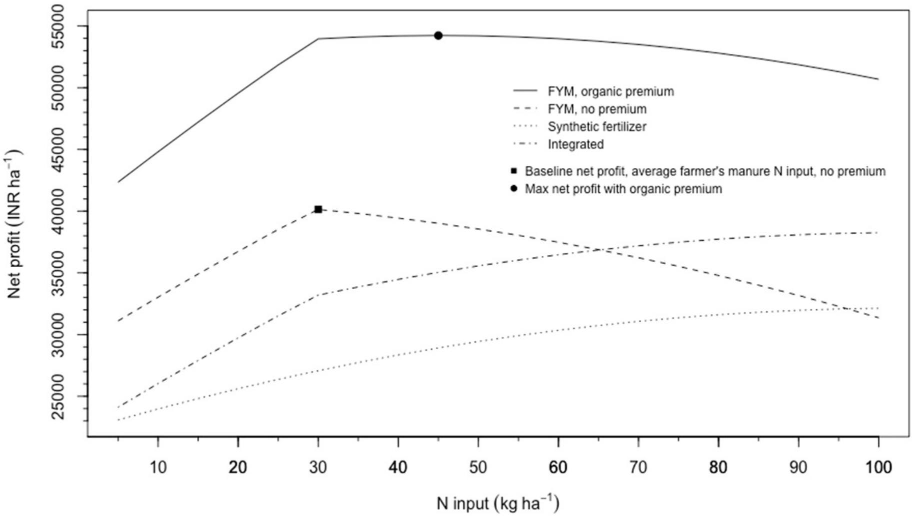

Fig. 4. Net profit response to incremental N input levels in purchased FYM (with and without organic premium), synthetic fertilizer, and integrated scenarios.

modifications would probably be to involve farmers in a participatory process of exploring whether the potential value of improvements can profitably be realized on their farms. Advisory efforts would therefore need to focus on creating awareness around the agronomic value of reducing nutrient losses associated with manure management and on processes that effectively involve farmers in choosing best-fit options for their farms. A co-learning activity following the farmer field school model (van de Fliert et al., 1995) is worth considering. If either the FYM or BGS interventions are promoted, extension training should also address proper handling and disposal of discarded plastic to avoid accumulation in the environment.

3.3.2. Green manuring

The panel confirmed that GM is feasible and promising from both economic and ecological viewpoints. Before GM is promoted, however, further research should address constraints such as projected changes in water availability, the supply, cost, and availability of *Sesbania* seeds on the local market, alternative GM species, and opportunities for seed saving or subsidy programs. Given the implication of an increased labor requirement, GM could be a particularly attractive option for both larger farms with access to a tractor and for smaller farms with a reliable household labor force.

3.3.3. Imported manure

The panel also agreed that purchasing FYM off-farm could bring short- and long-term benefits, and that where excess FYM and investment capital are both available, buying FYM to fill the nutrient gap could be quite attractive to smaller farmers with few livestock. However, the intervention has significant limitations. First, purchasing enough FYM to meet Basmati crop N needs would imply a substantial increase over the baseline cost of cultivating organic Basmati, a cost that must be paid at the beginning of the season and will not be outweighed by a profit increase until the mature crop is sold. Additionally, any increase in manure input would imply a parallel increase in the labor required for field preparation. Finally, the possibility of externalizing nutrient mining from the farm to the landscape must be acknowledged. An increased demand for FYM could tempt poorer arable farmers to sell their manure, possibly resulting in a lock-in where soil fertility and crop yields decline as manure leaves the farm gate and nutrient gaps are reinforced. While this scenario presents the most promising solution to nutrient mining at the Basmati field level, it requires further investigation into the capacity of the regional market to support the intervention.

