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Managing Manure for Sustainable Organic Basmati Rice Production: Farm-level trade-offs in Uttarakhand, India

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Abstract

Employing an agroecological framework, the research addressed the interconnected ecological, social and economic aspects of manure management on small-scale organic farms, investigating manure management as central to achieving the potential sustainability and livelihood benefits of organic farming. The primary objective of the work was to contribute to the advancement of knowledge around the performance dynamics, potential, and constraints of three manure management strategies (farmyard manure, vermicomposted manure, and biogas slurry produced from manure) at the farm level on smallholder, mixed, organic farms, and thereby identify opportunities for action to support farmers in the design and management of farm systems that better meet locally relevant sustainability and livelihood objectives. In order to address this objective, the case of smallholders producing organic Basmati rice in Uttarakhand, India was examined. On-farm surveys were coupled with literature review and simple systems modelling to generate integrated assessments of the sustainability of three manure management strategies at the farm level. Both vermicompost and biogas slurry were found to be improved technologies compared to farmyard manure. Vermicompost performed best on most sustainability indicator scales with the exception of yield and gross margin, where biogas slurry performed best. Improving the crop-nutritive value of manure-based fertilizers was identified as a crucial point for system improvement in the research context, implying a necessary shift in focus away from raising bulk manure inputs and towards system improvements that do not hinge on increased manure availability. Minimizing losses during handling, storage, and application were identified as important pathways to improving the crop nutritive quality of the small amount of manure fertilizers that farmers already have available. Key recommendations for reducing losses include using animal bedding, collecting urine, covering manure stockpiles with plastic sheeting, and making vermicompost when possible. Advisory support should be directed towards disseminating information on these improved manure management techniques. Future research efforts should focus on solutions for improving biogas slurry storage, since making biogas has such notable social benefits and biogas slurry will likely be the primary source of manure fertilizer for farmers making biogas.

Keywords: Smallholder organic farming; Farmyard manure; Vermicompost; Biogas slurry; Basmati rice; Manure management; Sustainability analysis

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Contents

1 Introduction

1.1 *Global context: agroecology, organic farming, and the role of smallholders*

The industrial agriculture paradigm is built on principles of scale, mechanization, and intensive monoculture production, principles that have allowed it to keep up reasonably well with a growing population's demands for food, fibre, and fuel in the last century. However, the negative environmental and humanitarian impacts of industrialized agriculture raise substantial concern regarding the sustainability of the current mainstream global food production system (Bennett et al., 2014; Foley et al., 2011; Gladek et al., 2016), as do the growing population and trends in consumer diets that show a shift towards Western preferences (Pretty & Bharucha, 2014; Tilman, Balzer, Hill, & Befort, 2011). To further complicate matters, the effects of climate change pose challenges to farmers worldwide in the form of variable seasonal weather patterns, fluctuating water availability, and rising temperatures (Wheeler & von Braun, 2013). In the face of these global changes and challenges, the growth and persistence of an extractive agricultural economy is increasingly constrained by the depletion of non-renewable resources.

In response to concerns about the ability of industrial agriculture to sustain both the planet and the population, an alternative agroecological paradigm has emerged that focuses on sustainability[1] rather than reaching maximum yield potentials. A key feature of this paradigm is a shift away from viewing agriculture in a simplified linear fashion, and instead viewing it as necessarily complex and cyclical (Kremen, Iles, & Bacon, 2012). In this way, agroecology implies a systems approach to the study and design of farms. An agroecological approach also acknowledges the essential interconnectedness of ecological, social and economic aspects of farm systems (Francis et al., 2003).

While 'agroecologically-sound food production' is not yet part of mainstream consumer vocabulary, organic agriculture is becoming increasingly embraced, as demonstrated by a steadily growing demand for organic food products (FiBL-IFOAM, 2015). Organic practices are sometimes assumed to be synonymous with an agroecological approach to farming, but in many cases, distinctions should be drawn. Definitions of organic are widely varied and contested in the academic community (Rigby & Cáceres, 2001), but generally the term refers to an agricultural practice that does not use chemical pesticides, herbicides, or fertilizers. Organic agriculture in its simplest form may merely be a practice of input substitution, whereas

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[1] The term *sustainability* has enjoyed widespread popularity among academics and policy makers in the environment, development and agriculture communities since the latter third of the 20th century, despite its often vague and diverse definitions (Bell & Morse, 2008). In the 21st century, sustainability is a normative goal; most agree that sustainability is a good thing, representative of endurance and humanitarian and ecological friendliness. However, to measure whether a system has *achieved* sustainability is incredibly challenging, and demands that amorphous and moving targets be fit into finite bounds. In the processes of attempting to measure what Bell & Morse (2008) call the "immeasurable," simplifications, omissions, and substitutions become necessary in order to represent the divergent definitions of sustainability that diverse stakeholders undoubtedly hold. Necessary simplifications, omissions, and substitutions have been made in this research in an attempt to assess the sustainability of different farm management practices; see Section 2.3.3.1 for a description of how sustainability was defined in this research.

an agroecological approach often calls for whole-system redesign. Organic agriculture should be broadly considered as a range of practices falling on a continuum, some versions of which are more agroecologically informed than others. Regardless of how it is technically defined, organic agriculture has the potential to be an important step away from the industrial paradigm and towards more sustainable food production.

For many farmers a switch to organic production is a lucrative strategic move, offering access to a growing market, higher premiums, and a better livelihood (Panneerselvam, Halberg, Vaarst, & Hermansen, 2012; Reganold & Wachter, 2016; Rigby & Cáceres, 2001). Under most conditions, a switch to organic farming practices reduces variable input costs because it eliminates the need to buy fertilizer, pesticides, and other chemical inputs (Reganold & Wachter, 2016). In some contexts, usually in tropical conditions where external inputs are low and production is not managed in an ecologically-sound manner, organic farms can achieve equal or better yields than conventional after a transition period (Ramesh, Singh, & Subba Rao, 2005). Despite these benefits, organic farming is knowledge-intensive and requires a greater reliance on human and natural resources.

Both agroecologically-inspired and organic farming methods utilize complex natural cycles and biological interactions, and therefore require intensive knowledge of each component of these cycles as well as the skills to manage their interactions. Not only does the growing organic market underline a need for more ecologically sound and efficient management of natural resources on-farm, it also highlights a need for programs that support farmers in successfully adopting these complex production methods if an organic and/or agroecological approach to food production is to be considered viable as a sustainability measure (Ikerd, 1993).

With their purchasing power, consumers who choose organic can support a global move towards more agroecologically sound production practices. The majority of the world's organic produce consumers are located in Europe and North America, but most of the organic food consumed globally is produced in developing countries in Asia and Latin America (Parvathi & Waibel, 2016). Although concerns should be raised about the long-term sustainability of a system that facilitates a net export of nutrients (in the form of produce, for example rice grain) from one continent to another, the arrangement opens a window for consumer preferences to positively direct rural development. Many organic producers are smallholder farmers in rural and poor regions with little access to education or state of the art agricultural technologies. For these farmers adopting organic methods presents an opportunity with the potential for multidimensional positive impact. Research shows that adopting ecologically sound production practices and tapping into organic markets can notably improve the livelihoods of smallholder farmers in the developing world (e.g. Panneerselvam, Hermansen, & Halberg, 2010), but farmers need skills and training in order to embrace this opportunity. Adequate farmer support will require further research, development, and transfer of transdisciplinary, systems-oriented agricultural knowledge.

1.2 *Nutrient management in mixed crop–livestock systems*

Organic farmers and agroecologists both recognize the potential of reintegrating crops and livestock as a way to move towards more sustainable food production (Bonaudo et al., 2014; Kremen et al., 2012). A prominent feature of the modern agricultural paradigm is the decoupling of these two kinds of production; this practice serves the mechanisms and objectives of industrialization, but also generates parallel problems of nutrient deficiencies on arable farms and nutrient excesses where livestock are concentrated (Naylor et al., 2005; Petersen et al., 2007). Conversely, traditional subsistence farming has commonly integrated both animal and crop production, often as a matter of necessity. On farms where access to synthetic fertilizers is limited or impossible, animals play an essential role in maintaining soil fertility (Schiere, Ibrahim, & van Keulen, 2002), and maintaining soil fertility in the long-term is a prerequisite for sustainable food production. Ruminants in particular are highly valued for their ability to make use of feed resources that humans cannot, like grass and crop residues, accelerating the return of nutrients to the soil in the form of manure and urine. Furthermore, mixed systems often make use of perennial fodder crops, which can protect soil from erosion, mobilize nutrients, stimulate soil micro fauna, and increase nutrient cycling. A farming system that includes animals has the potential to close nutrient loops more tightly, making it possible under many conditions for mixed crop–livestock farming to be more ecologically sustainable than specialized systems that produce only crops or animals. While many smallholder farmers in developing countries have traditionally practiced mixed farming, these systems are not necessarily managed in balanced or sustainable ways that take full advantage of ecosystem principles and services.

Well-managed and integrated crop–livestock systems are thought to play a key role in the development of sustainable agriculture, particularly among smallholders in tropical and developing countries (Herrero et al., 2013; Reddy, Kumar, Sharma, Acharya, & Dalal, 2005). However, because animals provide many social and economic benefits to smallholder farmers working under marginal conditions (Devendra & Thomas, 2002; Herrero et al., 2013; Paris, 2002), the management of animal resources is often directed by competing farm and household needs across spatial and temporal scales (Reddy et al., 2005; Zingore, Tittonell, Corbeels, van Wijk, & Giller, 2010), and ecosystem principles are not necessarily prioritized. For example, the use of animal manure as a source of soil fertility may be in competition with its use as fuel for cooking (Reddy et al., 2005). Even if agroecological principles such as nutrient cycling for soil fertility are a farmer's priority, the amount of manure he/she can apply to crop fields largely depends on the number of livestock he/she owns, as well as the amount and quality of feed he/she can afford to allocate to animals (Castellanos-Navarrete, Tittonell, Rufino, & Giller, 2015; Reddy et al., 2005). How manure is managed between excretion, collection, storage, and field application can also result in varying degrees of nutrient losses that directly affect both the quality and quantity of manure returned to the field (Rufino et al., 2007). Shah, Groot, Oenema, and Lantinga (2012) report that up to 50% of the nitrogen and carbon initially present in fresh manure can be lost during storage alone. Each manure management decision comes with trade-offs, often involving short-term gains at the expense of long-term sustainability or vice-versa (Castellanos-Navarrete et al., 2015).

In order to support smallholder mixed farmers in successfully adopting organic methods, research must be directed towards whole-farm-level management of manure resources, since in these systems animal manures are often the only organic fertilizer input. A substantial body of literature addresses the constraints associated with manure use on smallholder farms around the world (e.g. Castellanos-Navarrete et al., 2015; Reddy et al., 2005; Rufino et al., 2007; Tittonell et al., 2007). However, more attention must be given to understanding how farmers practically manage this limited resource, as well as to identifying opportunities for action to improve management practices. Understanding and analysis of actual management practices, how these compare to recommended practices, and the complex interlinkage of social and ecological factors at play, requires a system-level approach.

1.3 *Research context: organic Basmati rice in Uttarakhand, India*

This research was nested within an ongoing study of organic Basmati rice production (here forward referred to as the 'parent project') in the Nainital district of Uttarakhand, India conducted by researchers at ETH Zurich in close collaboration with the Govind Ballabh Pant University of Agriculture and Technology (GBPUAT) in Pantnagar, Intercooperation Social Development India (ICSD), and the Swiss development organization Helvetas Swiss Intercooperation, and funded by the World Food System Center COOP Research Program. A detailed description of the parent project background is located in Appendix A.1.

Uttarakhand is situated along the Western Himalayan foothills and within the Indo-Gangetic Plains (IGP), a productive agricultural region that follows the Pakistan–India border and sweeps across Northern India into Bangladesh (map in Figure 1). The major cropping system of the IGP is a rice–wheat rotation, with rice grown in the rainy season (known as the *kharif* season) and wheat and/or other crops grown in the dry months (the *rabi* season). In addition to climate changes (Chauhan, Mahajan, Sardana, Timsina, & Jat, 2012; Ojha et al., 2014), some residual effects of the Green Revolution have motivated farmers in the Indian IGP to adopt organic practices.

While the Green Revolution of the 1960s and 70s had many positive impacts on India's development, including raising per capita food production and improving food security on a national level (Jewitt & Baker, 2007; Panneerselvam et al., 2012), alternative research also shows that it failed to provide many of India's farmers with the secure livelihood it promised (Shiva, 1991), and generated numerous negative environmental and humanitarian impacts (Jewitt & Baker, 2007; Panneerselvam et al., 2012). One result of the Green Revolution was widespread abandonment of traditional soil fertility practices (such as the use of green manures, legume-based crop rotations, and animal manures) in favour of mono-cropping and synthetic fertilizers. Increased reliance on agro-chemicals has generated water pollution and health problems, and contributed to declining soil fertility and profit ratios (Jewitt & Baker, 2007). In response to these issues, some farmers have turned to organic methods for the higher premiums paid for organic produce (20–30% higher than conventional (Ramesh et al., 2010)) and the associated social and environmental benefits (Panneerselvam et al., 2012).

Uttarakhand in particular has become known for hosting a large number of smallholder farmers moving to adopt organic production methods (Panneerselvam et al., 2012). In the period between 2007 and 2011, the total certified organic cultivation area in the state grew by 15% (NCOF, 2016). This movement is partially due to an effort by the state's government to promote organic agriculture, as well as research, trainings, and farmer support generated by the Uttarakhand Organic Commodity Board, ICSD and other development NGOs, the organic farming research faculty at GBPUAT, and the Navdanya Foundation.

Uttarakhand is also known for being one of the few places in the world where Basmati rice is grown, a product coveted for its fragrance and quality (Jena & Grote, 2012). Basmati is currently under evaluation by the Indian government for Geographical Indication (GI) status, although the process has been delayed by complicated international relations since Basmati is also grown in Pakistan (Jena & Grote, 2012). Research has shown that products which gain GI status experience an increase in market size and consumer demand, necessitating a corresponding increase in production (Jena & Grote, 2012). Even without the official denomination of the GI label, consumers recognize the unique quality of Basmati rice and demand for the product is growing (Jena & Grote, 2012); between 2010 and 2015, India's export of Basmati grew by 56% for a total of 3.4 million Mg in 2014–2015 (APEDA, 2016).

A primary concern for scientists and agricultural advisors in study region, as in other resource-poor regions of the world, is whether there are enough organic resources available on smallholder farms to effectively and sustainably maintain profitable organic production. A willingness to adopt organic practices does not necessarily imply that farmers in study region are able to employ best organic management, as many are limited by the availability of natural resources, namely water and bulk manure fertilizer inputs. With the already present consumer demand, established organic and fair trade value chains, and the possibility of Basmati becoming a GI protected good in the future, it is important that the smallholder producers who supply this market are able to manage their farm systems in a more sustainable manner, so as to continue to reap the benefits of much improved profitability. It is therefore necessary to better understand what organic Basmati rice farmers in Uttarakhand actually practice as they process and allocate manure fertilizers, and to identify areas of manure management that could potentially be improved.

1.4 *Objectives and research questions*

The primary objective of the work was to contribute to the advancement of knowledge around the performance dynamics, potential, and constraints of manure management at the farm level on smallholder, mixed, organic farms, and thereby identify opportunities for action to support farmers in the design and management of farm systems that better meet locally relevant sustainability and livelihood objectives. In order to address this objective, the case of smallholders producing organic Basmati rice in Uttarakhand, India was examined. Specifically, this research addressed the farm-level trade-offs of three methods of managing and processing animal manures as a source of soil fertility for sustainable intensification of organic Basmati rice production: farmyard manure (FYM), vermicomposted manure (VC), and biogas slurry (BGS) produced from manure. In the research context, FYM is considered a traditional and unimproved practice. VC is considered in the literature as an improved practice resulting in a more stable and crop-nutritive product than FYM (Jeyabal & Kuppuswamy, 2001). While the health and economic benefits of biogas production are widely lauded, the agronomic and environmental impacts of using BGS as a fertilizer product are still under debate (Nkoa, 2013).

In order to address the primary research objective, the following research questions were asked:

- How can the management of manure resources in organic production systems contribute to improved sustainability and livelihood support of smallholder farmers?
    - Which manure fertilizers, and associated manure management practices, contribute most positively to sustainability and livelihood objectives, and how?
    - How can manure management practices be improved to better meet locally relevant sustainability and livelihood objectives?

To explore and answer these questions, research was driven by the following instrumental objectives:

1. Quantify on-farm nutrient availability for farmers adopting each of the three manure fertilizers.
2. Explore the effects of three manure fertilizers on crop performance and nutrient balances.
3. Identify the agronomic, social, and economic advantages and disadvantages, as experienced by farmers, of the management practices associated with producing each manure fertilizer.
4. Generate an integrated assessment of the sustainability of the manure management strategies associated with each manure fertilizer at the whole-farm level.
5. Identify opportunities to assist farmers in improving the management of manure resources so as to better meet locally relevant sustainability and livelihood objectives.

2 Materials, methodology and methods

2.1 *The study area*

The research was conducted in three blocks of Uttarakhand, India's hilly Nainital district: Kotabagh, Patkote (part of the Ramnagar block), and Betalghat (see map, Figure 1). The Nainital district (29°38'N, 79°45'E, 1500–2400 m above sea level) is warm temperate with a growing period of 270–300 days, 750–1800 mm annual rainfall, and average annual temperatures between 8° and 19°C (Panneerselvam et al., 2010; D. K. Singh & Pratap, 2009; P. C. Srivastava & Singh, 2009). Soils are loamy and shallow to medium-deep with poor water holding capacity (P. C. Srivastava & Singh, 2009).

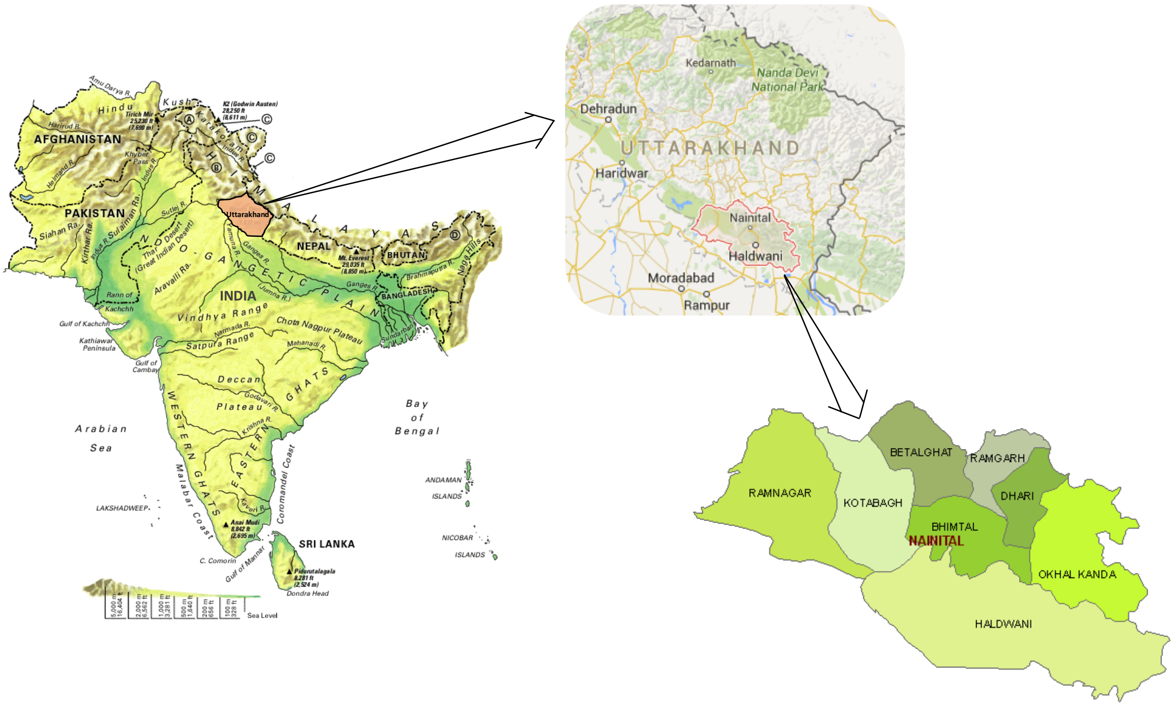

Figure 1. Topographical map of India (left) with the state of Uttarakhand highlighted in orange. Position of the Nainital district in the state of Uttarakhand (map top right, Nainital district outlined in red), and the blocks of the Nainital district (bottom right). Maps adapted from Britannica.com and Google Maps.

The Nainital district hosts a primarily agriculture-based economy, with more than 70% of landholdings less than 1 hectare in size and farmers practicing mixed crop–livestock farming (Tuteja, 2013). Commonly cultivated crops include paddy rice, soya, wheat, pulses, tomato, onion, and ginger, as well as a wide variety herbs and vegetables grown for home consumption. Prior to adopting organic methods, farmers in the Nainital district commonly used low doses of synthetic fertilizers in addition to FYM. All three village blocks studied are surrounded by wide areas of forest, which provide valuable resources such as firewood but also pose dangers due to large wildlife populations. Access to both Patkote and Betalghat requires long-distance travel on narrow and poorly maintained roads with infrequent public transportation services, and both village areas are regularly inaccessible by vehicle due to landslides and flooding.

The farms targeted for this study were already participating in the parent project, and characterized by their small size, mixed crop–livestock systems, organic production practices, and relative resource scarcity. A common cropping sequence was Basmati and soya in kharif, followed by wheat, tomato, and/or pulses in rabi. Small home gardens were maintained in both seasons. Farmers raised non-descript local hill breeds of cattle and buffalo for milk production and draught power, with the average farmer owning 4–6 livestock. Most farm households relied primarily on farm-based revenue, the majority operating on a total annual income of 15,000–60,000 INR (approximately $220–880 USD) (ICSD, 2014, unpublished data).

