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EDITED BY
Ademola Braimoh,
World Bank Group, United States

REVIEWED BY
Zipora Otieno,
Food and Agriculture Organization of the United Nations, Zimbabwe
Therese Mwatitha Gondwe,
Independent Researcher,
Lilongwe, Malawi

*CORRESPONDENCE
Toritseju Begho
toritseju.begho@sruc.ac.uk

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# Demystifying risk attitudes and fertilizer use: A review focusing on the behavioral factors associated with agricultural nitrogen emissions in South Asia

Toritseju Begho*, Vera Eory and Klaus Glenk

Rural Economy, Environment and Society, Scotland's Rural College, Peter Wilson Building, King's Buildings, Edinburgh, United Kingdom

Fertilizer use is environmentally unsustainable in South Asia. Ideally, farmers would follow optimal fertilization rates for crops based on scientific recommendations. However, there is ample evidence on why farmers under-fertilize or over-fertilize their crops. Important amongst them is that farmers' attitude to risk influences decisions on fertilizer use. This paper reviews studies on the effects of risk attitude on fertilizer use, the timing of application, and application intensity. We observe that the use of fertilizer is affected by perceptions of fertilizer as a risk-enhancing or risk-reducing input. In order to influence the future fertilizer decisions of farmers, several policy measures are suggested. Among these, gradual withdrawal of fertilizer subsidies, repurposing subsides toward improved technologies that increase productivity, improves nitrogen use efficiency (NUE) and reduce emission, providing enhanced-efficiency fertilizers and eliminating the fraudulent practice of fertilizer adulteration may be the most appropriate in a South Asian context.

KEYWORDS

**behavior, fertilizer, greenhouse gas, nitrogen, pollution**

**JEL classifications:** D81, D91, Q1, Q5.

## Introduction

Attaining sustainable food security is one of the major challenges confronting the agricultural sector globally. The sufficiency of food production relies on reactive nitrogen (Nr) being available to crops (Chang et al., 2021). Fertilizer provides crops with essential nutrients to enhance crop yields. As such, the efficient use of fertilizer[1] notably contributes to food security (Prasad, 2009; He et al., 2021). However, fertilizer use is environmentally unsustainable in many regions of the world because Nr is lost through leaching, denitrification and volatilisation. One of the main sources of global anthropogenic ammonia ($NH_3$) and nitrous oxide ($N_2O$) emissions is agriculture (Zhu et al., 2015; Aryal et al., 2020).

Compared to other regions of the world, South Asia had the biggest total change in nitrogen emissions (from domestic economy and international trade) between 1997 and 2017 (Malik et al., 2022). Specifically, Nr emissions such as $NH_3$ and $N_2O$ have almost doubled since the 1980s (Yang et al., 2022). This is partly attributed to a substantial dependency on nitrogenous fertilizer in South Asia (Mujeri et al., 2012; Aryal et al., 2020). This dependency could be traced to the Green Revolution, which brought high-yielding crops that were highly responsive to fertilizers, thus, driving the need for increased use of fertilizers in South Asia (Bilal and Aziz, 2022). Although the Green Revolution positively impacted overall food security (John and Babu, 2021), there are negative implications for the unsustainable use of nitrogen (N) inputs to attain high crop productivity when nitrogen use efficiency (NUE) is low.

The current fertilizer use intensity in South Asia is estimated at 121 kg $ha^{-1}$, which is projected to increase to 268 kg $ha^{-1}$ by 2050 at current trends (Amjath-Babu et al., 2019). Besides, South Asia's fertilizer use efficiency is very low at ∼25–48% (Farnworth et al., 2017; Bilal and Aziz, 2022). These statistics suggest the region is one of the hotspot areas of reactive nitrogen losses (Farnworth et al., 2017; Xu et al., 2019; Raghuram et al., 2021).

There is evidence that when fertilizers are not applied in line with science-based recommendations and the management practices are inefficient, there is either the possibility of nutrient mining from under-application or substantial adverse environmental impacts from over-application (Nie et al., 2009; Timsina et al., 2010). For example, In India, Pathak et al. (2010) attributed the increase in emissions of $N_2O$ (from 0.169 Mt to 0.217 Mt) to the increase in fertilizer use. Shahzad et al. (2019) reported that in Pakistan, between 1961 and 2014, N fertilizer use and N surplus increased, while nitrogen use efficiency[2] (NUE) declined sharply. Similarly, in Sri Lanka, between 1961 and 2013, N fertilizer use increased by 370%. In contrast, Afghanistan and some regions across Nepal, Bhutan, and the Maldives face issues predominantly with N mining (Lassaletta et al., 2014; Dorji et al., 2020; Devkota et al., 2021).