4. Conclusion

Through the four-phase methodological framework (Describe, Explain, Explore, Design), we were able to identify probable management-induced manure nutrient losses and make locally relevant, validated recommendations for system improvement. We found that integrating qualitative and quantitative tools including farm surveys, manure products sampling, simple systems modeling, and expert panel discussion was essential to address the problem of nutrient gaps on the resource-poor case study farms, and believe that the strategy could be used with equal success to address similar problems in other smallholder settings. In particular, our method facilitated systematic identification of local needs and the selection of locally relevant interventions from a range of academic and extension best practice recommendations.

In the study context, we were able to identify three interventions as economically, socially and environmentally viable for narrowing the nutrient gap and reducing soil mining. First was reducing losses through simple and relatively cheap manure management modifications (using bedding to capture urine, covering FYM stockpiles with plastic sheeting, enclosed BGS storage, and using BGS for improved compost production). Although the average farmer's nutrient input gap was larger than what can probably be retained by patching these system 'leaks', minimizing losses was deemed worthwhile as even small gains in productivity could improve a marginal farmer's livelihood while also mitigating negative environmental consequences. Second and third, importing nutrients via GM or purchased FYM were identified as showing potential. We predicted that these farm-scale interventions could contribute to balancing nutrients at the Basmati field level, thereby improving Basmati yields and magnifying the social and economic benefits of farmers' involvement in the organic and fair-trade market scheme. These interventions may also be applicable to smallholder systems in any setting where nutrient inputs to crop fields are constrained to less than agronomically optimal levels by low on-farm manure production.

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Appendix

A.1. Basmati yield response

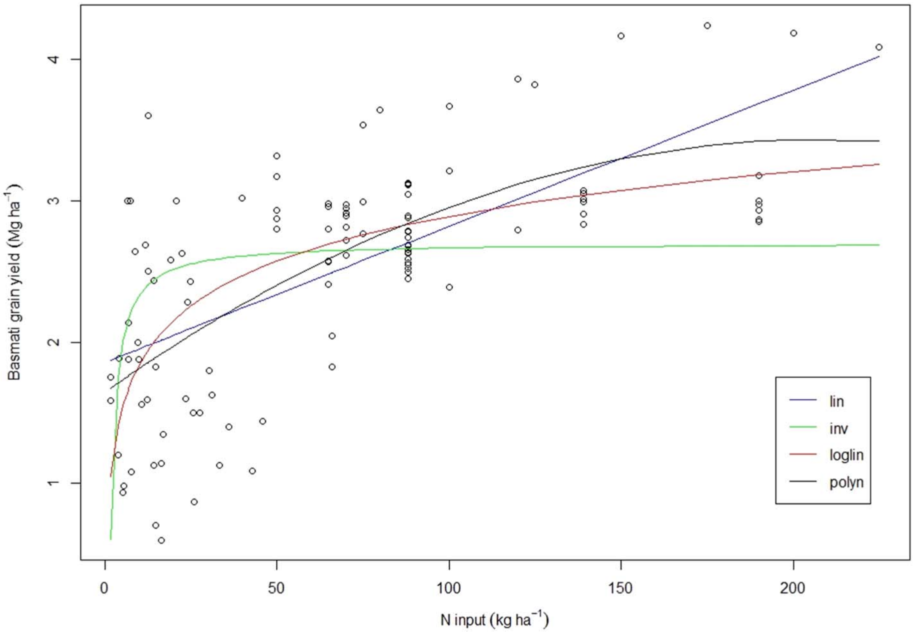

Fig. A.1. Model fit test for Basmati yield response to N input rate.

Table A.1

Akaike information criterion (AIC) values and model equations generated in the model fit test for Basmati yield response to N input rate.

Model type	AIC	Model equation
Linear	207.4256	$y = 0.009639x + 1.855217$
Inverse	249.5580	$y = -3.766 * 1/x + 2.703$
Loglinear	210.7845	$y = 0.4581 * \ln(x) + 0.7803$
Polynomial	202.6367	$y = -4\mathrm{E}^{-5}x^2 + 0.0173x + 1.6433$

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