2.2 *Methodology*

This study employed theoretical elements of participatory action research (PAR), a methodology widely recognized as effective for the study of complex agricultural systems (Méndez, Bacon, & Cohen, 2013). PAR locates the researcher within the field of study, rather than outside as an inactive observer (Checkland, 1999). This allows for dynamic and adaptive dialogue between researchers and stakeholders, where problem definition and inquiry can evolve based on a reflective practice (Packham & Sriskandarajah, 2005), a characteristic particularly relevant to this work because of its position within an already active context of participatory technology development. PAR also highlights a need for stakeholder involvement and reflective practice on the part of the researcher (Packham & Sriskandarajah, 2005), qualities which enhance the potential for the work to contribute to the advancement of co-learning between farmers, researchers, and advisors in the organic sector. PAR methodology is well suited to the field of agroecology, where stakeholder involvement is often considered as essential as empirical biophysical study. An agroecological approach includes the social dimension, so it was important that knowledge gained from the research could lead to the potential for positive action relevant to the actual conditions and concerns of the stakeholders involved. PAR methodology shifts the focus of research from knowledge for the sake of knowledge, to knowledge for the sake of action.

The research also took a systems-level view, seeking to understand the impact of manure management from a whole-farm perspective. The systems thinking theory utilized throughout this work was primarily derived from Bawden et al. (1984), Checkland (1999), and Wilson and Morren (1990). These authors theorize systems thinking as a holistic approach that addresses both the biotic and abiotic elements of a farm system, as well as the interplay of internal and external agronomic, environmental, social, and economic forces and sub-systems.

Within the participatory and systems-thinking framework, the research was designed to follow a four-phase methodology based on an adapted understanding of Kolb's learning cycle (Kolb, 1984) and the DEED framework described by Giller et al. (2008). The four phases of the hybrid methodology used in this thesis were defined as: 1. Describe; 2. Explain & Explore; 3. Evaluate; and 4. Act. These stages correlate with Kolb's Experience, Reflect, Conceptualize, and Act. The cyclical nature of the methodology facilitates an iterative approach to PAR, but due to the limitations of this project, the research cycle was completed only once. Because of time constraints, the Act phase did not involve direct action to implement solutions, but instead identified opportunities for possible future action. Figure 2 shows a schematic of the research phases as they fit into a cyclical process.

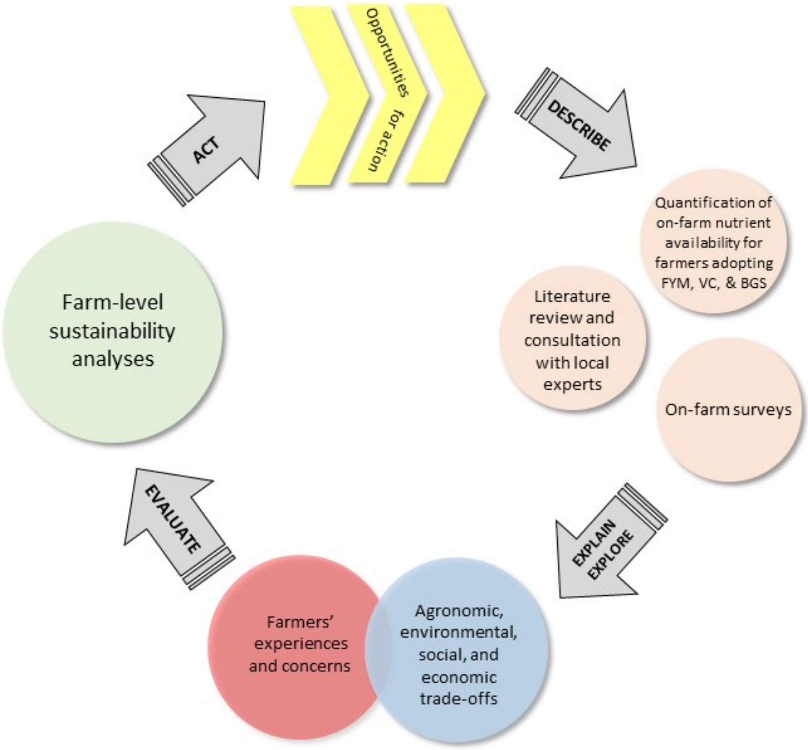

Figure 2. The four research phases as they were positioned within the methodological framework. Feedback loops and backtracking between phases was allowed for throughout the research process. Schematic inspired by Kolb's leaning cycle (Kolb, 1984) and the DEED cycle for science learning and innovation (Giller et al., 2008; Groot & Oomen, 2015).

2.3 *Methods*

2.3.1 Phase 1: Describe

In the first phase of the research, instrumental objectives 1–3 were addressed in order to generate a comprehensive 'description' of the farm systems and actual farmers' practices under study. Primary data were collected on farm size, livestock holding, area under Basmati cultivation, Basmati yield, manure production and collection, allocation of manure to different processing methods, fertilizer input rates, and farmer perceived advantages and disadvantages of each manure processing method. Literature was reviewed in order to generate default values for calculating the nutrient input of each manure fertilizer product.

Baseline demographic information for farmers participating in the parent project was provided by ICSD surveys (2010–2015, unpublished data), where both organic and conventional farmers in the study region were randomly selected and surveyed on general farm and household characteristics, field and crop management, farm economics, and labour inputs. Unpublished 2015 data from the field trial at GBPUAT were also employed. The field trial started in 2012, with ten treatments under a randomized block design with three replications: BGS 10 Mg ha^{-1} (alternate wet and dry (AWD)); Green manure (GM) + FYM (10 Mg ha^{-1}) (AWD); Organic AWD (FYM 10 Mg ha^{-1}); FYM 10 Mg ha^{-1} + VC 5 Mg ha^{-1} (AWD); SRI (FYM 10 Mg ha^{-1}, AWD); Direct seeded rice + Soy intercrop (FYM 10 Mg ha^{-1}, AWD); Organic control (continuous flooding (CONT)); Chemical control (CONT); FYM 5 Mg ha^{-1} + VC 2.5 Mg ha^{-1} (AWD); and GM + VC 2.5 Mg ha^{-1} (AWD).

2.3.1.1 Manure products default nutrient values

Although it would have been preferable to analyse locally collected samples, the fieldwork took place approximately two months before the start of the kharif season (when farmers sow Basmati), so direct sampling of manure fertilizers would not accurately represent the material farmers later applied to Basmati crops. Therefore, to estimate the nutrient contents of the three manure products under study, literature was reviewed and average values for dry matter (DM, as % fresh weight) and nitrogen (N), phosphorus (P) and potassium (K) (as % dry weight) were compiled. Due to the wide range present in the literature, a sub-group of references most relevant to the North Indian study conditions was isolated to calculate 'local averages' for both FYM and VC, which were then crosschecked by local experts for local validity. The range of literature values compiled and final default reference values are presented in Table 1. A complete table of all values and references compiled for calculating the default values of each manure product is located in Appendix A.2.

Table 1. Range of values found in the literature for DM (%) and NPK (%, dry weight basis) contents of farmyard manure (FYM), vermicomposted livestock manure (VC), and biogas slurry (BGS) from biogas produced with livestock manure. Default reference values (means adjusted to local conditions) used to calculate secondary variables are in bold.

		%, dry weight basis					
	% DM	N		P		K	
Manure product	default	range	default	range	default	range	default
FYM	**25**	0.27–0.95	**0.43**	0.15–1.00	**0.23**	0.30–1.31	**0.45**
VC	**40**	0.98–2.00	**1.03**	0.20–1.90	**0.74**	0.24–1.21	**0.65**
BGS	**6.74**	0.44–2.12	**1.65**	0.16–1.60	**0.77**	0.30–1.09	**0.85**

2.3.1.2 On-farm surveys

Quantitative and qualitative data on farmers' experiences with manure-based fertilizers and the management issues associated with each treatment were gathered through surveys of 58 farmer participants in three blocks of the Nainital district (Kotabagh, Patkote, and Betalghat) in Uttarakhand, India between February and April 2016. An initial draft of the survey was tested on six farmers in the Patkote area and then modified based on issues that arose from the exercise. The survey was conducted in Hindi through facilitation of a local translator (an employee of ICSD), and responses were recorded in English by the primary interviewer. Farmers were purposively selected for surveying from the pool already participating in the organic Basmati marketing scheme, using stratified sampling to achieve representation of at least 12 farmers from each of the three manure management practices under study. The survey consisted of four common sections (1. Survey ID, 2. Farm Profile, 3. General Basmati Crop Management, 4. Manure, General) which all farmers answered. A fifth section, with variations targeting issues specific to each FYM, VC, and BGS, was presented to farmers based on what they initially reported as their primary manure management practice. Survey templates are located in Appendix A.3.

2.3.2 Phase 2: Explain & Explore

In the second phase, secondary values were calculated from survey data to facilitate analyses of the trade-offs associated with each manure treatment at the farm scale. Qualitative and quantitative survey data were coupled with the results of simple systems modelling to build an integrated agronomic, ecological, and socio-economic understanding of the performance and trade-offs of each treatment.

2.3.2.1 Quantitative survey data

Livestock units

European standard livestock units (LSU) were used for comparing the stocking rates of different farms with different types and numbers of animals, where: cow = 1, calf = 0.4, ox = 1, buffalo = 1, and goat = 0.1. While Tropical Livestock Units (TLU) are considered more relevant to the research context, their calculation requires knowledge of the live weight (*lw*) of the livestock in question, which was not known in this case. The main difference between the two units is that TLU assumes overall smaller animal size than LSU. For the purposes of this research and given the lack of more detailed livestock data, it was deemed sufficient to use the LSU conversion factors in order to facilitate a simple comparison across farms; references to LSU here should be therefore considered in terms of relative units, not actual *lw* values. If more detailed analyses were to be performed using livestock holding as a variable, a more accurate calculation of TLU would be necessary.

Manure availability

Total raw manure available for use in the kharif season (M_{kharif}, kg) was calculated as:

$$M_{kharif} = M_{excreted} * m * 30 \tag{1}$$

where $M_{excreted}$ is the total fresh manure (kg) collected on-farm per day (survey question Q4.3) and m is the number of months manure is saved for use as fertilizer product in kharif (Q4.5).

Conversion of fresh manure to fertilizer products

Total manure fertilizer product obtained from fresh manure inputs (F_{total}, kg) was estimated based on conversion factors for FYM, VC, and BGS found in the literature and reported by local experts, in the following equation:

$$F_{total} = \sum_i ((M_{kharif} + d) * M_i * C_i) \quad (2)$$

where i is an index containing the elements FYM, VC and BGS, d is the amount of dung (kg) purchased by the farmer for use in kharif season (Q5.11), M_i is the fraction of total manure collected (M_{kharif}) allocated to FYM/VC/BGS production (Q4.6), and C_i is the conversion factor for each manure processing method. Here C_{FYM} = 0.5 and C_{VC} = 0.3, after Munroe (n.d.); and C_{BGS} = 0.12, following local expert knowledge.

Farmers' fertilization rates

NPK doses supplied to Basmati crops via manure fertilizers were calculated with the default reference values for DM% and NPK contents of FYM, VC, and BGS described in Section 2.3.1.1. Nutrient application rates to Basmati crops were calculated per farm (in kg ha^{-1}) as:

$$IN_{NPK} = (IN_{FYM} * DM_{FYM} * NPK_{FYM}) + (IN_{VC} * DM_{VC} * NPK_{VC}) + (IN_{BGS} * DM_{BGS} * NPK_{BGS}) \quad (3)$$

where $IN_{FYM,VC,BGS}$ is the total amount of manure product applied to the Basmati crop (kg ha^{-1}) (Q5.7 / Q6.17 / Q7.16; Q6.13 / Q5.12 / Q7.16; Q7.12 / Q5.12 / Q6.13), $DM_{FYM,VC,BGS}$ is the default percent dry matter of the manure product (Table 1), and $NPK_{FYM,VC,BGS}$ is the default nutrient concentration of each manure product (Table 1).

Recommended fertilization rates

Farmers' bulk manure fertilizer and NPK nutrient inputs were compared with local agronomic recommendations, as stated in ICSD's organic Basmati extension manual (A. Srivastava et al., 2014) and GBPUAT rice agronomists. The recommended fertilization rate for organic Basmati of the varieties grown by farmers in the study region is NPK 70:30:30 (kg ha^{-1}) (D. K. Singh, 2016). Bulk manure fertilizer recommendations are outlined in Table 2. NPK and manure input recommendations are general and do not account for variability between farms, but they can be used to draw a frame of reference for approximately how much manure a farmer would need in order to supply optimal Basmati crop nutrition. Ideally, inputs should be matched to potential uptake by the crop, as limited by crop variety and other factors like water, soil texture, climate, etc.

Table 2. Bulk manure fertilizer inputs for organic Basmati rice, as recommended by local agricultural advisors.

	Input rate (Mg ha^{-1})	
Manure fertilizer product	Fresh weight	Dry weight
FYM	35–40	10
VC *	19–20	7.8
BGS	150	10

* Rate assumes VC is sole manure fertilizer, basal dose. If applied as a top dressing in addition to FYM, recommended rate is 3–4.5 Mg ha^{-1} VC (fresh weight) 20–25 days after transplanting.

Modified primary practice groupings

Before being interviewed in depth, each farmer was asked to identify his/her primary manure processing method, and survey data were categorized based on these self-described treatment groupings. Later, for more accurate categorization during secondary calculations and treatment comparisons, farmer respondents were re-grouped by primary processing method based on to which manure processing method 50% or more of the total fresh manure available was allocated. These modified primary practice groupings also classified secondary manure processing methods to account for the fact that most farmers surveyed utilized more than one manure processing method. After reorganization, 17 farmers were classified as FYM farmers, 13 as VC, and 11 as BGS. Original survey response groups were employed for analysing qualitative survey data, and modified primary practice groups were employed for all quantitative group comparisons.

Yield corrections for differences in fertilizer rate

To compare yield between fertilizer types, reported yields were first corrected for differences in manure fertilizer input rates. Literature on the response of Basmati yield to fertilizer input rate was reviewed, and data were collated from five studies (see Appendix A.4 for all literature data with references). These data were analysed by linear regression (Figure 3).

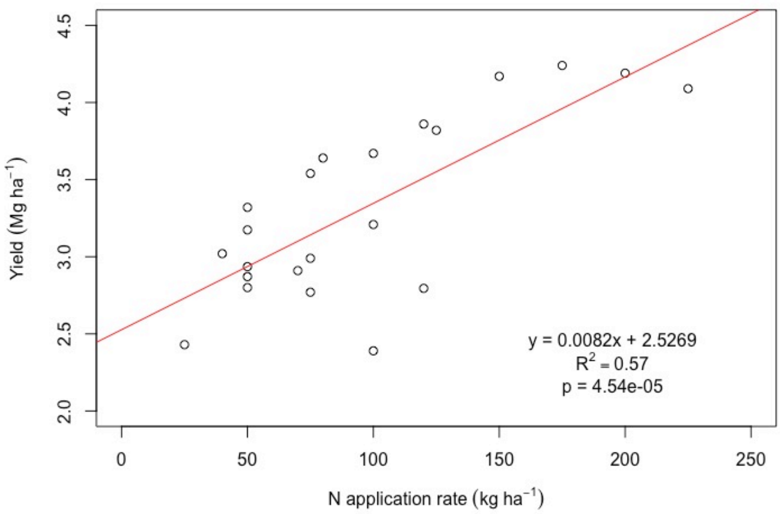

Figure 3. Relationship between Basmati rice yield and N fertilizer application rate based on data from Mannan et al. (2010); Manzoor et al. (2006); Pandey et al. (1999); Singh et al. (2016); and Singh et al. (2012). Data located in Appendix A.4.

The regression equation was used to correct reported yields for N application rate.[2] A standard mid-range N dose of 35 kg ha^{-1} was chosen for calculating the correction factor. Corrected yields were calculated as:

[2] It should be noted that the literature data may indicate a non-linear relationship between N input rate and Basmati yield after an initial linear increase. However, for the purpose of this research only a simple linear relationship was assumed, since the N dose used for correcting application rates was 35 kg ha^{-1}, a value which falls in the zone where the N input to yield relationship is still linear. It should also be noted that the slope of the regression line is steeper than should be expected for Basmati grown under the actual on-farm conditions of this study. The

$$Y_{corrected} = Y_{actual} * (Y_{35}/Y_{predicted}) \quad (4)$$

where Y_{actual} is the average yield (kg ha^{-1}) from 2013–2015 (Q3.5), Y_{35} is the yield (kg ha^{-1}) predicted by the regression equation for $x = 35$, and $Y_{predicted}$ is the predicted yield for $x = N_{input}$. Corrected farmers' reported yields were compared across the three primary practice groups using the statistical methods described in Section 2.3.2.3.

Nutrient balances

Simple field-level nutrient balances (kg nutrient ha^{-1}) were calculated for NPK by subtracting the nutrient uptake of Basmati ($UP_{N,P,K}$, in kg ha^{-1}) from the nutrients applied with manure fertilizer products ($IN_{N,P,K}$ in kg ha^{-1}, calculated with Equation 3), where $UP_{N,P,K}$ is calculated as:

$$UP_{N,P,K} = (Y * G_{N,P,K}) + (Y/HI - Y) * S_{N,P,K} \quad (5)$$

where Y is the average grain yield (kg ha^{-1}) from 2013–2015 (Q3.5), $G_{N,P,K}$ is the NPK uptake of rice grain (kg nutrient per kg grain), HI is the default Harvest Index of Basmati, and $S_{N,P,K}$ is the NPK uptake of rice straw (kg nutrient per kg straw). The default HI for Basmati used in this equation is 0.36, determined by taking an average from yield data from D.K. Singh et al. (2012) and the GBPUAT field trial (2015, unpublished data). Default values for $G_{N,P,K}$ and $S_{N,P,K}$ were derived from GBPUAT field trial data (2015, unpublished data). The default values for NPK contents of grain and straw used in Equation 5 are given in Table 3. Averages were calculated for the nutrient balances of farmers in each primary practice group and balances were statistically analysed as described in Section 2.3.2.3.

Table 3. Default values for NPK contents of rice grain and straw, derived from GBPUAT field trial data (2015, unpublished data) used to calculate N, P, and K uptake of Basmati rice.

	Nutrients (kg kg^{-1})	
	grain	straw
N	0.01286	0.00480
P	0.00244	0.00127
K	0.00243	0.01214

The method used here to calculate nutrient balances did not take into account inputs delivered via atmospheric deposition, irrigation water, or biological fixation, as these data were not collected in this study. It can be assumed, however, that these input pathways were similar across all farms in the study region due to geographic proximity, and therefore would not

experiments described in the reference literature were conducted under controlled experimental conditions (where irrigation and P and K nutrition were optimal and kept as constants), none of which were in the same specific climatic region as the farms surveyed for this research. Furthermore, the Basmati rice varieties used in these experiments were not the same varieties used by the surveyed farmers. As some of the experiments used high-yielding dwarf varieties with presumably different responses to N input rates, the literature-reported yields should be considered higher overall than what should be predicted for yields achieved with the traditional Basmati varieties grown by farmers in the study region.

heavily influence the comparison of balances across the three manure treatments. However, the inclusion of pulses in a crop rotation would imply larger N inputs through biological fixation; because there was probably large variation in crop rotation practices among the farmers surveyed, the omission of this input pathway in calculating nutrient balances is a definite limitation of the study. The calculated balances also did not account for native soil banks of available nutrients—this factor depends on both soil parent material and the history of agronomic practices on the farm. Furthermore, the balance calculations did not account for outputs occurring through leaching, erosion, denitrification or volatilization. The relative weight of these output pathways likely do vary across the three treatments, particularly for BGS which may be applied in various stages of wetness or dryness, and as a top dressing or at the time of ploughing. Finally, balance calculations are inherently limited in accuracy in that they were calculated using literature-derived default values for manure fertilizers rather than locally sourced samples. Therefore, nutrient balances based only on estimated nutrient input and crop uptake output should be considered as partial, rough and simplified estimates of a scenario that is in reality more complex.

Costs of processing

The annual cost of using each manure processing method was calculated as the sum of average seasonal materials costs and start-up costs spread over a 10-year payment period. In this scenario, the start-up cost of building a biogas plant was assumed to be 10,000 INR, the price a farmer would pay if he/she received full subsidies. The cost of building vermicompost pits was calculated as an average of farmer reports. Given the potential magnitude of start-up costs compared to mean annual farm revenue, calculations were done based on the assumption that a farmer must take out a loan to afford start-up costs. The life span of a biogas plant or vermicompost pit was conservatively estimated as 10 years. The annual cost of each method ($C_{FYM,VC,BGS}$, INR yr^{-1}, with start-up investment spread over a 10-year payback period) was calculated as:

$$C_{FYM,VC,BGS} = SM_{FYM,VC,BGS} + ((SU_{FYM,VC,BGS} + (SU_{FYM,VC,BGS} * i / 100)) / 10) \qquad (6)$$

where SM is the seasonal materials costs (Q5.2 / Q6.5), SU is the start-up cost (Q6.4 / Q7.4), and *i* is the interest rate on agricultural loans. The *i* value was set at 10.7%, based on the average interest rate of agricultural loans available in the region at the time of writing, as reported by the Ministry of Agriculture and Farmers' Welfare, Government of India (2015).