In most South Asian countries, the N application rates that maximize yield and profit may differ by a wide margin due to blanket recommendations of fertilizer. For example, an increase of 11.4% in rice yield was reported for site-specific nutrient management compared to blanket recommendations (Chivenge et al., 2021). The implication is that, depending on the risk[3] orientation of a farmer, they may prefer to avoid the risks associated with varying yield responses due to reduced nitrogen levels by applying fertilizer above the recommended levels. Also, farmers have to decide when to apply a given quantity of fertilizer. Decisions on the timing of fertilizer include whether to apply it only between growing seasons, which has the potential for some of it to be lost to the environment, —or applying single or split fertilizer during the growing season, which can increase the yield and the NUE but is also associated with greater risk. We return to this point later in section Empirical evidence. Also, there are decisions to be made on which fertilizer to apply (both in terms of compound fertilizers, various N forms of single nutrient fertilizers, and synthetic vs. organic fertilizers). These decisions are, in part, determined by risk attitudes. Although this paper does not deal with organic fertilizer due to a lack of sufficient studies examining risk attitude and organic fertilizer use decisions, we acknowledge that organic fertilizer matters for the mean gross margin (GM) vs. GM variance debate that will be discussed later in the paper.

In previous studies, variation in risk attitude has helped to explain variation in fertilizer use across farms. However, a comprehensive overview of the related literature is lacking both in South Asia and globally. Therefore, this paper integrates and synthesizes the findings of published research on the effects of risk attitude on fertilizer use, timing, and application intensity. Due to a lack of relevant studies in South Asia, this review highlights global empirical findings and condenses the literature to inform recommendations for future policy development regarding fertilizer use, aiming to reduce N emissions from agriculture in South Asia. In summary, we focus on South Asia as it is arguably the most prominent region of N overuse and one of the regions with very low fertilizer-use efficiency. This is combined with an ongoing struggle to meet the environmental aspects of the Sustainable Development Goals (SGDs) in many dimensions (Selim et al., 2018).

The organization of the remainder of the paper is as follows: Section Nitrogen pollution from excess fertilizer

1 Throughout the paper, we refer to synthetic fertilizer simply as fertilizer. In the case where the reference is to organic fertilizer, it is clearly stated.

2 Crop NUE is defined as yield per unit of available N. In its simplest form, it measures how much N a crop uptakes and how much N is lost, i.e., $NUE = (useful\ N\ output)/(N\ input)$. For a detailed introduction to NUE, readers can refer to Sharma and Bali (2017), Hawkesford and Griffiths (2019).

3 The working definition of risk as used in this paper refers to the potential deviation between expected and actual outcomes. It stems from the uncertainty and imperfect knowledge about an event which may result in adverse outcomes such as a deviation from the expected yield or the economic returns. The risk category which fertilizer use falls under is production risk. However, price-related risks also play a role in fertilizer use.

highlights the issue of pollution from inefficient use of fertilizer, Section Determination of optimal levels of nitrogen fertilization discusses the different biophysical models used to determine optimal levels of N fertilization, and Section Concepts of fertilizer as a risk-reducing or risk-enhancing input reviews the perceived risk or benefit of using fertilizer. Section Empirical evidence provides empirical evidence from previous studies. Section Reasons underlying fertilizer use decisions in relation to risk attitudes highlights the reasons behind fertilizer use decisions with respect to risk attitudes. Section The South Asia context focuses on the relevance of policy and interventions in the reduction of N emissions from agriculture across South Asia, while Section Conclusion concludes the paper.

## Nitrogen pollution from excess fertilizer

The inefficient use of fertilizer results in anthropogenic Nr emissions in the form of $NH_3$, $NO_x$ and $N_2O$. From 2000 to 2015, there was a 36% increase in $N_2O$ emissions in South Asia (Pawar et al., 2021). $N_2O$ emissions causes concern as the global warming potential of $N_2O$ is ∼300 times that of carbon dioxide, and it accounts for 6% of the global anthropogenic greenhouse gas source (IPCC, 2007). Although $NH_3$ emission is increasingly becoming a huge environmental issue, it has not received as much attention from policy targeted at mitigating emissions compared to other Nr forms (Sutton et al., 2013, 2020). The current levels of emissions make the Indo-Gangetic Plains (IGP) a global hotspot of $NH_3$ emission (Tanvir et al., 2019; Kuttippurath et al., 2020). An alarming example is that the atmospheric $NH_3$ in the IGP regions of India is reported to exceed values elsewhere globally (Kuttippurath et al., 2020). However, the simultaneous increases in $SO_2$ and $NO_x$ emissions have concealed the rise in $NH_3$ emissions in South Asia (Warner et al., 2017).

The environmental impact of $NH_3$ is numerous. $NH_3$ emissions influence the global nitrogen cycle, leading to air pollution and soil acidification, contributing to GHG emissions, and negatively impacting biodiversity (Liu et al., 2017). $NH_3$ also plays a role in the formation of particulate matter (Liu et al., 2017). When secondary particulate matter (PM2.5) is formed from $NH_3$ reacting rapidly with sulphuric and nitric acids (Hodan and Barnard, 2004; Warner et al., 2017), it exacerbates air pollution from non-agricultural sources resulting in the poor air quality in South Asia (Kumar et al., 2018).

Both satellite observations and models have been used to reach conclusions that the main driver of the high atmospheric $NH_3$ in the IGP is the increase in fertilizer use (Kuttippurath et al., 2020; Pawar et al., 2021). Therefore, a better understanding of the role of risk attitude in fertilizer use decisions is important to ensure that the farm's economic goals and environmental advocacies align. Furthermore, a better understanding could improve sustainability through reducing $NH_3$ and $N_2O$ emissions while simultaneously increasing NUE, yields and financial returns.

## Determination of optimal levels of nitrogen fertilization

The context in which "optimal" is used in the crop production literature refers to a farmer aiming to apply nutrients at rates that will result in maximum yield and economic returns and minimize environmental impact. However, the optimal recommendation of fertilizer developed by agricultural departments or universities and disseminated by extension agencies and governmental departments are mainly agronomic and yield-focused (Jat and Gerard, 2014; Ali, 2020). Until recently, environmental concerns were not prioritized in farm-level N fertilizer application decisions as much as crop yields (Banger et al., 2020). Historically, optimal input levels were determined by experience, and this may still be common practice in places where scientific/agronomic education and information are lacking. However, with advances in knowledge and underpinned by data from systematic experimentation and observation, curve fitting techniques and mathematical response models have been used to determine optimal levels of nitrogen fertilizer. The functions that dominate the literature on crop response[4] to fertilizer are the linear response and plateau (LRP) and polynomial functions (PF).

The PF assumes that inputs are perfectly controllable and linear in parameters, and the plateau is non-stochastic (Cox, 1996; Dhakal et al., 2019). The PF model has been criticized (see Paris, 1992; Dhakal et al., 2019) mainly because it depends on a forced substitution between nutrients and its potential to overestimate maximum yield and optimal fertilizer recommendation. This resulted in several studies concluding that models of crop response to N that exhibit a yield plateau are superior to functions that do not include a plateau. These limitations of the PF are addressed in the LRP model. The LRP model interprets the fundamental principles of the law of the minimum in crop response to a vital nutrient. In other words, the LRP fits with Liebig's Law of the Minimum, where crop growth is determined by the amount of nutrient the soil

4 Other functions used in the literature include the quadratic response plateau, quadratic, exponential, and square root functions. Considering that many production functions are asymmetric (plateau, quadratic plateau, Mitscherlich), this asymmetry results in more nitrogen being applied under uncertainty. That is, uncertainty (in terms of the production function, purity of the nitrogen input, etc.) leads to more nitrogen being applied (Babcock, 1992) under risk neutrality and expected profit maximization.

contains in its smallest quantity before another nutrient becomes limiting. The plateau yield is the constant yield achieved with additional input. The start of the plateau represents the optimal input (Dhakal et al., 2019). The main limitation of the LRP is that the estimation is cumbersome and rarely used in agricultural extension (Bäckman et al., 1997), albeit debatable as the "yield goal" approach has an indirect connection to a stochastic plateau. Modifying the LRP (e.g., in Tembo et al., 2008) permits certain parameter estimates to be stochastic. Thus, it improves the performance of the LRP in modeling yield response.

The specification of different biophysical models to determine optimal levels of N fertilization can lead to meaningful differences in the interpretation of the inferential analysis. This is not an exception for models of crop-fertilizer response functions. Grimm et al. (1987) and Cerrato and Blackmer (1990) find notable differences among these models in their prediction of economic optimum fertilization rates. On the one hand, for a PF, profit-maximizing N application rates increase with higher (resp. lower) output (resp. input) price. On the other hand, the profit-maximizing application rates of the LRP are not price-sensitive. This is because assuming fertilizer use from the limiting-input perspective; the optimal rate is zero for a crop that does not yield profit or is otherwise the minimum quantity necessary to obtain the yield plateau (Sheriff, 2005). In the case of the LRP model, if fertilizer prices are sufficiently low (relative to the value of the related marginal change in produce), then risk-neutral farmers over-apply N on average.

A more detailed account of the contention in the literature regarding the most appropriate models is beyond the scope of this paper (see Dhakal and Lange, 2021 for a review). However, we conjecture that any perceived or observed inefficiency of recommended fertilizer application rates that are based on either the LRP or PF functions (or any other crop-fertilizer response function such as the quadratic and the exponential response model) may induce different behaviors among farmers across various risk aversion levels.

## Concepts of fertilizer as a risk-reducing or risk-enhancing input

The effect of risk attitude on fertilizer use is dependent on whether farmers perceive fertilizer as a risk-enhancing or risk-reducing input.[5] There is a large body of evidence that fertilizer is a variance-increasing resource. These findings also favor the argument that fertilizer increases production risk (Antle, 2010; Monjardino et al., 2015; Chai et al., 2022). Furthermore, Haile et al. (2020) suggest that synthetic fertilizer is a good example of a high-risk, high-return agricultural technology. The consequence is that for a single input case, a risk-averse[6] farmer will use fewer inputs than a risk-neutral farmer if the input increases the variability of output, all else (i.e., expected yield) being equal (Feder, 1980; Mallarino, 2008). Specifically, in the case of N fertilizer application, considerations of risk should decrease the rate of N application for a risk-averse farmer relative to risk-neutral or risk-seeking farmers (Rajsic et al., 2009).