Labour

Labour requirements for each manure management method were calculated as the sum of the average days spent on the method per season, the average days spent managing paddy rice (56 days per season) as per ICSD baseline survey data (2010, unpublished data), and estimated average days spent collecting firewood (56.25 days per season). While it is not known precisely how many farmers used wood for fuel as opposed to LPG, farmer reports indicated that using firewood was a common practice in the study region. The time spent on firewood collection was estimated as 3 hours per day, a conservative average of reports by local farmers and ICSD field staff.

2.3.2.2 Qualitative survey data

Responses to the two qualitative questions asked at the end of each survey *("Do you face any problems with using FYM/VC/BGS to fertilize your Basmati? Please explain."* and *"What do you like about using FYM/VC/BGS to fertilize Basmati?")* were analysed using open, inductive coding following Gibbs (2007). All responses were transcribed into a spreadsheet and content topics were identified. Similar and/or associated subordinate topics were then grouped under a superordinate theme. For example, responses mentioning the structure, feel, colour, fertility, and/or water holding capacity of the soil were grouped under the theme 'Soil Quality.' Each superordinate theme was then colour coded, and each phrase of the transcribed responses was highlighted with a corresponding theme colour. Each superordinate theme was then tallied to give the frequency by which it was mentioned by respondents. Response frequencies were calculated as percent of total respondents mentioning the given superordinate theme.

2.3.2.3 Statistical analysis

Data were analysed for variance using the single factor ANOVA function and Turkey's Honest Significance Test (confidence level 0.95), both in standard R software (Version 3.2.1). Regression analyses were performed with the *lm* (linear model) function in R. Statistical significance was determined at $p < 0.05$.

2.3.3 Phase 3: Evaluate

The third phase of the research used the integrated results of Phase 2 to assess the effectiveness of the manure management practices under study in meeting sustainability and livelihood objectives. The sustainability of each treatment was measured with four categories of sustainability attributes—agronomic productivity, ecological impact, social feasibility, and economic viability—and displayed as comparative 'sustainability spider webs.' Farmers' actual manure management practices were then compared against best management practices recommended in the literature and by local advisors.

2.3.3.1 Sustainability indicators

In this research, sustainability was considered as a process rather than a destination, and systems were assessed based on whether they moved towards a more sustainable state. Here, sustainability was represented by a set of dynamic indicators meant to be revisited and revised as part of an iterative and reflective practice. These indicators were derived from a set of sustainability statements that were developed based on the Sustainability Assessment of Food and Agriculture systems (SAFA) framework (FAO, 2013) and adapted to both the research context and the available data. Following Bell and Morse (2008), sustainability statements can be seen as principles that "define what should and shouldn't be done in order for sustainability to become a reality" (p. 11), and are used in place of a single, static, broad-brush definition of sustainability. In this way, the sustainability of a given farm system is seen as unfixed and relative. Ideally, sustainability statements should be collaboratively developed through dialogue between all stakeholder groups involved in the project; due to the time constraints of this research, involving stakeholders in this way was not feasible.

The sustainability indicators developed for use in this research, and the sustainability statements they were derived from, are outlined in Table 4. Principles and processes of production were measured based on whether or not, and to what extent, they were moving *towards* an adaptable goal, and not by whether they had reached a fixed end-goal. Some indicators were here technically expressed in absolute terms (like yield), while others more explicitly imply movement in a positive or negative direction (nutrient mining, for example); the indicators were not meant to create snap shots of system quality that could be compared over time, rather they represent drivers of change in system quality, and were meant to be compared across treatments, not over time. To facilitate this comparison, indicator 'scores' were calculated as relative to reference averages taken from baseline surveys (ICSD, 2010–2015, unpublished data), the GBPUAT field trial (2015, unpublished data), and/or local agronomic recommendations. Although the indicators 'NPK deficit' and 'NPK surplus' are in some ways redundant with the indicator 'nutrient input,' they are included here so as to highlight the individual agronomic and ecological component issues associated with nutrient input rates. Similarly, the 'gross margin' indicator provides an alternate view of the 'yield' and 'production cost' indicators.

Table 4. Sustainability statements used in calculating indicators for comparing the relative sustainability of FYM, VC and BGS practices, grouped by sustainability attribute. Where applicable, baseline reference values are given.

Sustainability attribute	Sustainability statement	Calculation of indicator 'score'	Baseline reference
Agronomic productivity	Yield gaps should be minimized	Farmer yield relative to field trial average	2922 kg ha^{-1} [a]
	NPK inputs should meet recommendations for optimal Basmati fertilization	Nutrient input (kg ha^{-1}) relative to agronomic recommendation	N:P:K 70:30:30 kg ha^{-1} [b]
	Incidence of pest infestation should not increase	Fraction of farmers reporting less or about the same pests since adoption	N/A
Ecological impact	Nutrient mining should be avoided	NPK deficit (kg ha^{-1}) relative to recommended NPK input dose	N:P:K 70:30:30 kg ha^{-1} [b]
	Nutrient losses should be minimized	NPK surplus (kg ha^{-1}) relative to recommended NPK input dose	N:P:K 70:30:30 kg ha^{-1} [b]

Table 4. cont.

Social feasibility	Labour requirement should be minimized	Labour savings relative to baseline kharif season labour requirement	112 man-days [c]
	Weed management requirement should not increase	Fraction of farmers reporting less or about the same weeds since adoption	N/A
	Farmers should be satisfied with the method overall	Fraction of farmers reporting no problems with the method	N/A
Economic viability	Production costs should be minimized	Manure management cost as % of average total organic Basmati production cost	3416 INR season^{-1} [c]
	Profit should be maximized	Gross margin (INR season^{-1}, cost of production including manure management subtracted from the product of yield, average sale price, and area Basmati)	N/A

[a] GBPUAT field trial (2015, unpublished data)
[b] Local agronomic recommendation
[c] ICSD surveys (2010–2015, unpublished data)

2.3.4 Phase 4: Act

In the final research phase (Act), opportunities for action to improve manure management were derived from survey results, sustainability spider webs, and the comparison of actual farmer practices with best practice recommendations. Action opportunities were conceptualized as realistic recommendations for how to support farmers in adopting best manure management practices. Recommendations were organized based on an understanding of whole-farm manure management as comprised of four sub-systems, following Rufino, Rowe, Delve, and Giller (2006). Due to the time constraints of the research, implementation of recommendations was not possible; in this context, the 'Act' phase was realized rather as the articulation of concrete suggestions for future advisory and research efforts.

3 Results

3.1 *Describe*

3.1.1 General farm characteristics

Across all respondents, farm sizes ranged from 0.3 ha to 3.3 ha with an average of 1.1 ha; this range falls within the range previously reported (ICSD, 2010–2015, unpublished data), but the average is somewhat larger than the previously reported average, possibly a result of the stratified sampling method and/or the smaller sample size. Livestock holdings ranged from 1.4 LSU to 7.8 LSU with an average of 4.5 LSU (in this context equivalent to four cows and/or buffalo and one calf). The average stocking rate was 5.4 LSU ha^{-1}. The average percent of total cultivated land that farmers allocated to Basmati was 35%; although this fraction is larger than previously reported by ICSD surveys (2012–2015, unpublished data), the finding supports the observations of local advisors that farmers allocate 1/3 of their land to low-risk staple crops, 1/3 to home garden food production, and 1/3 to high-risk, high-value, and/or experimental crops (like Basmati). The average reported Basmati yield for the period 2013–2015 was 1816 kg ha^{-1}, which is lower than previous reports, possibly an artifact of the stratified sampling method and/or farmer recall error. Overall, farmers' yields were 38% lower than the average reported at the GBPUAT field trial. Figure 4 shows the distribution of survey responses for basic farm characteristics for all farmers surveyed.

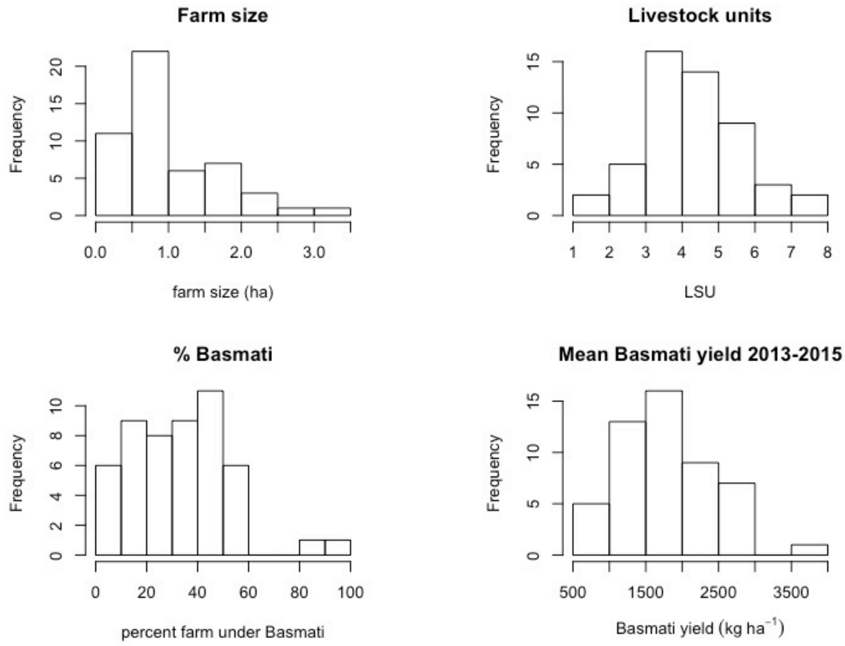

Figure 4. Distribution and frequency of survey responses for four basic farm characteristics: farm size (ha), total livestock units (LSU), percent farm under Basmati cultivation in kharif season, and mean Basmati yield for the period 2013–2015 (kg ha^{-1}).

3.1.2 Manure management

Production and allocation

Based on farmers' reports of daily manure collection, it was calculated that on average, each LSU produced 13 kg manure per day; this value is comparable with other estimates for livestock in the same region (NPCS, 2008). At an average livestock holding of 4.5 LSU, an average total of 58.5 kg manure was produced on-farm per day. All farmers surveyed reported collecting manure daily, and on average saved manure for 5 months prior to use in the kharif season. All farmers surveyed allocated fresh manure in similar ways: on average, 98% of all collected manure was allocated to processing as either FYM, VC, or BGS, 1% to burning as an insect repellent, and 1% to plastering floors in and around the home compound. After subtracting the 2% allocated to non-fertilizer related uses, the total fresh manure produced on-farm available for processing into fertilizer products for use in kharif season came to an average of 9683 kg per farm. This value is less than 1/3 of the recommended per hectare application rate for Basmati; assuming a reduction in mass during storage and processing, the average farmer surveyed lacked outright the raw manure resources to meet agronomic recommendations for Basmati fertilization.

Based on the percent of collected manure allocated to each manure processing method, five common practice groups were identified which described the characteristics of farmers' secondary manure processing methods as associated with primary methods; these groups, and the average percent of total manure allocated to each processing method per group, are displayed in Table 5. Further analyses and results are based solely on the three primary practice groups (only FYM, VC primary, and BGS primary, here forward referred to as FYM, VC, and BGS primary practice groups).

Table 5. Classification and manure allocation characteristics of modified farmer groupings as determined by primary and secondary manure processing method. The average percent of manure allocated to each processing activity is indicated for each group.

	% manure allocated to processing method		
Common practice group	FYM	VC	BGS
Only FYM (*n* = 17)	98	0	0
FYM primary, VC secondary (*n* = 5)	64	35	0
VC primary (*n* = 13)	43.5	54	0
BGS primary (*n* = 11)	30	0	69
FYM, VC and BGS (*n* = 5)	31.5	31.5	34

After processing manure into either FYM, VC, and/or BGS, farmers in all primary practice groups allocated finished manure fertilizers in similar ways. On average 71–75% of manure fertilizer was allocated to Basmati fields, 13–16% was allocated to other kharif crops, and 10–16% was allocated to home gardens; there was no statistical difference between primary practice groups in how manure fertilizers were allocated. It is notable that all respondents reported preferentially allocating manure fertilizers to Basmati, despite the fact that on average Basmati only occupied approximately 1/3 of cultivated land.

Storage

Table 6 shows the response frequencies for each storage and cover practice by primary practice group. The most common storage practice for FYM users was to pile materials in a heap on bare soil or mud, and to use no form of cover. All farmers in the VC group reported keeping the material enclosed in a cemented pit, which was most commonly located under the shade of a tree. 100% of BGS farmers kept the slurry in either a heap or shallow pit on bare soil with no form of cover. It was observed on-farm that common practice was first to collect liquid BGS in a shallow pit at the base of the effluent outlet, and then to shovel semi-dried slurry out into piles around the edge of the pit as it filled up. Additional actions taken to manage the storage and processing of manure fertilizers (i.e. turning and watering manure piles) are discussed in Section 3.1.6.

Table 6. Frequencies of responses for manure storage site and coverage method used by farmers making FYM, VC, and BGS.

		% of farmers using the method		
Storage		FYM	VC	BGS
	heap on bare soil or mud	88	0	50
	heap on cement surface	0	0	0
	pit, bare soil or mud	6	0	50
	pit, cement	6	100	0
Cover				
	no cover	47	31	100
	plastic tarp	18	0	0
	hard roof (tin, plastic, or cement)	0	8	0
	under a tree	35	62	0

(FYM n = 17, VC n = 13, BGS n = 12)

Conversion of fresh manure to fertilizer products

The average total fresh manure available for use in the kharif season was almost the same for farmers in the FYM and VC groups (10,000–11,000 kg ha^{-1}), and was lower for farmers in the BGS group at approximately 6000 kg ha^{-1}. After subtractions for non-fertilizer uses, the average total amount of fertilizer product available for use in kharif (on a fresh weight basis, estimated with Equation 2) was 4632 kg FYM for farmers only making FYM, 1537 kg VC + 2199 kg FYM for farmers making primarily VC, and 26,979 kg BGS + 1456 kg FYM for farmers making primarily BGS.

3.1.3 Manure fertilizer input rates

56% of farmers reported using more than one type of manure fertilizer on their Basmati fields. With the allocation parameters outlined in Table 5, average manure fertilizer input rates as the sum of all products applied were calculated for each FYM, VC, and BGS primary practice groups (Figure 5). On a dry weight basis, farmers in the FYM primary practice group input on average 2030 kg FYM ha^{-1}; farmers in the VC group input 2322 kg VC ha^{-1} + 1345 kg FYM ha^{-1}; and farmers in the BGS group input 1268 kg BGS ha^{-1} + 1113 kg FYM ha^{-1}. Across the three primary practice groups, farmers in the FYM group input the lowest total manure fertilizer, followed by the BGS group, with farmers in the VC group inputting the most total manure fertilizer. Although the average starting amount of fresh manure available for processing into fertilizers was similar for FYM and VC groups, the total dry weight mass conserved during conversion is higher for VC than for FYM, so the resulting input rates were notably higher for the VC group than for the FYM group.

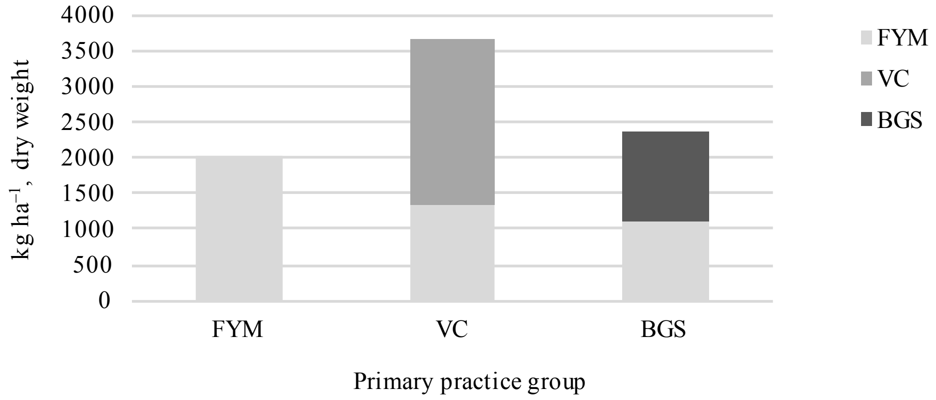

Figure 5. Average manure fertilizer inputs (kg ha^{-1}, dry weight basis) as the sum of all manure fertilizers applied for farmers in FYM, VC, and BGS primary practice groups.

Reported input rates were compared with the estimated total product available (calculated with Equation 2), and it was found that on average, farmers in the FYM and VC groups reported using about 1000 kg more product than was estimated to be available. Farmers' reports of BGS inputs were more closely in line with estimated available pools, and were on average about 20 kg over the available estimate. Estimates calculated with Equation 2, however, did not take into account biomass from added composting materials other than livestock excreta; it is therefore likely that actual values of F_{total} for the FYM and VC groups were higher than estimated here. Based on this likelihood, it can be assumed that farmers' estimates of input rates were quite accurate and do not represent a significant source of error in subsequent results.

On a nutrient basis, farmers input on average only 36% of the N, 50% of the P, and 61% of the K doses recommended for Basmati. Figure 6 shows the distribution of reported total N, P, and K inputs (kg ha^{-1}) supplied by manure fertilizers (sum of all manure fertilizers applied, calculated with Equation 3) for all farmers surveyed, compared to recommended doses. Only three of the farmers surveyed supplied the recommended NPK dose to their Basmati crop.

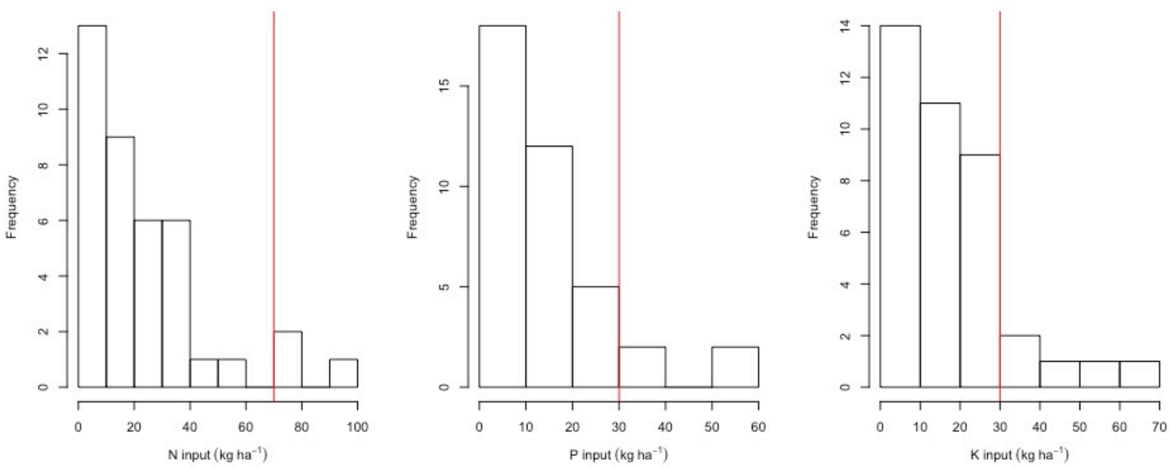

Figure 6. Distribution of reported NPK inputs (kg ha^{-1}) to Basmati crops via manure fertilizers (sum of all manure fertilizers applied) for all farmers surveyed. The recommended NPK doses for Basmati (70:30:30) are denoted with red vertical lines.

3.1.4 Nutrient balances

Most farmers surveyed were not maintaining zero or positive NPK balances. N, P, and K balances were distributed across a wide range, with most values falling between –40 and 20 kg ha^{-1} for N and –10 and 20 kg ha^{-1} for P, and mostly negative values for K (see Figure 7). K appeared to be the nutrient with the most potential for mining, probably because large quantities of K are removed from the field via crop residues (rice straw), and not returned with great efficiency. According to these results, P is the nutrient that farmers had the least problem with in terms of negative balances. Since none of the positive balances were especially high relative to recommended NPK input rates, nutrient losses as a result of surplus were not considered a major problem in the study area.

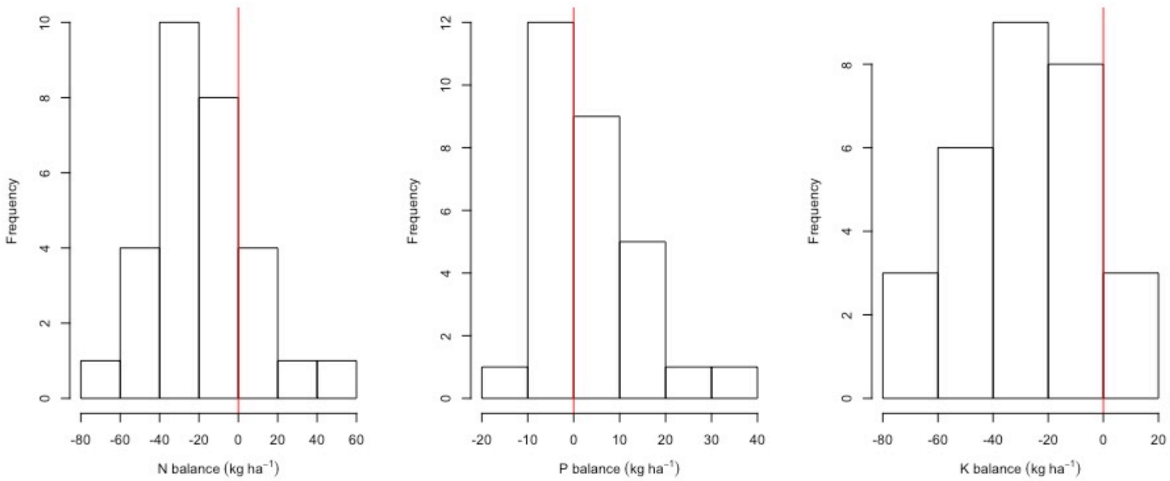

Figure 7. Distribution of partial N, P, and K balances for all farmers surveyed, calculated with Equation 5 with farmer-reported manure fertilizer input rates and Basmati yields. Values to the left of the red line (nutrient deficits) indicate potential nutrient mining scenarios, and values to the right of the red line (nutrient surpluses) indicate potential nutrient loss scenarios.