In many cases, there is a trade-off between maximizing the mean gross margin (GM) vs. minimizing the variance in farm financial decisions. The trade-off also involves how the natural inputs (soil, livestock, water, immediate and wider environment) are used. In deciding on input allocation, farmers sometimes have to decide between increasing efficiency or increasing resilience—the former results in a higher GM in the short term. The latter implies variability in the GM over time. For example, where an increase in fertilizer quantity results in a higher profit variability, the tendency is for a risk-averse farmer (i.e., broadly referring to the tendency to avoid uncertain outcomes over certain outcomes) to apply less fertilizer than their risk-seeking counterparts (Asci et al., 2015). This is in accord with the findings of Antle (2010) that risk-averse farmers prefer less fertilizer compared to risk-neutral farmers in the case where fertilizer increases profit variability. The implication is that depending on risk attitudes, farmers may apply lower quantities of fertilizer than optimal, which could result in soil N deficiencies.

A competing theory is that unobservable processes (for example, leaching or denitrification) affect soil N availability which could increase the variability of yields. In such cases, increasing fertilizer application could reduce the risk of low yield and variance in farm profit, particularly when soil nutrient levels are the main source of uncertainty. Hence, from this viewpoint, farmers consider N a risk-decreasing input (Stuart et al., 2014). This provides an explanation as to why risk aversion motivates higher fertilizer application. Sheriff (2005) and Moser and Mußhoff (2017) support this assertion as they observe that more risk-averse farmers use more fertilizer. Mukasa (2018) contend that while the use of chemical fertilizer is risk-decreasing, its purchasing costs, on the contrary, are risk-increasing. However, Babu et al. (1991) find that while organic manure is a marginal risk-reducing input, the same could not be said for synthetic fertilizer.

5 For simplicity, risk-reducing inputs are production inputs that improve the chances of better quantity and (or) quality of farm products.

6 Risk attitudes are reflections of subjective preferences. In the broad context, compared to a risk-loving farmer, a risk-averse farmer is more "cautious", as such, willing to forgo some expected profit to reduce the probability of a low profit when faced with choices that have the probability of high and low profit. As a result, when choosing between alternatives, the tendency is to avoid options that have a chance of loss, even if that risk is relatively small, i.e., the risk-averse farmer's preference is for a guaranteed outcome over a probabilistic one having identical expected value.

## Empirical evidence

In the agricultural economics literature, risk attitude has been employed to explain variations in input use. Specifically, previous studies have found that risk attitude influences fertilizer use. According to Fontaine and Sindzingre (1991), attitude toward risk is one of the most important factors determining the consumption of fertilizers. The discussion that follows focuses on the empirical findings on risk attitudes in relation to (I) decisions to use fertilizer, (II) fertilizer application rates, and (III) timing of fertilizer application. We also investigate the postulated reasons underlying fertilizer use decisions in relation to risk attitudes.

### Risk attitude and decisions to use fertilizer

Risk attitude plays a role in fertilizer use decisions from a production cost perspective. For unsubsidised fertilizer, the cost is non-negligible. Thus, risk-averse farmers may consider the risks and decide not to apply the optimal quantity of fertilizer. Based on data from Tanzania and Uganda, Mukasa (2018) highlights how the cost-increasing nature of fertilizer makes it risk-increasing. Relative to risk-neutral farmers, moderately risk-averse farmers buy less fertilizer—a finding which explains the low demand for fertilizer when the full cost is incurred.

Fertilizer use affects the mean and the variance of the net returns to production. This is because the quantity of fertilizer that would be applied has to be decided in the absence of certainty about the weather or output price and in the absence of perfect credit and insurance markets. From this perspective, the market prices of fertilizers have a differential impact on decisions depending on the risk attitudes. Besides, mediated by risk attitude, the cost of fertilizer determines fertilizer use decision. For example, in an assessment of potato farmers in Florida by Asci et al. (2015), risk-neutral farmers prefer lower fertilizer application rates than their risk-averse counterparts to circumvent the downward risk owing to the high cost of fertilizer. There are reasons to justify a farmer's decision to prioritize eliminating the downside risk. A risk-averse farmer that applies fertilizer above the recommended rate could do so as an insurance strategy if increasing the quantity decreases the probability of low yield (Selig, 1992).

Risk attitudes have also been found to influence decisions on fertilizer types. For example, Chen et al. (2018) found that risk attitude determines organic fertilizer use among rice farmers in China. They found risk-averse farmers were more likely to invest in organic fertilizers and less likely to invest in synthetic fertilizers. This finding is supported by Mwaijande et al. (2019), who find that risk aversion is correlated with the investment in different fertilizers. These findings indicate that synthetic and organic fertilizers are often perceived as substitutes.

Depending on the degrees of risk-aversion, the preferences for N use strategies will differ between individual farmers producing either cash or food crops. Some studies have shown that with regard to input use, risk aversion is more pronounced for cash crops than subsistence crops. This may be because many cultivated cash crops are mainly high-yielding varieties that require higher quantities of fertilizer (D'Souza and Mishra, 2018). Dequiedt and Servonnat (2016) show that the risk decreasing relationship with N fertilizer application varies by crop type and generally induces risk-averse farmers to increase the quantity of fertilizers applied.

### Gender dimensions in risk attitude and fertilizer use

A few studies provide empirical evidence on risk preferences of different gender and fertilizer use. For example, Sheremenko and Magnan (2015) studied farmers in Kenya. They found that female household heads with higher risk aversion are less likely to use "riskier" types of fertilizers, e.g., Diammonium phosphate (DAP). They also show that empowered females who are more risk-averse applied less fertilizer than their female counterparts who were not empowered. Using field experiments with farmers in Niger, Sanou et al. (2015) also find that when female farmers manage plots, they tend to use less fertilizer on average than men.

### Risk attitude and fertilizer application rates

Numerous studies have examined the effect of risk aversion on the level of N use and reported that fertilizer application rates are correlated with risk attitude. For example, Roosen and Hennessy (2003) find that risk-averse crop farmers in the US are more likely to apply less N fertilizer than risk-neutral farmers. Similarly, in Togo, Ali (2019) finds that risk-averse farmers used less fertilizer. However, not all studies found a significant association between risk aversion and fertilizer use. This includes, for example, Le Cotty et al. (2018) in their study of fertilizer use by maize farmers in Burkina Faso.

Several studies quantified the increase or decrease in application rates linked to risk aversion. For example, Khor et al. (2018) found that among Vietnamese maize farmers and across different wealth levels, a one-unit increase in risk aversion reduces fertilizer application by about 30–350 kg/ha, equivalent to 3–32% of the mean fertilizer use intensity.

Smith and Umali (1985) found that moderately risk-averse farmers apply 7–10 kg less fertilizer than the profit-maximizing N-rate. In contrast, Dequiedt and Servonnat (2016) found that risk aversion resulted in applying an additional 29 kg/ha$^{-1}$ of fertilizer compared with risk-neutral farmers representing a cost of 76 euros/ha.

The relationship between risk attitude and the optimum rates of N fertilizer application, which maximizes economic return and minimizes N losses, has been subject to investigation in several studies. Notably, the optimal rate varies as a function of risk attitude. Meyer-Aurich and Karatay (2019) showed that attitudes toward risk determine optimal fertilizer rates, albeit with a limited effect. Paulson and Babcock (2010) find that the optimal application rate for the risk-averse farmer across all levels of risk aversion is lower than that for the risk-neutral farmer. Risk aversion reduces fertilizer applications by up to 20% of the optimal rates (Shalit and Binswanger-Mkhize, 1985; Roumasset et al., 1989).

There are also indications that risk attitude influences fertilizer application techniques. For example, Sanou et al. (2015) examined the effects of risk attitudes on fertilizer use and micro-dosing practice. They find that risk aversion was crucial in both the decision to use fertilizer and the choice of application techniques. Likewise, Gandorfer et al. (2011) found that the optimal tillage/N strategies that resulted in a positive expected net income for both risk-neutral and risk-averse farmers were either to combine conventional tillage with standard N rates or to combine reduced tillage with increased N rates.

## Risk attitude and timing of fertilizer use

Regarding the timing for fertilizer application, it is difficult to draw a firm conclusion on whether the effect of risk aversion on the timing of fertilizer use is positive or negative. The reason for this mixed picture appears to be the crop-specificity of timing decisions. For example, Huang (2002) estimated N fertilizer application timing decision model among corn growers. The findings suggest that the optimal timing of application is before planting; however, this only applies to the risk-averse farmer, with a risk-averse farmer applying substantially more N fertilizer than a risk-neutral farmer to obtain the same corn yield. Although, this could also be observed with risk neutrality and expected profit maximization with a non-linear production function under uncertainty. Among cotton farmers in the United States, Huang et al. (1994) find that the optimal strategy for both risk-neutral and risk-averse cotton farmers is to split-apply nitrogen in cases where farmers may not be able to apply N fertilizer post-planting. As opposed to the case of corn farming described above, compared to a risk-neutral farmer, a risk-averse cotton farmer tends to use more N fertilizer before planting (Huang et al., 1994).

Considering that timing for fertilizer application can impact the quantity applied, farmers who apply fertilizer early tend to do so at levels above those recommended to account for the proportion of N lost *via* precipitation and denitrification. Huang et al. (2001) find that the reduction in N fertilizer use can be very substantial if a risk-averse farmer changes the timing of application from prior to planting to the growing season only.

## Reasons underlying fertilizer use decisions in relation to risk attitudes

Several explanations have been offered to understand how risk attitudes influence fertilizer use decisions. Farmers are not just simply being inefficient *per se*. For risk-averse farmers, it may be economically rational to use fertilizer above the recommended rates, especially in the case of blanket recommendations that do not account for farm-specific environmental factors affecting optimal rates (Sheriff, 2005). This example shows that understanding the underlying reasons facilitates the promotion of fertilizer decisions among farmers that simultaneously improve farm income and reduce environmental pollution from N fertilizers.

In line with the theory of limiting input, input overuse may be perceived as a mode of self-protection (Paulson and Babcock, 2010). Babcock (1992) opines that self-protection drives the application of a higher quantity of N fertilizer since farmers find it profitable to reduce the chances that they would have applied less fertilizer when the crop would have benefited from more. This possibly lends some explanation to the studies that argued that fertilizer is risk-increasing yet often overapplied.