3.1.5 Pests and weeds

Frequencies of responses to the survey question *"Since you started using FYM/VC/BGS, are there more, less, or about the same number of pests on your Basmati crop?"* are shown in Table 7. The majority of respondents in the FYM group reported that there were either more or about the same number of pests. It is not known how long, on average, farmers using FYM had been using the method, as when asked, most farmers responded "a long time;" it is therefore difficult to contextualize their answers to this survey question. It is also not known how many of the farmers surveyed had previously been using chemical pest control prior to organic conversion. VC farmers had on average been using the method for 5 years, and the majority said that there were either less or about the same amount of pests since they started using VC. BGS farmers had on average been using the method for 3 years, and the most frequent response for this group was "about the same amount of pests."

Table 7. Response frequencies for the survey questions "Since you started using FYM/VC/BGS, are there more, less, or about the same number of pests on your Basmati crop?" and "Since you started using FYM/VC/BGS, are there more, less, or about the same amount of weeds in your Basmati crop?"

	% of respondents		
Pests	FYM	VC	BGS
more	24	14	8.33
less	41	43	33.33
about the same	35	43	58.33
Weeds			
more	53	14	50
less	24	43	25
about the same	24	43	25

FYM n = 17, VC n = 13, BGS n = 12

In response to the question *"Since you started using FYM/VC/BGS, are there more, less, or about the same amount of weeds in your Basmati crop?"* FYM users most frequently stated that there were more weeds, whereas the majority of VC users said that there were either less or about the same amount of weeds. Half of the BGS farmers said there were more weeds, and half said there were either less or about the same weeds. Similar to pests, it is difficult to contextualize the responses of farmers in the FYM group.

3.1.6 Costs and labour

Start-up and seasonal costs

A summary of all start-up and seasonal materials costs incurred by famers using each processing method is presented in Table 8. 94% of farmers surveyed who used FYM as their primary manure processing method did not pay start-up costs, as the method simply involves piling materials on bare soil. Making both vermicompost and biogas, on the other hand, requires physical infrastructure. 100% of farmers surveyed who made VC paid start-up costs. To get started with vermicomposting, farmers build an enclosure (a VC pit), most commonly out of brick and cement. The cost of materials to build a VC pit varied depending on the size of the pit, the number of pits built, the distance from the farm to the nearest source of building materials, whether or not labour was hired to build the pit(s), and whether or not the farmer received subsidies from the government or another agency. An additional start-up cost associated with VC was the purchase of worms. 46% of farmers surveyed purchased worms in the first and/or second year of starting, and bought on average 2 kg for 400 INR per kg. Among the farmers surveyed, the total start-up cost of VC ranged between 2,000 INR (farmers who built only one pit, lived close to the market, did the labour themselves, did not buy worms, and/or received subsidies) and 11,000 INR (farmers who built more than one pit, paid for long-distance transport of materials, hired labour, paid for worms, and/or did not receive subsidies).

The start-up costs associated with biogas production were the highest among the three manure processing methods. Farmers in the study region commonly used the 3m^3 capacity Deenbandhu biogas plant; construction of this model requires building a mixing tank, subterranean digester and outlet tank, and piping from the digester to cooking facilities. At the time of research, the total cost to build this model was 32,000 INR. A rural development project coordinated by ICSD offers financial assistance and training for biogas plant construction and operation to farmers in the study area; farmers who participate receive 2/3 of the construction costs in subsidies jointly provided by ICSD and the Uttarakhand government. 58% of farmers surveyed received the full subsidy, and paid between 10,000 and 12,000 INR to build a biogas plant.

Table 8. Summary of the start-up and seasonal costs associated with the three manure processing methods. Costs are for each practice independently.

	FYM	VC	BGS
% of farmers who paid start-up costs	6	100	92
Total cost of start-up (INR)	0 – 3000	2000 – 11000	10000 – 35000
% of farmers who bought seasonal materials	24	0	0
Seasonal materials bought	plastic tarp	N/A	N/A
Average per-season materials cost if seasonal materials were bought (INR)	433	N/A	N/A
% of farmers who bought cow dung to supplement own production	29	23	17

(FYM n = 17; VC n = 13; BGS n = 12)

Across the three methods, only farmers in the FYM group paid regular seasonal materials costs, with a few farmers reporting that they bought plastic sheeting to cover the FYM pile; at the time of writing, the market price for plastic sheeting was 30–60 INR per square meter. Although none of the farmers in the VC or BGS groups reported buying seasonal materials, it is presumed that both VC pits and biogas plants require occasional maintenance; these costs are not reflected in the calculations, but can be assumed to increase the costs of these methods further compared to FYM.

Across the three methods, an average of 23% of farmers surveyed said they purchased cow dung to supplement their own production for processing into an organic fertilizer and/or applying directly to the field. The total amount of cow dung purchased varied widely between farmers (0.6–13.5 Mg, average 6.1 Mg), and cost 0.38–1.57 INR per kg, with an average price of 0.92 INR per kg.[3]

The annual cost of each manure management method as a percent increase over baseline organic Basmati production costs (ICSD surveys (2012–2015, unpublished data)) was lowest for FYM[4] and highest for BGS (Table 9); it is notable that the annual cost of VC was only 1% more than FYM. When considered as a percent of the average total annual farm income for

[3] Compared to the local market price of synthetic NPK fertilizer (IFFCO), on a nutrient basis, purchasing cow dung costs approximately 38% less than purchasing an equivalent nutrient dose in synthetic fertilizers.

[4] Baseline organic production implies that FYM is the sole manure processing method, and that no seasonal materials costs are incurred; here, it is assumed that farmers in the FYM group buy seasonal materials (plastic sheeting) in order to distinguish the potential additional cost of the method from baseline production practices.

farms in the study region (ICSD survey (2014, unpublished data)), FYM and VC management costs consumed the least revenue, followed closely by BGS. For farmers who previously purchased fuel, adopting biogas would theoretically result in substantial long-term savings; these savings were not accounted for here, as farmers were not asked to report on annual fuel costs and therefore the savings could not be quantified.

Table 9. Annual cost of manure management per method, based on a 10-year loan payback scenario, relative to baseline organic Basmati production costs and average annual farm income (ICSD surveys, 2010–2015, unpublished data).

	Baseline average	FYM	VC	BGS
Annual manure management cost (INR)		433	470	1107
Annual cost of organic Basmati production + manure management Cost (INR season^{-1})	3416	3849	3886	4523
Manure management as % increase over baseline production cost		13%	14%	32%
Manure management as % of average total annual farm income (INR)	55,501	0.78%	0.85%	2%

Labour requirements

Each manure processing method involved periodic management activities. For FYM and VC these activities included turning over and watering the pile, and in VC adding new worms. 65% of FYM farmers and 69% of VC farmers said that they turned the pile 1–2 times per season, an activity that on average took 2.6 hours. 88.5% of FYM farmers and 100% of VC farmers said that they watered the pile at least once per season, an activity that took on average 22 minutes. Only 24% of FYM farmers watered the pile more than twice per season, whereas for VC farmers it was 61%. Few VC farmers said that they added new worms to their pile seasonally, and for those that did, the time spent on the activity was considered negligible and therefore not added to the calculation of total management labour. Average total time spent on management activities was lowest for FYM, followed by VC and BGS (see Table 10). There was found to be no significant difference between the time spent on managing FYM vs. VC.

Management activities associated with BGS included feeding materials into the biogas plant and managing effluent. 100% of BGS farmers surveyed said that they made biogas daily. This activity included collecting manure, mixing manure and water for input into the digester, and managing the effluent (un-clogging the effluent outlet, directing effluent to the desired collection location). On average, BGS farmers spent 39 minutes per day on activities related to making biogas; this came to a sum of 102 hours average spent on management activities per season, significantly more time than FYM or VC ($p = < 0.001$). As noted in the costs section, time spent on maintenance of physical infrastructure (VC pit(s) and/or biogas plants) was not included in these calculations, but can be assumed to raise the average seasonal labour requirement for both VC and BGS methods.

Table 10. Summary of the average labour requirements for managing production of FYM, VC, and BGS. Labour requirements are for each practice independently.

	FYM	VC	BGS
Management activities	turn pile, water pile	turn pile, water pile, add worms	feed materials into plant, manage effluent
Average total management activity hours per season	4.95	6.1	102
Application to field average man hours per ha	205	162	154
Application to field average man hours per kg per ha	0.033	0.035	0.015

(FYM n = 17; VC n = 13; BGS n = 12)

Across the three methods, farmers reported that it took an average of 173 man-hours ha^{-1} to carry and spread manure products on the field (approximately two minutes per kg); this value was calculated only for farmers who did the activity manually (without a tractor). Based on the average area under Basmati cultivation and the average time spent carrying manure fertilizers to the field, farmers spent an average of eight man-days per season spreading manure fertilizers. Average time spent (hours ha^{-1}) to apply manure products to the field was calculated individually for the three manure products, and there was found to be no significant difference between products. Because the range of responses was so wide (from 30 to 750 hours ha^{-1}), it is assumed that a large variation in distance between manure storage site(s) and Basmati field(s), as well as miscalculations on the part of the farmers, confounded differences that may exist between the time required for spreading the different manure fertilizers.

Labour requirements for each manure management method were compared against the average seasonal labour requirement for paddy rice (ICSD survey (2010, unpublished data)), accounting for the assumption that farmers in the study region spent 3–4 hours per day collecting firewood. It was found that while the total labour requirement for BGS was significantly higher than either FYM or VC, the subsequent elimination of a need to collect firewood resulted in a substantial cumulative labour savings for the kharif season for farmers in the BGS group (Table 11).

Table 11. Labour requirements of each manure management practice relative to the sum of baseline labour requirements for paddy rice and fuel wood collection.

	FYM	VC	BGS
Wood collection, man-days season^{-1}	56	56	0
Paddy rice production, man-days season^{-1}	56	56	56
Manure management, man-days season^{-1}	0.62	0.76	12.75
Total labour, man-days season^{-1}	112.62	112.76	68.75
% labour savings, relative to baseline labour requirement	0	0	39

Costs and labour for groups using multiple practices

As indicated by the modified farmer groupings outlined in Table 4, both VC and BGS farmers also made FYM. Therefore, both the actual total cost of a farmers' practice and the actual time spent managing manure should be considered as the sum of the cost and labour requirements of all practices employed. An estimation of the actual sum cost and labour requirement for each primary practice group, accounting for both primary and secondary manure management practices, is outlined in Table 12. These calculations assume a 10-year loan-payback scenario, as previously described. However, given the significant financial impact of starting any single practice, the likelihood that a farmer would build infrastructure for multiple practices in the same year is probably low.

Table 12. Summary of the average cost and labour requirements for managing manure processing per primary practice group, calculated as the sum of both primary and secondary practices.

Primary practice group	Average annual cost, including start-up (INR)	% of annual farm income spent on manure management	Average total labour (man-days season^{-1})	Labour savings relative to kharif season baseline
Only FYM (*n* = 17)	433	1%	113	0%
VC primary (*n* = 13)	4,868	2%	114	0%
BGS primary (*n* = 11)	10,433	3%	69	39%

3.1.7 Farmer perceived advantages and disadvantages

In general, few of the farmers surveyed mentioned disadvantages of the three methods; all disadvantages noted are outlined in Table 13. FYM farmers who cited disadvantages mentioned not having enough FYM to satisfy their crops' needs, the cost of purchasing supplemental cow dung, and issues with termites present in the FYM. Farmers who spoke about problems with termites stated that they believed FYM was a vector in the spread of pests to the field. One BGS farmer who cited disadvantages mentioned the labour involved with feeding materials into the biogas plant daily, another noted that the slurry was difficult to carry to the field, and another said that with BGS his rice crop gained nutrients more slowly compared to fertilization with FYM. Only 14% of VC farmers mentioned disadvantages, and among these respondents, only two issues were mentioned: pest problems and a higher labour requirement.

Table 13. Frequencies of disadvantages and advantages mentioned by farmer regarding their use of either FYM, VC, or BGS as a manure processing method and source of organic fertilizer for Basmati rice.

	% of respondents who mentioned the issue		
Disadvantages	FYM	VC	BGS
Not enough FYM/VC/BGS to meet crop needs	18	0	0
Costs too much to buy	12	0	8
Difficult to make	0	0	8
Poor effect on crop growth	0	0	8
Pest and/or weed problems	18	7	0
Requires more labour	0	7	8

Table 13 cont.

Advantages	FYM	VC	BGS
Improves soil quality	82	79	75
Good for human health	71	36	67
Good for environment	41	0	42
Good for crop growth	71	43	33
Good for crop quality	18	21	0
Crop gets better price (because it's organic)	6	7	0
Farmer is against chemicals	41	14	0
Ease of use	0	43	17
Method creates multiple useful products	0	0	75
Method saves money	12	0	8
Method saves time	0	7	8

FYM n = 17, VC n = 14, BGS n = 12

Farmers were much more likely to name things that they saw as advantages of using each method—100% of all farmers surveyed mentioned at least one advantage of the method they used (Table 13). For farmers using FYM, the three most commonly cited advantages were improvement in soil quality, positive implications for human health, and positive impact on crop growth. One farmer stated, "FYM is a vitamin complex for the soil." Another said, "FYM increases the life of the soil." Among farmers using VC, improvement in soil quality was also the most cited advantage, followed by positive impact on crop growth and ease of use. Multiple VC farmers said that they have to do less work with VC than with FYM, because "the work is done by the earthworms;" however, no quantification was given of what work specifically, or how much, was saved by using the method. BGS farmers also most frequently mentioned improvement in soil quality, as well as the fact that the process created multiple useful products (biogas for cooking and slurry for fertilizing crops). The third most cited advantage of BGS was positive implications for human health, which in this context probably referred to the replacement of smoke-producing cooking fuel with smokeless biogas, as well as a reduction in the time spent collecting wood in the forest, and activity perceived as dangerous due to the presence of wild animals.

3.2 *Explain and explore*

3.2.1 Correlations between general farm characteristics

No correlation was found between farm size and percent farm under Basmati, nor between LSU and percent farm under Basmati, which indicates that farmers' decisions regarding how much Basmati to grow were not necessarily factors of land or livestock endowment. A positive correlation was observed between farm size and livestock holding (Figure 8). This finding indicates that farmers with larger land holdings were statistically likely to have larger livestock holdings than farmers with smaller land holdings.

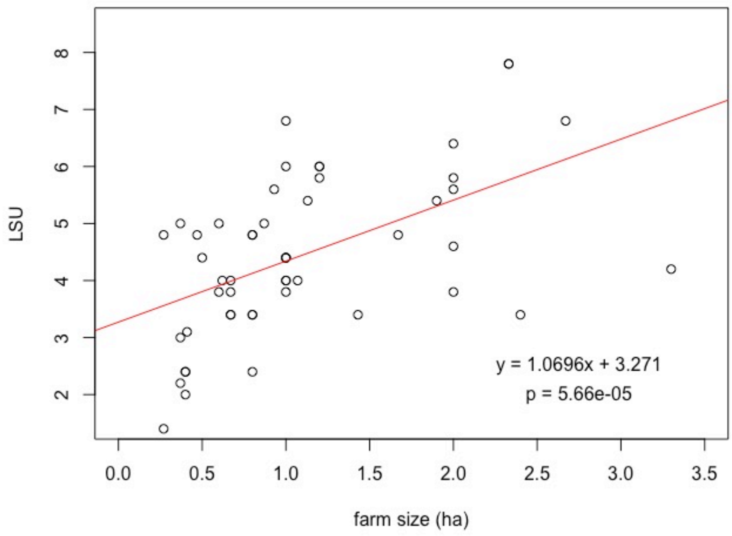

Figure 8. Regression line fit plot for total livestock units (LSU) per farm as a factor of farm size (ha).

A negative correlation was observed between the ratio of available fresh manure to cultivated land and farm size (Figure 9). Despite the positive correlation between farm size and livestock holding, farmers with larger farms had less fresh manure available per hectare of cultivated land than farmers with smaller land holdings.

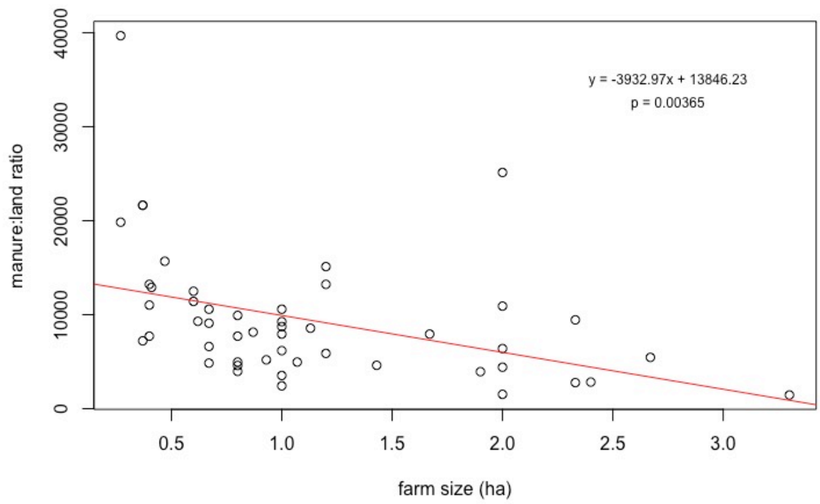

Figure 9. Regression line fit plot for the ratio of available fresh manure (kg) to cultivated land area (ha) as a factor of farm size (ha).

The area of land allocated to Basmati production was not correlated with the absolute amount of manure available for allocation to Basmati fields, which is notable considering that all farmers reported using 71– 75% of available manure fertilizers on Basmati fields.

3.2.2 Comparisons between treatments

3.2.2.1 General farm characteristics

Ranges of farm characteristics for farmers in each primary practice group are shown in Figure 10. Farm characteristics were not found to be significantly different between groups. After correcting for N input rates, no significant difference was found in the yields achieved between groups.

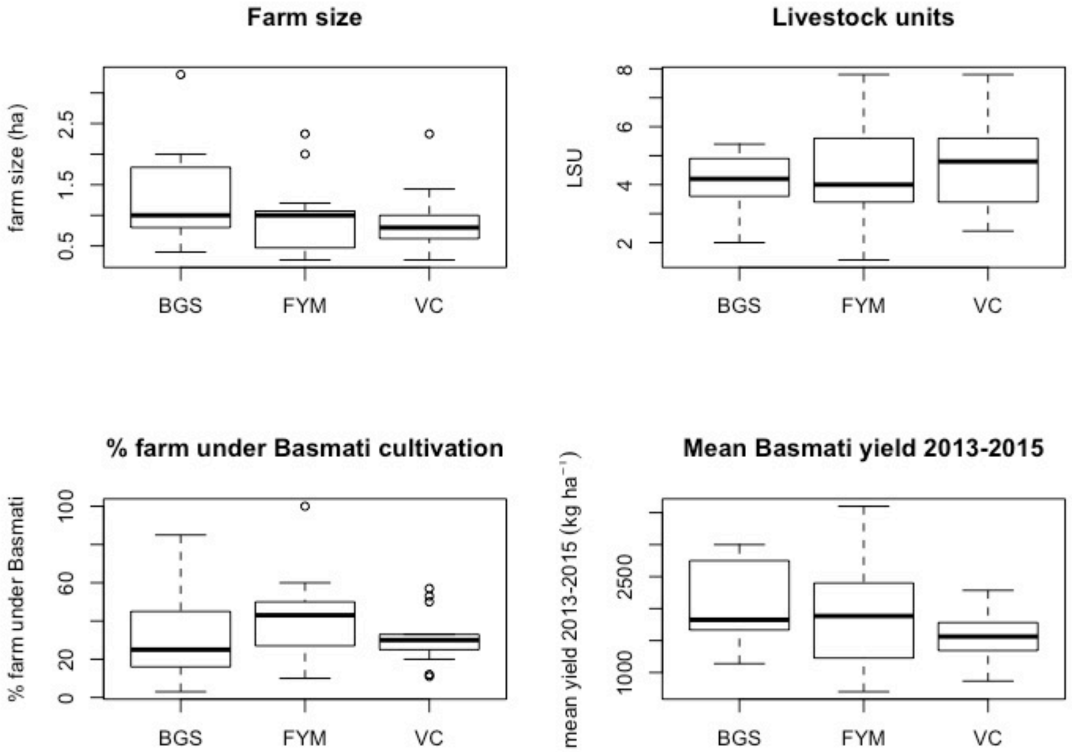

Figure 10. Ranges for basic farm characteristics per primary practice group. Boxes outline upper and lower quartile data values, bold lines mark median values, 'whiskers' mark min and max values, and circles mark outliers.

3.2.2.2 Nutrient input

Total nutrient inputs were lowest for farmers in the FYM group, who input on average 9 kg N ha^{-1}, 5 kg P ha^{-1}, and 9 kg K ha^{-1}. In the VC group, farmers input on average 30 kg N ha^{-1}, 20 kg P ha^{-1}, and 21 kg K ha^{-1}. In the BGS group, average inputs were 25 kg N ha^{-1}, 12 kg P ha^{-1}, and 15 kg K ha^{-1}. The ranges for each nutrient input (as the sum of all manure fertilizers applied), per primary practice group, are shown in Figure 11. The largest fraction of input nutrients (for all nutrients and across all three groups) came from VC applications, and the lowest nutrient contribution came from FYM. For all nutrient inputs, a significant difference was observed between VC and FYM primary practice groups ($p = <0.01$), a result of both larger total mass applications for farmers in the VC group as well as larger amounts of original manure NPK retained in the finished fertilizer product for VC than for FYM.