From a different perspective, Isik and Khanna (2003) relate the influence of risk attitudes on fertilizer use decisions to missing information or misinformation on the quantity of fertilizer needed by crops. Considering that farmers do not have precise information on the available N in their plots, risk-averse farmers tend to over-apply fertilizer if they perceive that it is less costly than growing a crop in soil lacking N, which otherwise will prevent the crop from attaining full potential.

Aside the cases where the recommended fertilizer rates are not applied mainly due to information asymmetries, one problem peculiar to lower-and middle-income countries is the possibility of purchasing low-quality fertilizer due to adulteration. This casts doubt on the effectiveness of fertilizer in the absence of opportunities to test the nutrient content. For example, according to Mohiuddin et al. (2017), the adulterated proportion is up to 40% of all fertilizers in Bangladesh. The situation is similar in Nepal and India (Raut and Sitaula, 2012; Devilal et al., 2020). Therefore, when the expected fertilizer content is low due to adulteration, risk-averse farmers apply more than the optimal level to ensure that the crop will produce sufficient output to meet their needs. In addition, where there is uncertainty regarding fertilizer quality, synthetic fertilizer could also be substituted with other risk-reducing inputs (Takeshima et al., 2016), for example, with bio-organic fertilizers, which may not necessarily be less polluting when over-applied.

Typically, when a farmer invests in production inputs, the farmer also anticipates the expected range of returns. For example, suppose the farmer takes out a loan to fund the purchase of fertilizer. In that case, the expectation is that the product will be sold at a price that allows at least repaying the loan while accounting for potential risks involved in production. From this perspective, a risk-averse farmer may be more likely to choose fertilizer quantities which reduces the variance of income at the expense of expected profit. In other words, a risk-averse farmer may prioritize reducing the risk of defaulting on the loan.

Production uncertainty, for example, due to weather, can also influence input application and result in risk-averse farmers using more fertilizers (Isik and Khanna, 2003). The variability of rainfall is likely to prompt risk-averse farmers to make neither yield nor profit-maximizing decisions. In response to poor seasonal conditions, a farmer's adaptation strategy could be to lower N and other inputs, which would be reflected in reduced investment costs. On the other hand, farmers may increase fertilizer application above the recommended rate to take advantage of favorable weather. Another reason underlying fertilizer use decisions is that, compared to the cost of sub-optimal application of fertilizer in the "good" years, the cost of fertilizer application at rates exceeding the yield maximizing levels tends to be lower, and, crucially, farmers can avoid the uncertainties linked to the unpredictability of the yield response at reduced nitrogen levels (Selig, 1992; Rajsic et al., 2009). Besides, from the farmer's perspective, the evidence of applying less fertilizer is clearly visible through the yield response, but this is not the case up to a degree when excess N triggers a plant response when excess fertilizer is applied (Rajsic et al., 2009).

Considering the heterogeneity in soil nutrient content across farms, farmers may also be overapplying fertilizers due to biased, subjective beliefs regarding yield response. Moreover, this effect may be intensified depending on risk attitudes. SriRamaratnam et al. (1987), for example, observed that subjective overestimation of the level of response of sorghum yields to nitrogen fertilizer resulted in farmers overapplying N.

The differential use of decision heuristics may also result in variation in fertilizer use (Feder, 1980). Some studies also suggest that risk averse farmers prefer small chances of high yields compared to small chances of crop failures, assuming expected yields are equivalent. Within the confines of prospect theory, a farmer who over-weights the probability of a bad year and underweights the probability of a good year will apply less fertilizer (Kemeze et al., 2020). Holden and Quiggin (2018) show that the over-weighting of small probabilities (e.g., bad events such as drought) was linked with reduced fertilizer application on all maize types, especially the case with the riskier improved maize types.

## The South Asia context

In sections Introduction and Nitrogen pollution from excess fertilizer, we discussed the N emissions position of South Asia within the global context. Majumdar et al. (2000) propound that even a 5–10% increase in fertilizer-use efficiency will result in considerably lower $N_2O$ emissions and reduced production cost, consequently increasing returns to farmers. However, attaining such targets poses a challenge across South Asia, as N fertilizers, in many cases, are managed as blanket recommendations formulated based on crop response data averaged over large geographic areas (Ali, 2020). Blanket recommendations do not consider the spatio-temporal variability in N supplying capacity of soils and crucially fail to account for risk attitudes. This is further aggravated by the fact that tailored fertilizer recommendations based on soil testing are beyond the reach of smallholder farms in South Asia due to limited availability, challenges with accessing testing facilities, cost implications and time involved (Sapkota et al., 2021). However, there is the question of whether there is much of a production risk to farmers if they reduce their N use by a small percentage. Given that with the plateau profit functions, there is a variability where the expected yield is not decreasing much relative to an optimum. Thus, the question is how far blanket recommendations vs. spatio-temporal heterogeneity is a problem. One could argue that perhaps farmers move away from an optimum if they follow blanket recommendations, but the yield response/decrease would be low.