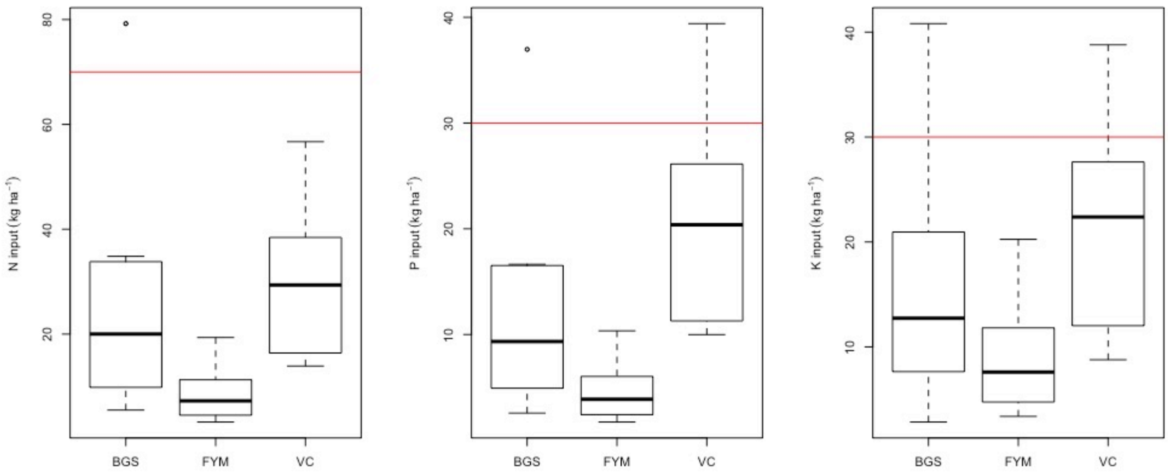

Figure 11. Ranges for N, P, and K inputs by primary practice group. Boxes outline upper and lower quartile data values, bold lines mark median values, 'whiskers' mark min and max values, and circles mark outliers. Red lines mark the N, P, and K input rates (70:30:30 kg ha^{-1}) recommended by local rice agronomists.

No linear relationship was found between N, P, or K inputs (kg ha^{-1}) and Basmati yields (see Figure 12), which probably indicates that in this context, other variables had more influence on yield variability between primary practice groups than nutrient input. At such low NPK input rates, it could be that other limiting factors like water or climate had a stronger influence on yield. This finding, however, should not be mistaken to imply that bulk nutrient inputs do not have an influence on yield—it could be that due to other confounding factors and/or the low range of NPK inputs, the relationship was just not clear enough to identify.

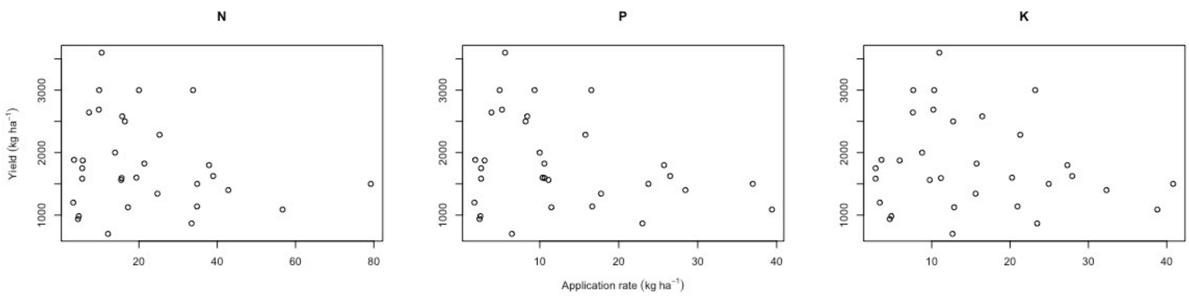

Figure 12. Basmati yield plotted against NPK application rates. Results are not conclusive regarding a correlation between NPK input and yield.

3.2.2.3 Nutrient balances

It was found that on average, only farmers in the VC group had balances close to zero for N, and these farmers also had the most positive average P balances. The average NPK balances for farmers in the FYM group were all negative, indicating that the NPK applied to Basmati via FYM was not sufficient to match crop nutrient uptake. BGS users on average had negative N and K balances, and positive P balances; this finding is somewhat surprising given the high N content of BGS, and points to the likelihood that a large portion of the N initially present in fresh BGS was lost during storage. The range of results for partial NPK balances for each primary practice group are displayed in Figure 13. Mean values are given in Table 14.

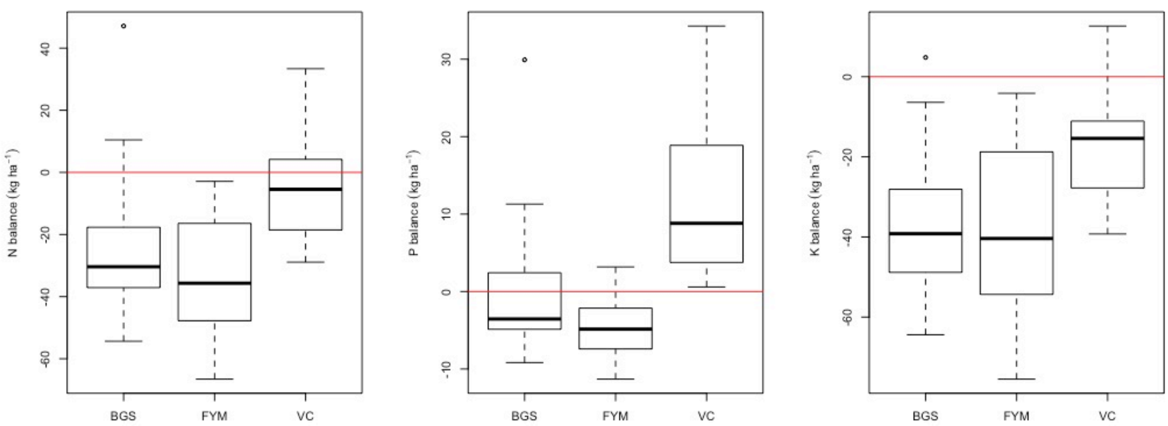

Figure 13. Ranges for N, P, and K balances for each primary practice group. Boxes outline upper and lower quartile data values, bold lines mark median values, 'whiskers' mark min and max values, and circles mark outliers. Values falling under the red horizontal lines indicate negative balances (potential nutrient mining scenarios), and values above the red line indicate positive balances (potential nutrient loss scenarios).

Table 14. Average partial balances for N, P, and K for each primary practice group.

	Nutrient balance (kg ha^{-1})		
	N	P	K
FYM	–31.53	–4.17	–36.04
VC	–2.71	13.17	–15.22
BGS	–20.72	1.96	–36.26

(FYM n = 17, VC n = 13, BGS n = 11)

In a comparison of the nutrient balances across the three treatments, a significant difference was found between the N balances for farmers using VC as their primary nutrient source versus those using FYM; balances for VC farmers were significantly more positive than those of FYM farmers (p = < 0.01). For P balances, a significant difference was also noted between VC and FYM (p = < 0.001), where VC balances were more positive than FYM. For K balances, no statistical difference was found between groups, although mean values for the VC group were notably less negative than for the FYM and BGS groups.

3.3 *Evaluate*

3.3.1 System-level sustainability

Figure 14 summarizes the sustainability indicator scores for the three manure management practices relative to the baseline, and shows that for some indicators the difference between practices was small, while for others the difference was notable. As previously noted, the data upon which sustainability was measured lacks statistical evidence to prove that differences observed between primary practice groups were directly correlated to manure management practice. Without more detailed data on farm biophysical characteristics, crop management, and farmer knowledge, it is difficult to isolate primary manure management practice as the key variable affecting performance indicator scores. Valuable preliminary conclusions can be drawn from the results of the sustainability analysis, but it should be noted that these results are probably over-simplifications of a scenario in which differences are not solely related to manure management practice.

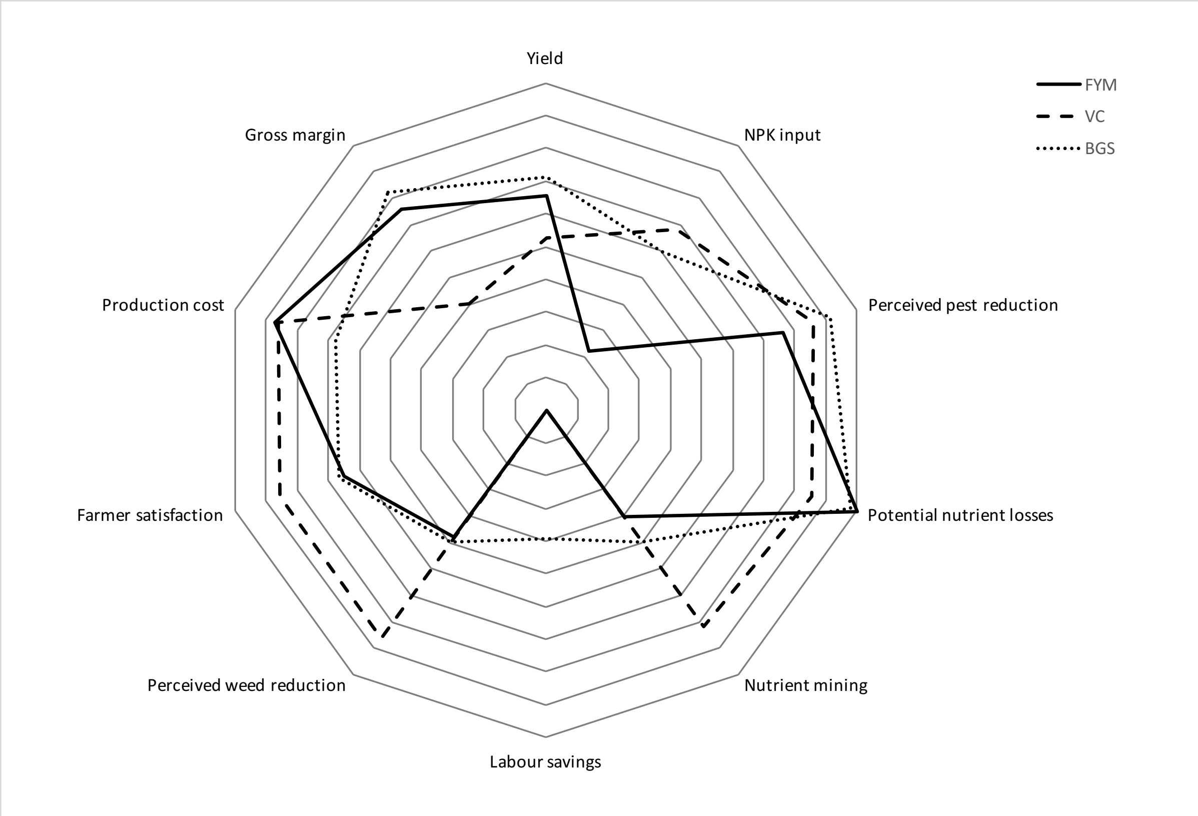

Figure 14. Comparison of the agronomic, ecological, social, and economic performance of three manure management practices. Scores for each sustainability indicator were calculated as relative to a local baseline and scaled from 0–1, where 1 (the outer edge of the web) is 'optimal'. Here, individual N, P and K component scores for NPK input, potential nutrient loses, and nutrient mining are represented as composite scores under one indicator.

3.3.1.1 Agronomic productivity

For the agronomic indicator Yield, farmers in the BGS group performed best, achieving a yield gap of just under 30% compared to the GBPUAT field trial, while VC farmers had the lowest average yield with a yield gap of over 40%. This is notable when compared with the indicator scores for NPK Input, where VC farmers had the best score. The fact that Yield and NPK Input scores were not aligned is an indication that variability in yields between farms was probably more heavily influenced by factors other than manure fertilizer type or NPK input. The NPK Input score highlights a major weak point of the FYM group, where the average NPK input was under 30% of the recommendation for Basmati rice.

The BGS group received the highest score for Perceived Pest Reduction, and FYM received the lowest score. This indicator was based on farmers' qualitative observations, but it is possible that given what is known about farmers' limited management of FYM piles (i.e. they were not actively composted), it is possible that the low-temperature, dry environment of an FYM pile could be conducive to population by insects, which could then be carried to the field when the manure fertilizer product is spread.

3.3.1.2 *Ecological impact*

Due to the low nutrient inputs across all three practices, scores for the indicator Potential Nutrient Losses were close to 1 (1 = zero surplus) for all groups. VC farmers had slight NPK surpluses, so the potential for losses resulted in a slightly lower score than for FYM and BGS. Given these scores, nutrient loss to the environment because of excess fertilization is not considered a major point of concern for organic farmers in the study region. Nutrient Mining scores were correlated to both Nutrient Input and Potential Nutrient Losses, with VC farmers performing best (higher nutrient input rates resulted in less negative nutrient balances). Nutrient Mining again highlights a weak point for the FYM group, which had the lowest score. It is likely that soil fertility on the surveyed farms has improved since adoption of organic practices, but as long as nutrient inputs remain lower than crop uptake, Nutrient Mining scores will conceivably get worse over time.

3.3.1.3 *Social feasibility*

BGS got a notably higher score for Labour Savings than FYM or VC, which both scored very close to zero. While neither FYM nor VC required a great increase in seasonal labour over the baseline, and while managing biogas production required a significantly larger daily labour input than making FYM or VC, elimination of the daily need to collect firewood made BGS a labour-saving method at the whole-season level. These savings (nearly 40% over the baseline sum of wood collection and paddy rice labour for kharif season) are substantial, and represent the most notable advantage of BGS in practice.

VC received the highest score for Perceived Weed Reduction, which could be because of higher weed seed kill rates in the more active composting environment of the VC pit. Since weed management requires significant labour and time inputs throughout the season, the implied social benefit of reduced weed problems is notable. Weed infestations can also impair crop performance and thereby reduce yields, making a reduction in the incidence of weeds an economic benefit as well.

Farmer Satisfaction scores showed a range and pattern similar to Perceived Weed Reduction, with VC scoring highest, and FYM and BGS receiving similar mid-range scores. Given the overall labour savings afforded by BGS, it is surprising that this group scored so low for Farmer Satisfaction; this could be a factor of the relative newness of the technology in the study area, which may make issues and concerns more apparent to farmers who have recently adopted the practice.

3.3.1.4 *Economic viability*

BGS unsurprisingly scored lowest for Production Cost, since it was the method that required the largest initial investment. Interestingly, when spread across a 10-year loan payback period, the cost of VC was not much more than the cost of FYM. Given VC's top performance in other indicator categories (NPK Input, Nutrient Mining, Perceived Weed Reduction, and Farmer Satisfaction), it is notable that the cost was relatively low, indicating large benefits for relatively low investment in the long run. Interestingly, despite higher production costs, BGS scored the best for Gross Margin, an artifact of its superior performance in the yield category.

3.3.2 *System-level trade-offs*

In the research context, FYM was considered the 'traditional' practice, requiring the least special knowledge and infrastructure. Therefore, adopting VC or BGS represented potential changes over the 'baseline' of practicing FYM. In this vein, the costs and benefits of VC and BGS were compared to FYM in order to facilitate an understanding of the trade-offs of adopting each of these 'new' practices. Summaries of the sustainability scores for VC and BGS, relative to FYM, are presented in Figure 15. Here, the Agronomic and Environmental indicators are grouped together into one spider web and Social and Economic indicators into another in order to show Agronomic and Environmental indicator component scores in detail.

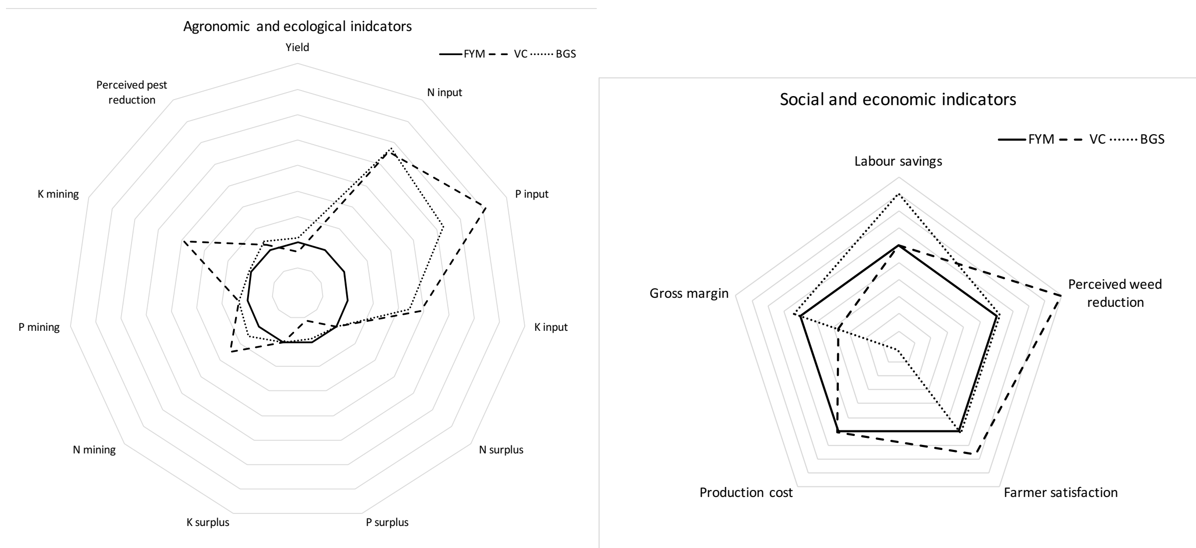

Figure 15. Performance of VC and BGS relative to FYM as the baseline. Agronomic and ecological performance indicators are displayed in the diagram on the left, and social and economic performance indicators are displayed in the diagram on the right.

3.3.2.1 *Farmyard manure*

Making FYM in itself is a low-cost and low-labour method that requires little infrastructure, skill, or special knowledge. However, assuming a farmer does not purchase LPG fuel, firewood collection is necessary and therefore FYM is time-consuming on a whole-season scale. The relative ease of using FYM as a primary manure processing method is greatly offset by its relative disadvantages. Because the nutrient content of FYM is low, and farmers had a relatively small amount of livestock manure to work with in the first place, making FYM gives a poor return on input nutrients and results in a fertilizer product with relatively low plant-nutritive value. To supply a Basmati crop with adequate nutrients for a high yield, a larger amount of FYM is needed than could be supplied by most farmers in the study region. Major trade-offs of making FYM with the average available manure in the study area are thus NPK inputs under the recommended rate and a greater likelihood of nutrient mining over time. Furthermore, using FYM may result in higher incidences of pests and weeds if composting is not active.

3.3.2.2 Vermicompost vs. farmyard manure

The primary benefit of adopting VC is higher retention of C, N, P, and K during the composting process, which results in a manure fertilizer product with greater soil-amending and plant-nutritive value than FYM on a dry weight basis. Overall, nutrient inputs for the VC group were larger than for FYM despite starting with a similar amount of fresh manure, and therefore problems with NPK mining were less pronounced. However, despite higher nutrient input rates, the VC group scored lower than FYM on the yield indicator; this could be a result of a number of other variables affecting crop production on the farm scale that override or negate the larger nutrient inputs, and should not necessarily be attributed to VC alone. Lower yields were offset by a relative improvement in all but one of the social and economic indicator categories. While production costs and labour requirements were not much better for VC than for FYM, adopting VC could apparently result in a significant improvement in weed reduction (thereby lowering labour inputs), as well as a reduction in pests compared to FYM, and greater farmer satisfaction overall.

3.3.2.3 Biogas slurry vs. farmyard manure

The primary benefits of BGS were improved yields (and thus a higher gross margin) and a significantly lower labour requirement than FYM. Higher yields were probably related to higher NPK inputs in the BGS group than in the FYM group, but could also be a factor of the characteristic skills and knowledge of farmers who opt to adopt biogas production. These benefits came with the major trade-off of much increased production costs, as well as more pronounced K mining. For farmers making little income (as is the norm in the study region), the relatively high cost of adopting BGS could disproportionately weight this disadvantage against the long-term benefits of potentially improved yields and a less taxing labour demand. From a nutrient cycling efficiency perspective, a trade-off of BGS is that it is an inefficient product—while the nutrient content of BGS can be much higher than FYM on a dry weight basis, the ratio of nutrients retained in BGS to those input via manure is lower for BGS than for FYM.

4 Discussion

4.1 *Explain and Explore*

4.1.1 Adoption of different manure management practices

In order to understand better the results of sustainability analyses for the different manure management practices, it is relevant to explore the conditions under which farmers adopt certain practices, and to draw connections between the characteristics of farmers who adopt the same practices. As no statistical correlations were found between farm characteristics and the adoption of different primary manure management strategies, quantitative conclusions cannot be drawn. However, some preliminary, pragmatic generalizations can be tentatively deduced regarding the characteristics of farmers who adopt either FYM, VC, or BGS as their primary manure processing method.

Because building VC pits and biogas plants both require a significant up-front investment, farmers who adopt these methods must have the cash resources to fund the investment and/or the ability to take out a loan, and/or have the knowledge, time, and motivation to pursue subsidized funding. Furthermore, in order to make biogas production a viable investment, a farmer must have enough livestock to provide the amount of manure required to produce enough biogas to meet household needs on a daily basis. In the study region, farmers who had biogas plants had on average a LSU to household member ratio of 0.8:1, which equates to nearly one calf, cow or buffalo per household member. For farmers with fewer animals, and/or larger fuel needs, a biogas plant may not be a viable option. It follows that a small household with few livestock and/or less financial resources may be more likely to adopt FYM or VC.