In the presence of the shortcomings (of blanket recommendation and access to soil testing) and the (transaction) cost associated with more precise information, motives related to "self-protection" and "caution" might be triggered and drive the application of a higher quantity of N fertilizer, with variation depending on risk attitudes (a situation that occurs under expected profit maximization). In what follows, we discuss recommendations that account for behavioral factors influencing fertilizer use decisions and may contribute to reducing emissions from synthetic fertilizer use. A better understanding of the existing problems through a synthesis of the literature will also help develop solutions tailored to eradicate unwanted spillover effects (such as low levels of adoption of improved crop varieties[7] arising from the influence of risk attitude on fertilizer use.

7 For example, in Simtowe (2006), risk aversion toward fertilizer is found to be correlated with low levels of hybrid maize adoption. Thus, there are reasons to contend that risk attitudes toward fertilizer use could be contributing to the low adoption of improved varieties in South Asia.

## Relevance of policy and measures in the reduction of nitrogen emissions from agriculture across South Asia

Policy responses related to fertilizer use in the literature range from extension advice, behavioral nudges, and different types of incentives and regulations. Also, a combination of these interventions has been recommended to change fertilizer decisions. We discuss the different recommendations made across the globe and highlight potential solutions that are likely suitable and relevant for the South Asia context.

The purchase of insurance is a contested measure that both discourages and encourages the over-use of fertilizers (Capitanio et al., 2015). Crop insurance has the potential to drive optimal N fertilizer rates. Irrespective of yield distribution, in the presence of crop insurance, farmers find it optimal to tolerate more risk even if much of this risk is perceived and, thus, choose fertilizer rates accordingly (Capitanio et al., 2015). Huang (2002) also posit that insurance is a reasonable risk management tool to encourage risk-averse farmers to adopt better timing of N fertilizer application as it helps reduce the cost of actual or perceived risk. Performing its core function, easing access to crop insurance in South Asia will increase income in bad years and decrease income in good years. This will "restrain" risk-averse farmers from overweighting the probability of a bad year and underweighting the likelihood of a good year, consequently resulting in more optimal fertilizer application. Therefore, subsidizing insurance premiums for farmers in South Asia may be useful as an incentive for risk-averse farmers to take up crop insurance.

When fertilizer is underutilized due to risk aversion, obtaining fair insurance will increase fertilizer utilization because it will shift risk aversion so that risk-averse farmers will behave similarly to risk-neutral farmers (Kusadokoro, 2010). Sanou et al. (2015) argue that insurance as a risk-spreading instrument could encourage the use of fertilizer among risk-averse farmers. Haile et al. (2020) advocate for weather index-based crop insurance (WICI) as a means of reducing risk aversion since insurance could decrease risk aversion by up to 90% and encourage synthetic fertilizer use. Notably, one pathway through which this could be achieved is that insurance reduces income and consumption variability and consequently reduces the effect of risk aversion.

Gradual rollback on subsidies is reported to have the potential to address fertilizer over-application. Marenya et al. (2014) postulate that fertilizer subsidies encourage increased use of fertilizer by offsetting the financial cost associated with its adoption as well as the risks related to its use. As a result, when fertilizer is obtained at subsidized rates, farmers generally tend to apply more, especially risk-averse farmers. Across South Asia, fertilizer is heavily subsidized. Thus, gradual withdrawal of fertilizer subsidies could curb fertilizer overuse.

However, the rollback of subsidies would not be as effective as repurposing subsides toward improved technologies that increase productivity, improves NUE and reduce emissions.

Environmental taxes based on the polluter-pays principle are, in theory, an effective instrument in reducing emissions but are either not employed or in itself sufficient for reducing agricultural N pollution in South Asian countries (Mahaseth, 2017; Nizami et al., 2021). In many countries, for example, in Nordic countries, regulations have been used to replace taxes. This may be related to the uncertainty on the abatement results achieved *via* restricting fertilizer use by increasing the expenditure associated with its use. The effect of a fertilizer tax will likely lead to varying levels of reduction in fertilizer use depending on the level of risk aversion. Finger (2012) provides empirical evidence that N taxes will induce higher reductions in N use for risk-averse farmers, leading to lower abatement costs for this category of farmers. Therefore, if N taxes are to be used in South Asia, they should be implemented with caution. The impact of reducing N fertilizer with a tax is not uniform across all levels of risk aversion (Meyer-Aurich et al., 2020). Also, Jayet and Petsakos (2013) have shown that outcomes contrary to the aim of introducing the N tax, e.g., an increase in N pollution, are probable under different policy scenarios and at different scales for uniform implementation.

Given that nonpoint source pollution from fertilizer cannot easily be controlled using penalties, farmers in South Asia should be encouraged and supported to voluntarily follow fertilizer recommendations. This could be achieved through increasing avenues for knowledge creation, enhancing the effectiveness of information communication on sustainable N management practices and facilitating the uptake of technologies through extension services.

Another important instrument is command and control *via* regulation either by direct fertilizer regulations that set strict limits to N fertilization per hectare or by controlling N outputs such as maximum ammonia emissions within a defined area (Dalgaard et al., 2014). There may be geographic differences in regulation, for example, with more strict regulation targeting N hotspots, therefore taking the region-specific geology, soil, climate, and ecosystems into consideration (Blicher-Mathiesen et al., 2014). However, non-point pollution sources are challenging to regulate, and the outcome may be disproportionate to the polluter-pays method. For example, if risk-seeking farmers feel they are randomly fined for non-point pollution, such farmers may abate less compared to their risk-averse and risk-neutral counterparts. Such behavior has been observed in experimental studies (e.g., Camacho-Cuena and Requate, 2012). Notably, there are substantial transaction costs with respect to administrating, monitoring and enforcing regulatory instruments (Krutilla and Krause, 2011). Thus, direct regulation may be a challenge to implement in South Asia.

Across South Asia, technologies and management practices (such as precision agriculture) could concurrently reduce production risk and N emissions and variance in gross margin. However, adoption barriers such as initial cost mean farmers are unable to make the change. Improved access to credit is often recommended in many adoption studies. According to Feder (1980), easing farmers' credit constraints results in fertilizer use becoming independent of risk aversion. Access to credit also encourages the adoption of precision fertilizer application techniques such as fertilizer micro-dosing (Sanou et al., 2015). However, we agree with several studies that using credit as a tool to spread risk over time may not be entirely sufficient in situations where risk attitude is a factor and credit adds further elements of risk. Since credit repayment relies on future income, the economic uncertainty is extended into the future (Fontaine and Sindzingre, 1991). Subsidizing specific pollution mitigation technologies is more likely to encourage the adoption of such technologies and lead to significant reductions in N pollution.

Farmers who apply fertilizers before planting tend to apply fertilizers above the recommended rates to minimize the risk of potential losses. Thus, improving access to controlled-release fertilizers could reduce application rates across the region. Another solution is to introduce farmers in South Asia to practices that can reduce the pollution potential of fertilizers, for example, through certain tillage methods. Regarding the issue of risk attitude in the face of adulterated and substandard fertilizers, regular monitoring of fertilizer quality, mainly at the retail level, by governments in South Asia in cooperation with stakeholders in the sector could reduce or eliminate the fraudulent practice of fertilizer adulteration. This will increase trust in fertilizer nutrient content and result in farmers, irrespective of their levels of risk aversion more likely to apply fertilizer at recommended levels.

Recognizing that most inputs such as water, N and phosphorus and other trace nutrients necessary for crop production are complementary, multi-approach measures that take into consideration the risk attitudes of farmers and distribution of returns associated with the use of complementary input can help farmers in South Asia adhere to recommended N application rates. Overall, the preference should be for the most cost-effective, practical and feasible policy or measure or a combination of these. The challenge, however, is assessing risk aversion levels in the field, e.g., by extension officers—a discussion for future studies. However, the literature is vast in this aspect, with suggestions varying from self-report, scales for specific decisions, and behavioral tests to psychometrically valid measures of general risk aversion.

## Conclusion

We review studies that examine the relationship between risk attitudes and fertilizer use. Several studies provide empirical evidence that fertilizer use impacts variability of production risk and that risk attitude could substantially affect optimal fertilizer use. In many cases, the difficulty in predicting actual risk in advance means perceived risk attitude has a considerable effect on fertilizer use. Thus, whether farmers perceive fertilizer as a risk-enhancing or risk-reducing input determines the application practice. We conclude that there is potential for N (particularly $NH_3$ and $N_2O$) emission reductions from agriculture and efficiency improvements through knowledge creation, enhancing the effectiveness of information communication, providing enhanced-efficiency fertilizers, eliminating the fraudulent practice of fertilizer adulteration and subsidizing the cost of adopting sustainable technologies and management practices.

Research, particularly with a focus on South Asia, is needed to provide a deeper understanding of the role risk attitude plays in fertilizer use and the relative importance of risk attitude relative to other factors so that recommendations can be made with more confidence. Notably, there is contention about whether it is actually about risk or the misconception of yield response to N, thus, highlighting the complexity in the relationships between risk attitude and N use. If misconceptions drive fertilizer use, then there is the argument of whether to exploit aspects that target risk attitudes as interventions or aspects that target misconceptions, or both.

A research agenda on risk attitudes and fertilizer use in South Asia should cover the conceptual and methodological gaps highlighted in section Determination of optimal levels of nitrogen fertilization, for example, by estimating response functions with a stochastic plateau that can capture random effects. Besides, progressing beyond a static partial budget analysis should take a central focus than is currently the case. Such static estimations do not account for the effect of uncertainty and the consequent increase in expected profits if farmers use fertilizer above the agronomic recommended rates. Considering that there is a lack of studies examining risk attitude and organic fertilizer use decisions, targeting research to fill this gap will be an important step toward improving environmental and economic sustainability. Further, there is the need to dig deeper into the behavioral factors that influence fertilizer use decisions through experimental and quasi-experimental approaches. Experiments may be a good alternative to isolate and understand the systematic relationship between attitudes, behavior and fertilizer application decisions. Finally, there is the need for future studies to identify the socio-demographic predictors of risk attitudes as it relates to fertilizer use.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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