For farmers with a high LSU to household member ratio and/or simply a large livestock holding, it is feasible that more than one manure processing method can be used. A standard biogas plant of $3m^3$ can only accommodate a certain daily input, so if more manure is being produced than can be used for biogas, an alternate ‘overflow’ site will be required. If a famer is already investing daily labour into making biogas, it follows that the overflow method should be one requiring the least management effort, which in this case is FYM. Furthermore, a farmer who has already spent money to build a biogas plant is probably not likely to spend money soon after to also build vermicompost pits to accommodate manure overflow. These assumptions are backed by the finding that among the farmers surveyed, most making biogas also used FYM as a secondary method. On the other hand, some farmers whose household fuel needs are lower and/or have more reliable access to alternative fuel materials might opt for using funds and effort to build VC pits rather than a biogas plant, in which case overflow manure will probably be managed as FYM.

These pragmatic generalizations illuminate three main points that should direct the development of action opportunities. First, because resource endowment probably plays a key role in the adoption of different manure management practices, action should be directed towards helping farmers achieve better yields, since the yield indicator directly affects farm income and thereby affects a famer's ability to invest in improved technologies. Furthermore, maintaining a profitable yield is pivotal to maintaining a viable livelihood. Second, the generalizations indicate a continued need for subsidies and outreach to help smaller farmers start making VC, since a switch from FYM to VC can bring significant farm-scale sustainability improvements. Third, they point to a need to help farmers better manage FYM, since all farmers in the study region, regardless of resource endowment, will probably make at least some FYM even if they adopt other improved technologies. The following Discussion sections (4.1.2 and 4.1.3) further explain and explore the case for improved yields and manure management practices, and thereby lay the foundation for action opportunities.

4.1.2 Yield variability: a factor of manure processing method?

Despite higher NPK inputs in the VC and BGS groups, the results of survey data analyses showed there to be no clear correlation between manure management method and crop performance, making it difficult to trust the comparison of yield indicator scores in the sustainability analysis. In general, the range of NPK inputs reported on-farm was in the lower end of the Basmati yield response curve (illustrated in Figure 3), and was below the nutrient demand of Basmati, as reflected by the mostly negative NPK balances. It is likely that the range of on-farm NPK inputs was not wide enough to make clear the yield effects of NPK input and/or manure fertilizer type, and that at such a low range of NPK input rates, other variables had a larger effect on yield at the farm scale. These variables could be abiotic (soil type and texture, water availability, climate, elevation), biotic (soil biology, pest and weed communities) and/or agronomic (seeding rate, time of sowing, transplanting method, plant spacing, crop rotation, use of green manure), many of which could be active at not just the farm level but also the landscape scale. Furthermore, local advisors hypothesize that farmers who recognize the humanitarian and environmental value of biogas production may also be more skilled in crop husbandry, a factor potentially affecting the higher yield performance of the BGS group.

In general, not enough information is known yet to draw conclusions about the other variables potentially affecting variability in yields between farms. To this end, it is not possible to point to manure processing method as a definitive variable affecting yield variability. However, this should not discredit the validity of other sustainability indicators, nor should it detract from the implication that improved yields play a key role in positively affecting other performance indicators.

4.1.3 Farmers' practices vs. recommended practices

Although this research is not conclusive enough to prove a link between crop performance and primary manure processing method, the Basmati yield response curve illustrated in Figure 3 points to the likelihood that NPK input rate, as a factor of volume of manure fertilizers applied, is a key variable affecting a yield gap between farms and the GBPUAT field trial. The quality of manure products farmers are able to apply, in addition to quantity, probably plays a part in affecting yield outcomes. As long as the presence and weight of other variables (crop rotation, water, climate, etc.) affecting farmers' lower yields remain unknown and the primary limiting variable(s) has not yet been identified, nutrient input is a logical point of focus for understanding how to help farmers achieve better yields with the limited resources they have available. To this end, the following discussion focuses on improving manure management practices as a way to increase NPK inputs via manure fertilizers.

The wide range of values for NPK contents of FYM, VC, and BGS found in the literature (Table 1) indicate that there is potential for optimizing livestock and manure management practices in order to achieve the upper range of nutrient retention. Therefore, it is worth examining the effects of manure storage and processing methods on the plant nutritive quality of resulting fertilizer products. In order to identify ways that farmers' manure management systems could be improved, focus was first placed on how farmers' manure management practices differ from best practice recommendations. The techniques recommended by scientists and advisors both in the study region and elsewhere may be ideal from a reductionist perspective, but are not necessarily practical in the context of the farm as a whole and interconnected social-ecological system. To this end, it is necessary to study and compare manure management techniques from multiple angles, and to address the implications of each method from agronomic, ecological, social, and economic perspectives.

Rufino et al. (2006) conceptualize nutrient cycling efficiency in crop–livestock systems as the product of the efficiencies of four sub-systems. These sub-systems are: 1. Livestock, 2. Manure collection and handling, 3. Manure storage and composting, and 4. Soil availability, crop capture and crop conversion. This conceptualization is useful for framing an analysis of farmers' practices versus recommended practices as a way to identify potential areas of system weakness where nutrient retention could be improved. Castellanos-Navarrete et al. (2015) found that on Kenyan farms where manure management practices were similar to those on farms surveyed for this study, on average 73% of N excreted by livestock was lost before manure was applied to the field. Minimizing losses during handling, storage, and application could be important pathways to improving the crop nutritive quality of the small amount of manure fertilizer product that is available to farmers in the study region.

4.1.3.1 Livestock sub-system

Little can be said about the livestock sub-system in the study region, as this study did not focus on an animal care or feeding regimens. Further research on what and how animals are fed, as well as the partitioning of nutrients between animal products, could provide valuable insights into the degree to which nutrients are being unnecessarily lost between feeding and excretion.

4.1.3.2 Manure collection and handling sub-system

According to Rufino et al. (2006), manure collection and handling is the sub-system with the highest uncertainty in terms of nutrient cycling efficiencies because of the great variability in ways livestock can be managed. How and where animals are kept, if and how often they are grazed off-farm, and how frequently manure is collected all impact how much of the nutrients in excreta can be collected. In the study region, off-farm grazing is not a major vector of nutrient cycling inefficiency, because most farmers do not graze livestock off-farm, so little manure is lost off-farm. Furthermore, all of the farmers surveyed reported collecting manure on a daily basis, so it is unlikely that frequency of collection has a major influence on variability in nutrient cycling efficiency in the systems under study.

Theoretically, in a system with little off-farm grazing and frequent manure collection, nearly all the nutrients in excreta can be collected (Rufino et al., 2006). In the context under study, animal housing is most likely the key factor at play in the manure collection and handling sub-system; it was observed that farmers used various techniques, keeping their animals on bare soil and/or stone floors, and with or without bedding materials. When animals are kept on bare soil and without bedding, there is a higher likelihood that nutrients in excreta will be lost though leaching and/or volatilization (Rufino et al., 2006). On stone surfaces without bedding, the magnitude of nutrient losses may be similar to bare soil surfaces unless gutters are used to channel urine into a collection container so it may be later utilized. In the study area, few farmers reported using bedding materials or gutters to collect urine, so it is likely that the nutrient cycling efficiency of this sub-system is lower than the potential because of this loss pathway.

A variable that was not examined in this study but was certainly relevant to the manure handling sub-system is the off-farm sale of manure; local advisors report that the practice is common among the poorest farmers as a way to bring in extra income. While the frequency and magnitude of these sales are not yet known, it can be assumed that for some farmers, manure sale is an important nutrient loss pathway in the collection and handling sub-system.

4.1.3.3 Manure storage and composting sub-system

Storage

Shah et al. (2012) state that up to 50% of the N and C in manure can be lost during storage alone, a finding which points to the importance and potential positive impact of improved storage techniques in increasing nutrient cycling efficiency at the farm level. In particular, findings in the literature point to cover as a primary factor in the potential improvement of nutrient retention in the manure storage and composting sub-system. Despite recommendations issued by local advisory services, in practice very few farmers surveyed said that they took measures to cover their manure piles in any way, indicating that on-farm manure management practices are likely resulting in maximum nutrient losses from the storage and composting sub-system. In the research context, storage of FYM and BGS have the most room for improvement.

Tittonell, Rufino, Janssen, and Giller (2010) conducted an experiment comparing the carbon and nutrient losses from FYM stored using different practices, and found that manure kept under a roof retained significantly more mineral N and K than manure stored in the open air. An alternative and lower-cost option for improving manure storage is to cover heaps with plastic sheeting, as indicated by the findings of Shah et al. (2012). In a study on the effect of storage technique on N and C losses in FYM, the authors found that C and N losses were greatly reduced in manure heaps covered with plastic sheeting compared to other techniques. Furthermore, after application to the field, the manure fertilizer from heaps kept under cover provided more available N compared to aerobically composted manure, and the residual N fertilizing effect in subsequent years was higher than composted manure. On the other hand, manure stored under plastic sheeting was less stable than composted manure, and more prone to NH_3 emissions after field application due to a larger mineral N content (Shah et al., 2012).

The recommendations given by advisors at GBPUAT during famer training sessions follow similar principles as those in the literature, suggesting that FYM piles should be covered with a plaster made of cow dung and mud. This allows the pile to actively compost, reaching temperatures that will kill weed seeds and pathogens, while protecting the compost from rain and drying sun. ICSD issues similar recommendations, stating that FYM piles should be covered with a thick layer of straw or with plastic sheeting.

Managing the storage of BGS presents an opportunity for significant system improvement in the study context, but also probably requires significant additional infrastructure. Wet biogas effluent contains a high concentration of N upon immediate release from the digester tank, with a high ammonia content due to the anaerobic conditions of the digester (Jaiswal, Wadhwani, Jain, & Chhabra, 1971). However, almost all of the ammonia-N is lost when the slurry is dried in the sun (Jaiswal et al., 1971). To obtain the benefit of its higher initial N concentration and ensure that the nutrients reach the crop, ICSD recommends that BGS be collected in a tank, preferably made of cement and sealed to prevent leaching and protect from sunlight, rather than in a shallow pit open to the air and sun as practiced by farmers in the study region. None of the farmers surveyed used BGS collection tanks, so it is likely that nutrient losses could be much reduced with improved storage techniques.

Composting

What materials are added to manure for composting, and to what extent the manure pile is actively composted, are factors that have an impact on both the quality and quantity of the finished manure fertilizer product and therefore play a key role in the nutrient cycling efficiency of the manure storage and composting sub-system (Rufino et al., 2006). Both GBPUAT and ICSD recommend that farmers making FYM should build piles using alternate layers of manure, green weeds, and carbon-rich materials like crop residues. ICSD also suggests regular watering to keep the pile moist, and thorough mixing by turning the pile twice during the storage period. Farmers' reports showed some variability in layering, turning, and watering practices, but overall these activities were reported with low frequency. It appeared that in general, the approach to making manure compost was more practically based on time and labour than on awareness of how to manage the nutritive quality of the compost product, indicating that there is room for improvement.

Periodically turning a manure pile to facilitate active composting results in a more stable compost product, and can help to suppress pathogens and kill weed seeds as aeration of the pile stimulates microbial activity and results in an increase in the temperature of the compost (Parkinson, Gibbs, Burchett, & Misselbrook, 2004). On the other hand, turning a manure pile can result in significantly higher C and N losses as increased aeration accelerates aerobic decomposition (Shah et al., 2012). Parkinson et al. (2004) also reported that both gaseous and leachate nutrient losses were highest in manure piles turned once or more, compared to those left static. For farmers in the study region, the incidence of weeds is likely of primary concern, since weeding is probably the crop management activity that demands the most time and labour. Eghball and Lesoing (2000) found that weed seed viability could be significantly reduced in piles where composting materials were kept moist even if the temperature of the pile never reached the level considered critical (≥60ºC) for weed seed destruction. This finding indicates that it may be possible for farmers to achieve the benefits of weed seed reduction without turning manure piles and thereby avoiding the nutrient losses associated with turning.

The trade-offs between compost stability, weed seed reduction, and C and nutrient loses, as well as labour requirements and water availability, must be considered when making recommendations for turning and watering practices. The infrequency with which farmers turn and/or water their manure piles could be an indication that manure-processing management activities are perceived as low-priority compared to other more pressing farm and/or household activities like animal care, weeding, collecting firewood, cooking, etc.; if this is in fact the case, recommendations from advisors would likely make little impact on farmers' actual practices. Water shortages during the dry rabi season (when manure fertilizer is made for use in the kharif season) could also be a factor affecting whether or not a farmer waters a manure pile that will not necessarily be influenced by pointed recommendations.

As an alternative to keeping wet BGS, ICSD suggests using BGS as a component in compost heaps, layered with plant biomass (weeds, tree prunings, crop residues, etc.); none of the farmers surveyed reported using this technique. It is likely that because the impetus to make biogas is not to use it as a manure processing method, rather as a source of energy, farmers' approach to managing BGS may differ from those making FYM or VC. If the slurry is regarded as simply a useful by-product rather than the primary end-goal, the approach to managing it will probably be different from a farmer whose primary motivation is to produce a fertilizer product; there is room for future advisory efforts to cater outreach to BGS farmers based on this factor.

4.1.3.4 Soil availability, crop capture, and crop conversion sub-system

The response of a Basmati crop to manure fertilizer input depends not only on the quantity and nutrient content of fertilizer applied, but also on other manure fertilizer quality factors, whether the fertilizer is applied before transplanting or while the crop is standing, the characteristics of the crop variety, and environmental conditions (Rufino et al., 2006). Release of nutrients into crop-available forms are linked to the composition of the soil microbial community, as well as to the physical and chemical composition of the manure fertilizer product, which is linked to all three previously discussed sub-systems. Furthermore, how a manure fertilizer product is applied and whether or not it is incorporated into the soil can affect nutrient losses. Due to the complexity of the processes and variables involved in the soil and crop sub-system, it is probably the hardest to understand and control, and has the lowest nutrient cycling efficiency compared to the other three sub-systems (Rufino et al., 2006). However, some things can be controlled on-farm to improve nutrient cycling at this level.

Generally, the recommendation is to turn manure fertilizers into the soil upon application in order to reduce losses from volatilization (Rufino et al., 2006); most farmers surveyed reported using this practice, so it is not considered a point of potential improvement in the research context. Timing of manure fertilizer applications with crop needs may provide more opportunity for farmers to improve the nutrient cycling efficiency of the soil and crop sub-system, as few mentioned applying fertilizers at any time other than field preparation. If farmers have both FYM and VC available, rice agronomists at GBPUAT recommend a basal dose of FYM incorporated at the time of field preparation, and a top-dressing of VC 25 days after transplanting. If only FYM is available, GBPUAT agronomists say it is best used only as a basal dose, turned in at the time of ploughing. If a farmer has BGS, ICSD advises that the most benefit can be gained when it is applied to the field in its wet form, and suggest mixing it with irrigation water if possible. Alternatively, GBUAT agronomists recommend using BGS in place of VC as a top-dressing applied 25 days after transplanting. In order to optimize plant nutrient availability and reduce losses, Shah et al. (2012) suggest timing field application so that it directly precedes irrigation or forecast rainfall.

4.2 *Evaluate*

Sustainability analyses can provide a valuable tool for understanding the integrated impacts of management decisions on the farm scale, but the results of these analyses are meaningless if they are not contextualized within the scope of the actual priorities and concerns of the stakeholders involved. To this end, it is essential that farmers' experiences be the focal point of interpreting sustainability analyses and directing action opportunities. As previously noted, sustainability assessments are most valuable when sustainability is collaboratively defined by stakeholders and researchers. Although time constraints did not allow for in-depth dialogue with farmers regarding their concept of sustainability, data gathered on farmers' perceptions of the advantages and disadvantages of each manure management method can be used as a preliminary framework for contextualizing sustainability analysis results. Contextualization helps to highlight instances where certain sustainability indicators may hold more or less weight than others.

As indicated by the superordinate themes that arose out of qualitative survey data analyses, farmers' concerns revolved primarily around crop production and time and labour issues. Across all three manure processing methods, the most commonly cited advantage of using each method was a perceived improvement in soil quality; this indicates that farmers were aware of the impact using manure-based fertilizers had on their soil, and that it was perceived as an important outcome of using organic methods. Commonly, improvement in soil quality was linked to a positive impact on crop production, a topic that was among those most frequently cited in all three farmer groups. For marginal farmers relying on crop production as their primary source of income, even small increases in the production of a high value crop like Basmati could have a positive impact on the financial situation of the household. Farmers' perceptions of the positive impacts of manure fertilizers on soil and crop quality parameters were not specifically or quantitatively reflected in the sustainability analyses, as all perceived advantages were imbedded in the Farmer Satisfaction indicator. However, given the residual positive impact of these parameters on issues of high importance to farmers (namely crop production), it should be noted that a more thorough sustainability analysis would directly account for their contributions.

Although it was not quantified in the sustainability indicators used in this study, improvement in soil quality can also result in a corresponding reduction in labour. A few farmers mentioned that since they started using manure-based fertilizers, their fields required fewer passes with the plough because the soil had become finer and softer. For many smallholders in the region ploughing is done with draught animals, a time-consuming and laborious practice. Even a reduction of one less pass with the plough could make a significant positive impact on labour loads, and this factor should be kept in mind when considering the results of this study in context. A more thorough sustainability analysis would include a score for improvement in soil quality, and this score could be considered more heavily weighted than some of the other indicators given the correlated positive effects on parameters with high importance to farmers.

Labour is obviously an important issue for farmers whose subsistence relies solely on farming; in this study, only one sustainability indicator addressed labour impacts, so it could be considered to hold more relative weight compared to other indicators. An important labour issue not represented in the sustainability analysis here is the relative ease of carrying different manure fertilizers to the field. As a result of land fragmentation, many farmers cultivate fields located a long distance from their home compound, so the impact of carrying manure fertilizers to the field is an important factor in determining the amount of time and labour required to manage soil fertility. Several farmers mentioned the impact of carrying different products when discussing time and labour issues—a few VC users noted that it was easier to carry because it weighed less than FYM, and a few BGS users stated that carrying the material to the field was problematic because it was heavy and messy if wet—but it was not possible with the available data to quantify differences between treatments. As previously noted, variability in the distance between manure storage and field(s) was likely a confounding factor in this analysis. Given that farmers themselves noted differences, a sustainability assessment that more accurately accounts for farmers' labour concerns would include a quantification of these differences.

A final issue that was of primary concern to farmers in the study region but not addressed in this analysis was water scarcity. Although respondents were not prompted directly to discuss the topic, water came up often in conversation, and is indeed related to manure management in some ways. A few farmers who mentioned an improvement in water holding capacity as linked to soil quality specifically noted that since they started using manure fertilizers, the water stayed longer in the field after irrigating. For farmers in areas with water scarcity problems, even a minor improvement in the water holding capacity of the soil could be a major benefit to crop production. Issues related to water were not directly addressed in the sustainability analyses presented here, but should certainly be considered as paramount to the research context and included in any further studies on farming system sustainability in the Nainital district. It is possible that water issues, when incorporated into sustainability analyses, could change the outcome of results comparing FYM, VC, and BGS practices.

4.3 *Act*

As previously noted, the manure management techniques recommended by scientists and advisors both in the study region and elsewhere may not be practical in the context of actual on-farm conditions when considered at the system level. By examining recommended practices through the lens of the research context, it is possible to identify ways farmers' methods can be improved while remaining within the realistic limits of available resources.

4.3.1 Improving manure management

Given the unique characteristics and constraints of farmers in the study region, and keeping in mind the improved practices recommended by researchers and advisors in both the study region and elsewhere, a few opportunities for system improvement are apparent. These findings indicate that rather than focusing on ways to increase the bulk quantity of manure applied to Basmati crops as highlighted by agronomic research, the focus instead should turn towards how to best utilize the resources farmers already have available, as well as towards system improvements that do not hinge on increased manure availability. In the research context, whole-system redesign and adoption of complex new technologies may not be necessary for farmers to see immediate benefits from improved practices; advisors and project field staff should focus on teaching farmers simple ways to improve the systems they already have in place.

As nutrient input is considered here as a primary factor influencing low on-farm Basmati yields, and nutrient input is directly linked to the quality and quantity of manure fertilizers applied to the crop, improving nutrient cycling efficiencies at the farm level through improved manure management is an essential point of focus. A summary of the recommendations for improved manure management distilled from this research are displayed in Figure 16; these recommendations are organized within the same framework applied in Section 4.1.4. Improvements implemented at the sub-system level can theoretically have a cumulative positive effect on nutrient cycling at the whole-farm level.

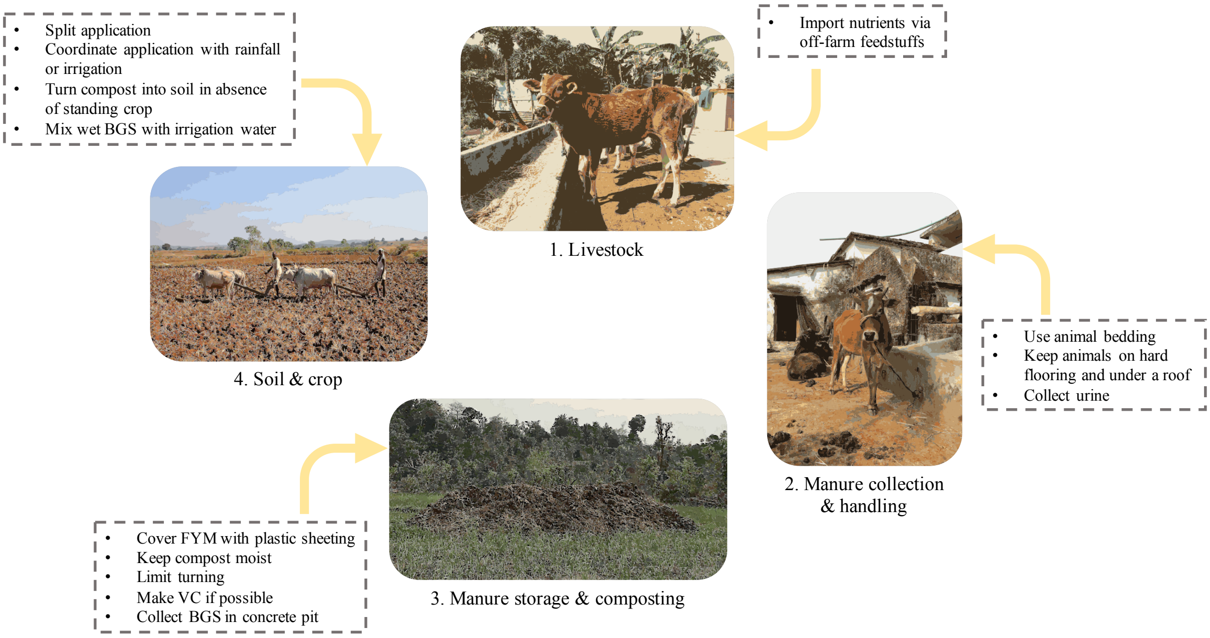

Figure 16. Recommendations for improved manure management distilled from the research findings, organized within the four manure nutrient cycling sub-systems conceptualized by Rufino et al. (2006).

4.3.1.1 Livestock feeding

With so little yet known about the animal feeding practices of the surveyed farmers, it is difficult to identify points of potential improvement in the livestock sub-system. However, it may be worth exploring ways that nutrients could be imported onto farms, either via purchased feed stuffs (for example food processing wastes like oil cake or sugar cane press mud), or via collection of feed materials from surrounding forest areas. Further research would be required to investigate the cost and local availability of feed materials that meet organic standards, and to estimate the quantity and feed value of forest plants that could be collected, as well as associated labour requirements.

4.3.1.2 Manure collection and handling

As previously noted, there is little room for improvement in regards to off-farm losses and frequency of manure collection. However, the conditions under which animals are kept could be slightly modified to reduce nutrient losses in the manure handling sub-system. First, farmers should be advised to keep animals on bedding materials whenever surplus leaves and/or crop residues are available, even in the dry season. Bedding can capture nutrients otherwise easily lost to leaching and/or volatilization, and can then be added to the compost pile to ensure maximum transfer of nutrients to the manure storage and composting sub-system. Second, if resources and infrastructure already exist or are easily acquired, animals should be kept on hard flooring (stone, brick, or cement) and under a roof to reduce losses via soil contamination and volatilization.

Livestock urine is probably the most underutilized nutrient source in the study context, and is a valuable fertility resource; Rufino et al. (2006) estimate that on average, more than 50% of the total N excreted by livestock is contained in urine. According to regional estimates, Indian livestock (cattle and buffalo) excrete an average of 7.7 litres of urine per day (NPCS, 2008), a quantity which is currently lost to the environment. If actively managed, urine collection could greatly improve the nutrient cycling efficiency of the manure collection and handling sub-system. In addition to using bedding materials, farmers could build simple gutters into their animal yards (and/or more frequently use gutters if they already exist) to capture the nutrients in urine and recycle them back into the farm system. Collected urine could then be poured over FYM piles to facilitate absorption and retention by carbon-rich materials.

4.3.1.3 Manure storage and composting

In this context, the handling of FYM and BGS during storage are the practices that offer the most room for system improvement; nutrient losses from manure products during storage can probably be significantly reduced with the introduction of simple, improved technologies. Farmers making FYM should cover their manure piles to reduce losses resulting from exposure to sun, air, and rain. Covering piles with plastic sheeting is the solution most applicable to the study region because it does not require access to special building materials, significant funds, or labour.[5] Plastering a manure heap probably has similar effects as covering with a plastic sheet and would allow farmers to capitalize on some of the nutrient retention benefits of covering manure during storage without requiring any additional materials cost. However, plastering can only be done once, whereas a plastic sheet can be easily removed to allow the addition of new materials to the pile. Farmers using plastering would have to manage manure in a more pre-planned and intentional way, which might not be realistic or possible for some. Furthermore, farmers would first have to stockpile manure until a pile was big enough to be plastered, during which time nutrient losses would occur. Laying down lightweight plastic sheeting would allow farmers to cover manure immediately after it is collected, and would require less labour than plastering a large manure pile, thereby allowing for greater ease and flexibility in managing manure storage.

Improving the management of BGS is less simple. While seemingly the best way to reduce nutrient losses would be to keep slurry in concrete tanks, this technology would require farmers to build significant additional infrastructure. The materials and labour costs of building such a tank would probably be prohibitive to most farmers. Other ways to retain nutrients should be explored. For instance, rather than building a whole concrete tank, farmers could simply cement the floor of the pit they use to collect biogas effluent; in this way, leaching losses would be reduced but materials costs would be less than building a whole tank. Alternatively, BGS

[5] At around 30–60 INR per meter, plastic sheeting would add a yearly cost of approximately 300–600 INR depending on the amount of plastic sheeting required to cover the manure pile. This sum could theoretically be offset by the improved yields gained through reduced carbon and nutrient losses; a total yield increase of just 9–18 kg Basmati (a 0.5–1% increase over the current on-farm average) would cover the cost of plastic sheeting. Alternatively, the cost of plastic sheeting could be covered by subsidies or price premiums.

pits could be lined with durable plastic sheeting. Local advisory services should investigate the options and consider including the cost of building effluent collection tanks in the subsidies provided for installing biogas plants. In the meantime, farmers could cover piles of semi-dried slurry with plastic sheeting, as discussed in reference to FYM, when effluent pits are emptied to accommodate overflow. Another option would be to produce compost by spreading BGS between layers of carbon-rich materials like leaves and/or crop residues. If this was done periodically, smaller BGS storage tanks would be required.

If a farmer has the motivation, time and resources to pursue vermicomposting, this practice could help them to generate a more effective manure fertilizer product. In a field trial, Jeyabal and Kuppuswamy (2001) showed that on an equal N basis, VC had a better effect on rice crop growth than either FYM or BGS. For farmers with smaller livestock holdings, vermicomposting could be an effective way to add value to the small amount of manure they have available.

No matter what the processing method, farmers should be advised to keep composting materials moist and to limit turning to just once. Limiting turning and keeping piles moist could help to reduce the impact of nutrient loss pathways in the manure storage and composting sub-system and improve compost quality without compromising on weed seed reduction. Improving the plant-nutritive quality of manure fertilizers would mean that more of the available nutrients transfer to the crop-capture sub-system, an effect that should theoretically manifest as economic gains as yields increase over time.

4.3.1.4 Soil availability and crop capture

One way to ensure that more of the nutrients available in manure fertilizers make it to the crop is to modify the timing of application(s) so that supply is synchronized with demand. As previously noted, rice agronomists at GBPUAT suggest that a split application of FYM at the time of field preparation and then a top dressing of VC 25 days after transplanting can better match crop nutrient needs. For farmers making both FYM and VC, split application could be a feasible option. The technique could also be an option for farmers making only FYM if active composting methods were employed. Synchronizing nutrient supply with demand would theoretically imply that less nutrients are lost to the environment and therefore recycled into the farm system.

Method of application could also influence the ratio of nutrients made available to the crop versus those lost to the environment. Farmers using any of the three methods could be taught to time the spread of manures with irrigation or predicted rainfall so as to reduce volatilization losses, especially if spreading wet BGS on dry fields, and to till the manure product in immediately after application if no crop is standing. Whenever possible, farmers using BGS could add buckets of fresh slurry to irrigation water (as is recommended by ICSD) as a way to retain the plant nutritive value of the manure product and reduce post-application volatilization losses without having to carry the messy and heavy liquid slurry all the way to the field. Since only one of the farmers surveyed mentioned using this method, there is notable room for advisory efforts to make an impact around this topic.

4.4 *Limitations of the research and topics for further investigation*

The primary limitation of this work was the lack of stakeholder involvement in the definition and development of sustainability indicators. While farmers' priorities and concerns could be deduced through analysis of qualitative survey response data, conclusions drawn from this analysis should be not considered as all encompassing of the issues farmers face around manure resource management at the farm scale. A more relevant and accurate assessment would rely heavily on the collaboration, input, and iterative feedback of all stakeholders involved in the project, especially farmers.

A limitation of the sustainability indicators used in this work was the omission of indicators for soil organic matter (SOM) build-up and greenhouse gas (GHG) emissions. While these factors have implications at the field, farm, and global levels, the data available at the time of writing did not allow for their inclusion. SOM balances would have been particularly useful in understanding the long-term agronomic implications of each manure fertilizer treatment, and GHG emissions would have given a more complete picture of the environmental impacts of each method.

The results of this work were also limited by the heavy reliance on farmer recall for key data points, namely yield records. Because yield was a sustainability indicator with multidimensional residual impact, accurate representation was essential to the analysis overall. More accurate yield data might have made it possible to identify potential statistical differences between treatments and correlations with NPK inputs, and would certainly have made for more accurate comparisons of the farm-level impacts of the different management methods.

The limitations of the research point to four additional areas of interest that should be further investigated. First, in order to more appropriately cater recommendations to farmers with different characteristics and resource endowments, it would be useful to better understand the conditions under which farmers choose to employ one manure management method over another, and to identify more concretely the characteristics of farmers who use primarily FYM, VC, or BGS. To this end, it would be useful to conduct another survey using random sampling, and to construct more up to date farm typologies with manure management method as a key variable.

Second, it would be highly relevant to investigate solutions for improving BGS storage, and to implement participatory technology development with different storage options. Biogas production has clear humanitarian and environmental benefits, and will probably continue to gain popularity in the study region. For farmers who use this method now and/or adopt it in the future, BGS will be the main source of manure fertilizer applied to Basmati crops, so ensuring that it is of high crop-nutritive value is important.

Third, in order to better understand the system-level sustainability and livelihood impacts of manure management, the issue of manure sales and purchases should be examined, with particular emphasis on the availability, cost and impact of purchasing supplemental manure as a way to invest in soil fertility. A cost–benefit analysis could evaluate the cost of purchasing enough manure to meet input recommendations against the predicted increase in yield that such an input would facilitate.

Finally, future research should investigate the economic and social viability of growing green manures in the summer season, as this practice could facilitate a reduced need for bulk manure fertilizer inputs to Basmati crops. Green manuring with a leguminous crop could be an effective way for farmers to increase the nitrogen supplied to the Basmati field without increasing their livestock holding.[6] The economic feasibility of growing a green manure, in addition to the supplemental water and labour required to manage the crop, should be further investigated to understand fully the implications of the practice in terms of sustainability at the farm scale.

5 Conclusions

Overall, the results of this study point to the multidimensional effects manure management can have on smallholder organic farms at the whole-system level. The sustainability analysis indicated that when compared to the baseline practice of making FYM as the primary method of producing manure fertilizer, both VC and BGS were improved technologies in the research context. From an agronomic and economic perspective, VC provided a manure fertilizer with the highest return on initial manure nutrient input for the lowest cost. BGS could theoretically also provide a high-quality fertilizer, but the product requires proper handling, and the cost of implementing the method is significant even if subsidies are acquired. Although farmers in the BGS group achieved the highest mean yields among the three groups surveyed for this study, it is possible that their yields were not a result of the manure fertilizer product itself, rather the knowledge and skills characteristic of the kind of farmer most likely to seek out and adopt biogas technology. When the trade-offs of each method were weighed at the farm scale and with farmers' concerns and priorities in mind, VC emerged as the method with the greatest potential for improved sustainability and farmer satisfaction.

Improving the plant-nutritive quality of manure fertilizers by increasing the nutrient cycling efficiency of farm-level manure management practices was identified as the logical focus for translating sustainability analyses into practical advisory efforts. With the level of systems

[6] Studies show that a good green manure crop (8–25 Mg fresh biomass ha^{-1}) can add 60–90 kg N ha^{-1} when turned into the soil, which is equivalent to the contribution of 3–10 Mg ha^{-1} FYM (Dahama, 1997). Taking the lowest end of these ranges, a farmer would need 3–4 additional head of livestock to achieve the same N contribution in the form of FYM. It is important to consider, however, that green manures only supply external N (through biological N fixation), and not P or K. A green manure crop may mobilize P and K already in the soil into plant-available forms, but using a green manure does not imply a net input of P or K. Therefore, it is important that when using a green manure, subsequent crops be supplied with other fertilizers that offer a net input of P and K, so as to maintain nutrient stocks in the long term.

knowledge afforded by this study, not enough was known about individual farmers' practices to draw pointed conclusions regarding the source of variation in yields between farms, but it can be said that maintaining profitable yields is central to achieving sustainability and livelihood objectives. Low average on-farm nutrient input rates relative to the recommendation was identified as a variable probably affecting the yield gap between farm and field trial. Increasing bulk manure fertilizer application is probably not economically feasible for most farmers in the study area, as it would require either investment in more livestock and more feed or purchasing cow dung off-farm. However, the results of this research indicate that there are ways farmers can adjust management practices to retain more of the nutrients in manure they already have, and thereby provide higher quality manure fertilizers to Basmati crops.

Evaluating farmers actual practices against literature findings and local recommendations indicated that small efforts to improve manure management at the practical level could have positive impacts on nutrient cycling efficiency at the whole-farm level. Three key recommendations for pointed advisory efforts emerged from the research. First, as VC performed best on most sustainability indicators, more resources should be directed towards teaching farmers about the benefits of vermicomposting, training farmers in vermicomposting techniques, and providing accessible subsidies for start-up costs. Second, because all farmers in the study area are likely to make at least some FYM, all farmers should be provided with plastic sheeting (or the subsidies to pay for it) and informed of the impact covering FYM piles can have on the quality of the resulting manure fertilizer. Third, all farmers should be educated on the value of livestock urine as a source of fertility, and advised to use animal bedding whenever materials are available, not just in the rainy season.

When integrated at the system level, the research findings indicate that implementing improved manure management practices can help smallholder organic farmers invest in the long-term productivity and sustainability of their farms. By minimising nutrient losses, retaining more of the nutrients already in farm systems, and producing higher quality manure fertilizers, farmers can build soil fertility, move towards more closely meeting crop nutrient needs, and feasibly increase yields. Maintaining profitable yields is pivotal to achieving several other sustainability and livelihood improvements that could in turn allow a farmer to make additional farm-level investments, for instance by purchasing supplemental cow dung, another head of cattle, or the materials to build a vermicompost pit. In this way, a focus on manure management in the short term can have radiating farm-scale sustainability and livelihood benefits in the long term.

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7 Appendix

A.1 *Background of the parent project*

In 2011, Helvetas Swiss Intercooperation and the Swiss retail chain COOP collaboratively started a market-driven agricultural development project titled "Sustainable Production of Organic and Fair Trade Rice in India and Thailand" (ICSD, 2015). The project is coordinated locally by ICSD (a sister organization to Helvetas), and has opened up the organic Basmati value chain to many smallholder farmers in Uttarakhand by connecting them to global buyers. Farmers involved in the project receive a guaranteed price premium and gain access to an international marketing scheme hosted by the exporter Nature Bio-Foods, Reismühle Brunnen and the supermarket chain COOP, which sells organic Basmati rice to consumers in Europe under an organic and Fair Trade label. In the first five years of the project, the premium paid to participant farmers under the label averaged 32% above the conventional market price (A. Srivastava, 2016).

The Nainital district was chosen by ICSD as a project site because farmers in this area were largely already practicing organic and/or low external input agriculture by default because access to synthetic fertilizers and chemical weed and pest control was limited and/or too costly, so contamination by chemical drift was not a major concern. Furthermore, the farmers in this district were identified as a population in need of livelihood improvement. Prior to the project's inception, Basmati rice was not commonly grown in the Nainital district. Leading up to 2011, land fragmentation had led farmers to abandon high risk and high value crops in favour of subsistence farming to ensure household food security. As the focus of production shifted, marketing opportunities for specialty crops like fine aromatic rice varieties diminished. Since 2011, the number of farmers opting to produce organic Basmati has fluctuated with changes in market prices. At the time of writing, an estimated total of 4,500 farmers were registered as organic producers under the project, with 2,938 farmers selling organic Basmati to Nature Bio-Foods in 2015 (A. Srivastava, 2016).

The parent project is based in the context of ICSD's development work in the Nainital district. The work takes a value-chain approach and aims to improve smallholder livelihoods through the development of sustainable intensification practices and Participatory Technology Development (PTD) in organic Basmati rice production. The project utilizes both field trials at the GBPUAT experimental farm and on-farm trials conducted by farmer participants in the region, aided by the support of agricultural advisors and ICSD field staff, to test a suite of eight organic management practices. These practices include alternative planting and irrigation techniques, use of green manures, intercropping, bio-fertilizers, and organic pest control, and the application of three manure-based organic fertilizers. Within the parent project, which is a development project, a research project headed by ETH Zurich in collaboration with Wageningen University and all aforementioned partners was started in 2015 under the title "How to sustainably intensify organic Basmati rice production in Uttarakhand, India? (BasmaSus)." The research project aims to investigate in more detail effects of the different management practices at both the research trial and the farm scale on indicators in the agronomic, ecological, social, and economic sustainability dimensions. Central features of the research project are its integrated and participatory approach, a special focus on greenhouse gas emissions, and use of the modelling platform FarmDESIGN as a tool for systems understanding, trade-offs analysis, and sustainability assessment.

A.2 *Manure products NPK concentrations used for calculating default values*

Table A1. Values found in literature citing the nutrient composition of farmyard manure. Sources highlighted in green were deemed most relevant to local conditions based on consultation with local experts, the averages of which were used as default reference values when calculating secondary variables from primary survey data.

FARMYARD MANURE	nutrient composition (%, dry weight basis)		
Source	**N**	**P**	**K**
Singh et al. (2007)	0.75	0.20	0.55
Choudhary & Suri (2009)	0.82	0.26	0.99
Kadian et al. (2008)	0.27	0.15	0.67
Bhadoria et al. (2003)	0.70	0.18	0.61
Kumar et al. (2015)	0.75	0.25	0.80
Debnath et al. (1996)	0.75	0.18	0.55
ICSD Organic Basmati crop guide	0.95	0.60	1.10
Singh et al. (2016)	0.50	0.18	0.60
Jaiswal et al. (1971)	0.93	1.00	1.31
Dahama (1997) "general average"	0.95	0.60	1.10
Dahama (1997) "Indian average"	0.30	0.15	0.30
Dahama (1997) "composted organic manure traditional method"	0.75	0.60	0.50
Gaur et al. (1984)	0.50	0.20	0.50
Raverkar (2016) "farmers practice"	0.40	0.40	0.40
Raverkar (2016) "scientific practice"	0.90	0.60	0.60
Literature average	0.68	0.37	0.71
"Local" average	**0.43**	**0.23**	**0.45**

Table A2. Values found in literature citing the nutrient composition of vermicompost generated from cattle manure. Sources highlighted in green were deemed most relevant to local conditions based on consultation with local experts, the averages of which were used as default reference values when calculating secondary variables from primary survey data.

VERMICOMPOST	nutrient composition (%, dry weight basis)		
Source	**N**	**P**	**K**
Singh et al. (2007)	1.60	0.60	0.80
Bhadoria et al. (2003)	1.30	0.20	0.94
Kumar et al. (2015)	2.00	1.05	1.00
Bejbaruha et al. (2009)	1.52	0.90	1.21
Jeyabal & Kuppuswamy (2001)	0.98	0.79	0.55
ICSD Organic Basmati crop guide	1.13	0.48	0.93
Singh et al. (2016)	1.00	0.80	0.24
Gupta (2003)	1.94	0.47	0.70
Raverkar (2016)	1.00	0.90	0.90
GBPant vermicompost pamphlet	1.50	1.90	1.00
Literature average	1.40	0.81	0.83
"Local" average	**1.03**	**0.74**	**0.65**

Table A3. Values found in literature citing the nutrient composition of slurry effluent generated from the production of biogas using cattle manure. Literature averages were used as default reference values when calculating secondary variables from primary survey data.

BIOGAS SLURRY	nutrient composition (%, dry weight basis)			
Source	**N**	**P**	**K**	**DM (%)**
Singh et al. (2007)	0.87	0.65	0.70	
Kadian et al. (2008)	0.44	0.16	0.82	
Terhoeven-Urselmans et al. (2009)				7
Debnath et al. (1996)	1.6	1.6	1	
Banik & Nandi (2004)	1.33	0.21	0.3	
Jeyabal & Kuppuswamy (2001)	1.78	0.76	0.88	6
ICSD Organic Basmati crop guide	2	1.25	1	
Jaiswal et al. (1971)	2.07			
Chandra (2005)	1.62	1.41	1.09	
Dahama (1997)	1.75	1	1	
Gaur et al. (1984) a (Mann et al. 1972)	2.07	0.35		8
Gaur et al. (1984) b (Laura & Idnani, 1972)	1.81	0.4		5.5
Gaur et al. (1984) c (Chetan & Parkash, 1976)	2.12	0.41		8.2
Gaur et al. (1984) d	1.99	1.02		5.73
Literature average	1.65	0.77	0.85	6.74

A.3 *Farm survey templates*

Common sections 1–4

1.	SURVEY ID
1.1	**Survey number:**
1.2	**Name of head of household:**
	Name of respondent (if not head):
	Relationship to head (if not head):
	Gender of respondent: Male □ / Female □
1.3	**Address:**
	Village: PO:
	Block: District:
	Mobile:
1.4	**GPS data:** Latitude: Longitude:
	Elevation (meters a.s.l):
1.5	**Names of enumerators (survey staff):**
	Name(s) of translator(s):
1.6	**Date of interview (dd.mm.yy):**
	Time of interview start:
	Time of interview end:

2.	FARM PROFILE
2.1	**Total farm size (ha):**
2.2	**How many people live in this farm household?** **How many of the household members work on this farm?**
2.3	**How many animals do you have? Please specify each type and current number.**

Animal type	Number

3.	GENERAL CROP MANAGEMENT: BASMATI
3.1	**Since when have you grown Basmati rice on this farm?**
3.2	**Since when have you grown *organic* Basmati on this farm?**

3.3 What variety(s) of Basmati do you grow here?

		code
HBC19 (Taraori)		1
Type 3 (Dehraduni)		2
Other (specify)		3

3.4 What is the total area of your farm under Basmati cultivation?

3.5 Please estimate your Basmati yield for the last three years.

	Estimated total Basmati yield (quintals)
2015	
2014	
2013	

3.6 Which of the following practices do you use on your Basmati crop?

Fertilizers	Water management	Pest Control	Whole system approach
FYM	Regular flooding	Biocontrol	System of Rice Intensification (SRI)
Vermi-composting	Alternative wetting and drying	Chemical pesticides	Soya-dhan (DSR + soy intercrop)
Biogas slurry			Regular transplanting
Biofertilizer			
Green manure			
Synthetic fertilizer			

4.	MANURE: GENERAL
4.1	**Check the boxes on the calendar to show where your animals are during the year:**

	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct
Stable or shed												
Yard												
Own grazing land												
Off-farm grazing land												
	Rabi				Summer			Kharif				

4.2 How often do you collect the manure from these places?

Location	Never	Sometimes	Often	Always
From stable				
From yard				
From own grazing land				
From off-farm grazing land				

4.3 How much total manure do your animals produce each day?

Total production (tokri or kg/day)

4.4	After you collect it, how do you store the manure?

Storage site		code
Heap on bare soil or mud		1
Heap on cement surface		2
Pit, bare soil or mud		3
Pit, cement		4

Cover		code
No cover		1
Tarp (polythene)		2
Hard roof (tin, plastic, or cement)		3
Under a tree		4

4.5	When do you start saving manure for using in the kharif season?

4.6	Of the total manure that you save for using in the kharif season, what % do you allocate to the following activities?

Activity	% of total used
Make FYM	
Make vermicompost	
Make biogas	
Burn for fuel	
Use for building material	

4.7	Do you have enough feed to have more animals? - If yes, how many more animals could you feed?

		code		
Yes		1	----> How many more?	
No		2		

Farmyard manure

5.	FARMYARD MANURE (FYM)
5.1	How did you fertilize your Basmati crop before you started using FYM? *(Ask only if applicable)*
5.2	Do you purchase materials to manage the FYM?

		code
Yes		1
No		2

- If yes, how much do they cost?

5.3	What do you add to the FYM? - How much do you add each time? - How often do you add these materials?

		code	How much?	How often?
Animal bedding materials		1		
Cow urine		2		
Crop residues		3		
Weeds		4		
Leaves and/or tree trimmings		5		
Household kitchen waste		6		
Other (specify)		7		

5.4	Do you do any of the following activities to manage the FYM pile? - How often do you do this activity? - How long does this activity take?

Activity		code			Time spent doing activity each time
Turn the pile		1	-------> How often?		
Water the pile		2	-------> How often?		
Other (specify)		3			

5.5	About how much total FYM do you make for using in the kharif season?
5.6	Of the total amount of FYM that you make for using in the kharif season, what % do you use for fertilizing Basmati, other kharif crops, and for home garden?

	% of total FYM used in kharif	Which crops?
Fertilizer for Basmati		
Fertilizer for other kharif crops		
Fertilizer for home garden		

5.7	When do you apply FYM to your Basmati crop? - How much do you apply at these times? (per bigha) - Do you till it in or use it as a top-dressing?

		Amount applied/ bigha/application	Nr. times per season (note *when*)	Tilled in or top dressing?
After rabi harvest	1			
When preparing field, beginning of kharif season	2			
During the kharif growing season	3			

5.8 How long does it take you to apply FYM to one bigha?

nr. of people working	hours/bigha

5.9 Do you receive help with the application of FYM to your Basmati crop?
- **From who?**
- **If hired, how much does it cost?**

		code		Rs/time unit
No help (only farm household members)		1		
Hired labor		2	Cost of hired labor to apply FYM	
Work trade		3		

5.11 Do you buy any FYM or cow dung from off-farm for fertilizing Basmati?
- **If yes, how much do you buy per kharif season?**
- **What is the price?**

Amount bought/kharif season	Price of bought Rs/unit

5.12 Which additional fertilizers do you add to your Basmati fields?
- **How much do you add?**
- **When do you add it?**

		kg/bigha	When?
Vermicompost			
Biogas slurry			
Biofertilizer			
Green manure			
Synthetic fertilizer			
Other (specify)			

5.13 Since you started using FYM to fertilize you Basmati crop, have you noticed any changes in the quality of your soil?

Color		Texture		Water holding capacity		Nr. plowings required	code
Lighter		Softer		More		More	1
Darker		Harder		Less		Less	2
No change		No change		About the same		About the same	3

5.14 Since you started using FYM to fertilize your Basmati, are there more pests, less pests, or about the same?

		code
More pests		1
Less pests		2
About the same amount		3

5.15 Since you started using FYM to fertilize your Basmati, are there more weeds, less weeds, or about the same?

		code
More weeds		1
Less weeds		2
About the same amount		3

5.16 Since you started using FYM to fertilize your Basmati, have you noticed any changes in the quality of the rice grain?

Yield		Grain size		Grain strength		Smell		code
More		Bigger		Stronger		More		1
Less		Smaller		Weaker		Less		2
About the same		About the same		About the same		About the same		3

5.17 Since you started using FYM to fertilize your Basmati, is the amount of rice straw more, less, or about the same?

		code
More straw		1
Less straw		2
About the same		3

5.18 Please listen to the following statements about FYM and say whether you agree or disagree with the statement. There is no "correct answer" – we are interested in your personal experience and opinion.

		1 Agree	2 Neutral	3 Disagree	4 Undecided
A	FYM has a good effect on Basmati crop growth				
B	The time and labor required to manage FYM is manageable				
C	The cost of using FYM is not too much				
D	I have the materials and equipment I need to make FYM				
E	If I need to buy it, FYM is easily accessible				
F	I have enough FYM to satisfy the nutrient needs of my Basmati crop				
G	Using FYM is safe for my health				
H	Using FYM is safe for the environment				
I	I have good knowledge of how to use FYM as fertilizer for Basmati				
J	I am satisfied overall with using FYM to fertilize my Basmati crop				

5.19	**Do you face any problems with using FYM to fertilize your Basmati? Please explain.**
5.20	**What do you like about using FYM to fertilize Basmati?**

Vermicompost

6.	VERMICOMPOST (VC)
6.1	**Since when have you been using vermicompost to fertilize your Basmati crop?**
6.2	**How did you fertilize your Basmati crop before you started using vermicompost?** *(Ask only if applicable)*
6.3	**Do you have your own vermicomposting system, or do you share one with other farmers?**

		code
Own		1
Shared		2

6.4	**How much did it cost you for the materials to get started making vermicompost?**
6.5	**Where do you get the worms that you use in your vermicompost?** - **If you buy them, how much do they cost?**

		code	Cost/unit
Buy them		1	
Find them in the soil		2	

6.6	**How do you store the vermicompost?**

Storage site		code	Cover		code
Heap on bare soil or mud		1	No cover		1
Heap on cement surface		2	Tarp (polythene)		2
Pit, bare soil or mud		3	Hard roof (tin, plastic, or cement)		3
Pit, cement		4	Under a tree		4
In a container		5	Other (specify)		5
Other (specify		6			

6.7	**In addition to manure, what do you add to the vermicompost?** - **How much do you add each time?** - **How often do you add these materials?**

		code	How much?	How often?
Animal bedding materials		1		
Cow urine		2		
Crop residues		3		
Weeds		4		
Leaves and/or tree trimmings		5		
Household kitchen waste		6		
Other (specify)		7		

6.8	**Do you do any of the following activities to manage the vermicompost?** - **How often do you do this activity?** - **How long does this activity take?**

Activity		code		Frequency	Time spent doing activity
Turn the pile		1	-------> How often?		
Water the pile		2	-------> How often?		
Add new worms		3	-------> How often?		
Other (specify)		4			

6.9 For how long do you usually store the vermicompost before using it?

		code
0 – 1 month		1
1 – 3 months		2
3 – 6 months		3
6 months – 1 year		4
More than 1 year		5

6.11 About how much total vermicompost do you make for using in the kharif season?

6.12 Of the total amount of vermicompost that you make for using in the kharif season, what % do you use for fertilizing Basmati, other kharif crops, and for home garden?

	% of total VC used in kharif	Which crops?
Fertilizer for Basmati		
Fertilizer for other kharif crops		
Fertilizer for home garden		

6.13 When do you apply vermicompost to your Basmati crop?
- **How much do you apply at these times?**
- **Do you till it in or use it as a top-dressing?**

		Amount applied/ bigha/application	Nr. times per season	Tilled in or top dressing?
After rabi harvest				
When preparing field, beginning of kharif season				
During the kharif growing season				

6.14 How long does it take you to apply vermicompost to one bigha?

nr. of people working	hours/bigha

6.15 Do you receive help with the application of vermicompost to your Basmati crop?
- **From who?**
- **If hired, how much does it cost?**

		code		Rs/time unit
No help (only farm household members)		1		
Hired labor		2	Cost of hired labor to apply vermicompost	
Work trade		3		

6.16 Do you buy any vermicompost or cow dung from off-farm for fertilizing Basmati?
- **If yes, how much do you buy per kharif season?**
- **What is the price?**

Amount bought/kharif season	Price of bought Rs/unit

6.17 Which additional fertilizers do you add to your Basmati crop?
- **How much do you add?**
- **When do you add it?**

		code	kg/bigha	When?
FYM		1		
Biogas slurry		2		
Biofertilizer		3		
Green manure		4		
Synthetic fertilizer		5		
Other (specify)		6		

6.18 Since you started using vermicompost to fertilize you Basmati crop, have you noticed any changes in the quality of your soil?

Color		Texture		Water holding capacity		Nr. plowings required		code
Lighter		Softer		More		More		1
Darker		Harder		Less		Less		2
No change		No change		About the same		About the same		3

6.19 Since you started using vermicompost to fertilize your Basmati, are there more pests, less pests, or about the same?

		code
More pests		1
Less pests		2
About the same amount		3

6.21 Since you started using vermicompost to fertilize your Basmati, are there more weeds, less weeds, or about the same?

		code
More weeds		1
Less weeds		2
About the same amount		3

6.22 Since you started using vermicompost to fertilize your Basmati, have you noticed any changes in the quality of the rice grain?

Yield		Grain size		Grain strength		Smell		code
More		Bigger		Stronger		More		1
Less		Smaller		Weaker		Less		2
About the same		About the same		About the same		About the same		3

6.23 Since you started using vermicompost to fertilize your Basmati, is the amount of rice straw more, less, or about the same?

		code
More straw		1
Less straw		2
About the same		3

6.24	Please listen to the following statements about vermicompost and say whether you agree or disagree with the statement. There is no "correct answer" – we are interested in your personal experience and opinion.

		1 Agree	2 Neutral	3 Disagree	4 Undecided
A	Vermicompost has a good effect on Basmati crop growth				
B	The time and labor required to manage vermicompost is manageable				
C	The cost of using vermicompost is not too much				
D	I have the materials and equipment I need to make vermicompost				
E	If I need to buy it, vermicompost is easily accessible				
F	I have enough vermicompost to satisfy the nutrient needs of my Basmati crop				
G	Using vermicompost is safe for my health				
H	Using vermicompost is safe for the environment				
I	I have good knowledge of how to use vermicompost as fertilizer for Basmati				
J	I am satisfied overall with using vermicompost to fertilize my Basmati crop				

6.25	Do you have any problems with using vermicompost to fertilize your Basmati? Please explain.
6.26	What do you *like* about using vermicompost to fertilize Basmati?

Biogas slurry

7.	BIOGAS SLURRY (BGS)
7.1	Since when have you been using biogas slurry to fertilize your Basmati crop?
7.2	How did you fertilize your Basmati crop before you started using biogas slurry? *(Ask only if applicable)*
7.3	Do you have your own biogas plant, or do you share one with other farmers?

		code
Own		1
Shared		2

7.4	How much did it cost you to build the biogas plant?
7.5	How often do you make biogas?

		code
Every day		1
Every few days		2
Once a week		3
Once every few weeks		4
Other (specify)		5

7.6	How much manure do you use each time you make biogas?
7.7	How long does the activity of making biogas take each time you do it?
7.8	After you make biogas, how do you store the slurry?

Storage site		code	Cover		code
Heap on bare soil or mud		1	No cover		1
Heap on cement surface		2	Tarp (polythene)		2
Pit, bare soil or mud		3	Hard roof (tin, plastic, or cement)		3
Pit, cement		4	Under a tree		4
In a container		5	Other (specify)		5
Other (specify		6			

7.9	For how long do you usually store the biogas slurry before using it?

		code
0 – 1 month		1
1 – 3 months		2
3 – 6 months		3
6 months – 1 year		4
More than 1 year		5

7.11	Of the total amount of biogas slurry that you make in the kharif season, what % do you use for fertilizing Basmati, other kharif crops, and for home garden?

	% of total BS used in kharif	Which crops?
Fertilizer for Basmati		
Fertilizer for other kharif crops		
Fertilizer for home garden		

7.12 When do you apply biogas slurry to your Basmati crop?
- **How much do you apply at these times?** (per bigha)
- **Do you till it in or use it as a top-dressing?**

		Amount applied/ bigha/application	**Nr. times per season** (note *when*)	**Tilled in or top dressing?**
After rabi harvest				
When preparing field, beginning of kharif season				
During the kharif growing season – spread on field				
During the kharif growing season – mixed with irrigation water				

7.13 How long does it take you to spread biogas slurry on one bigha?

nr. of people working	**hours/bigha**

7.14 Do you receive help spreading biogas slurry on your Basmati field(s)?
- **From who?**
- **If hired, how much does it cost?**

		code		**Rs/time unit**
No help (only farm household members)		1		
Hired labor		2	Cost of hired labor to apply biogas slurry	
Work trade		3		

7.15 Do you buy any biogas slurry or cow dung from off-farm for fertilizing Basmati?
- **If yes, how much do you buy per kharif season?**
- **What is the price?**

Amount bought/kharif season	**Price of bought Rs/unit**

7.16 Which additional fertilizers to you add to your Basmati fields?
- **How much do you add?**
- **When do you add it?**

		code	**kg/bigha**	**When?**
FYM		1		
Vermicompost		2		
Biofertilizer		3		
Green manure		4		
Synthetic fertilizer		5		
Other (specify)		6		

7.17 Since you started using biogas slurry to fertilize you Basmati crop, have you noticed any changes in the quality of your soil?

Color		**Texture**		**Water holding capacity**		**Nr. plowings required**		code
Lighter		Softer		More		More		1
Darker		Harder		Less		Less		2
No change		No change		About the same		About the same		3

7.18 Since you started using biogas slurry to fertilize your Basmati, are there more pests, less pests, or about the same?

		code
More pests		1
Less pests		2
About the same amount		3

7.19 Since you started using biogas slurry to fertilize your Basmati, are there more weeds, less weeds, or about the same?

		code
More weeds		1
Less weeds		2
About the same amount		3

7.21 Since you started using biogas slurry to fertilize your Basmati, have you noticed any changes in the quality of the rice grain?

Yield		**Grain size**		**Grain strength**		**Smell**	code
More		Bigger		Stronger		More	1
Less		Smaller		Weaker		Less	2
About the same		About the same		About the same		About the same	3

7.22 Since you started using biogas slurry to fertilize your Basmati, have you noticed any changes in the amount of rice straw produced?

		code
More straw		1
Less straw		2
About the same		3

7.23	**Please listen to the following statements about biogas slurry and say whether you agree or disagree with the statement. There is no "correct answer" – we are interested in your personal experience and opinion.**

		1 Agree	2 Neutral	3 Disagree	4 Undecided
A	Biogas slurry has a good effect on Basmati crop growth				
B	The time and labor required to manage biogas slurry is manageable				
C	The cost of using biogas slurry is not too much				
D	I have the materials and equipment I need to make biogas slurry				
E	If I need to buy it, biogas slurry is easily accessible				
F	I have enough biogas slurry to satisfy the nutrient needs of my Basmati crop				
G	Using biogas slurry is safe for my health				
H	Using biogas slurry is safe for the environment				
I	I have good knowledge of how to use biogas slurry as fertilizer for Basmati				
J	I am satisfied overall with using biogas slurry to fertilize my Basmati crop				

7.24	**Do you have any problems with using biogas slurry to fertilize your Basmati? Please explain.**
7.25	**What do you *like* about using biogas slurry to fertilize Basmati?**

A.4 *Basmati yield response*

Table A4. Data collected from the literature on the response of Basmati yield to N fertilization rates, used in linear regression analysis.

	N dose (kg ha^{-1})	yield (t ha^{-1})
Mannan et al. (2010)	25	2.43
	50	2.8
	75	2.77
	100	2.39
Manzoor et al. (2006)	50	3.32
	75	3.54
	100	3.67
	125	3.82
	150	4.17
	175	4.24
	200	4.19
	225	4.09
Pandey et al. (1999)	40	3.02
	80	3.64
	120	3.86
D.K. Singh et al. (2012)	120	2.795
D. K. Singh et al. (2016)	100	3.209
	75	2.99
	50	3.174
	50	2.936
	50	2.871
	70	2.91

A.5 *Personal reflection*

I started this thesis with no particular interest in Basmati rice or manure management, per se, rather a desire to practice a particular research methodology. At the end of my second semester of coursework, I took a class called Analysis and Design of Organic Farming Systems at Wageningen University. In that class, I was introduced to a research methodology and complementary modelling program called FarmDESIGN. We practiced the methodology by conducting a case study on an actual working farm, and the experience was a milestone in my journey as an agroecology student because it allowed me to synthesize and contextualize everything I had learned to date. The experience confirmed for me that practicing agroecology is as much about understanding complex biophysical processes as it is about stepping back and looking a farm as just one piece of a much bigger puzzle at the landscape, community, and global scales. I decided then that I wanted to continue to practice the methodology in my thesis work, and set out to find a project that would make it possible. In that way, the thesis topic I landed on was not driven by the specific content of the research, but by the opportunity to engage a specific *kind* of research.

The methodological framework I used in this thesis was directly adapted from what we had done in the course at WUR, and provided an essential backbone for my research process from start to finish. Conceptualizing the research as a four-phase cycle allowed me to divide my work into logical and manageable sub-systems while also keeping an eye on the whole, in a sense practicing what the agroecology team at NMBU call 'flickering.' Moving both forwards and backwards through the research cycle forced me to zoom in and out continually in a process that I found both incredibly rewarding and quite challenging. I learned in my first semester that I score off the charts in both green and blue personality traits (admittedly not a very scientifically sound finding), so it is not surprising that I would be simultaneously drawn to and annoyed by the messiness that flickering facilitates. I grappled with this messiness right up to the point of handing in the thesis.

On a practical level, the work was also both rewarding and challenging. Many technical aspects of the project I had originally designed became impossible along the way, and I had to revise my plan and adapt my work up to nearly the moment of submitting the final draft. While the roadblocks I encountered certainly caused moments of real frustration and disappointment, in the end I know that the experience of practicing adaptive management is probably one of the learning outcomes most relevant to whatever professional experiences come next for me.

About half way through the research, I had to let go of FarmDESIGN, and this was particularly hard because the model had been the axis around which all the other project components revolved. In retrospect, however, I see that I was able to engage an almost identical process successfully without the model. In fact, having to do the work of the model on my own, albeit in a much simplified form, was probably a better learning experience because it forced me to think through each step and decision point that the model would have done for me 'behind the scenes.' If I do have the opportunity to conduct research with FarmDESIGN in the future, I am confident that I will be better prepared for it than I would have been at the start of the thesis.

An essential component of the thesis learning experience was navigating a cultural context that could not have been more different from what I had become accustomed to as a student in Norway. Despite having spent significant time in India on previous trips, I was not fully prepared for the task of conducting fieldwork there. In particular, I found the pace of work incredibly slow. I admit that I never fully overcame my annoyance around this point (in fact I think it got worse over time), but I can recognize now that had I actually been able to accomplish everything I had originally planned, I might have been working on writing my thesis for several more months. A big part of working through the practical challenges of the fieldwork was maintaining a practice of journaling throughout. What started as a logistical solution to keeping advisors on multiple continents up to date on my progress turned into a platform for processing my observations, ideas, and frustrations. Having an outlet to document and work through practical challenges was invaluable in the long run, and I am sure it helped me to eliminate the bias of my frustrations when I sat down to write the actual thesis.

Writing the thesis was a unique challenge in itself. The research framework, with its four phases, provided an organizational structure that made sense intuitively, but was somewhat difficult to fit into the conventions of scientific writing. I struggled with finding a balance between thoroughness and concision, finding it difficult at times to manage large quantity of data I had to work with and to write a document that cohesively stitched together all of the information I had gathered. In the end, I omitted several components that I found interesting but hard to incorporate. While on the one hand I know there are ways I could have streamlined the structure and content of the thesis even more, I also feel it was important to maintain a broad scope given the systems-thinking approach of the research.

Overall, I feel both a sense of accomplishment and a sense that I could have done so much more. A large portion of the data I collected never made it into my thesis, and I am sure there are other papers to be written with the results. I also have several lingering questions that I wished I had asked in my farm survey, and many ideas for how to better execute this kind of research should I get the opportunity again in the future. While it is somewhat frustrating to recognize mistakes and omissions only in hindsight, I understand the value of having new questions and a desire to do more, better work—without this motivation, my career in science would be over before it starts.

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