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How do price (risk) changes influence farmers' preferences to reduce fertilizer application?

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Abstract
The decision of farmers to reduce fertilizer applications and, thus, the achievement of agri-environmental policy goals interacts with market price developments. In this study, we analyze how changes in price levels and volatility over time (i.e., 1991–2006 vs. 2007–2022) affected farmers' preferences to reduce fertilizer application using statistical inferences of stochastic dominances. The analysis considers two cropping systems and fertilizer reduction measures: (i) grassland-based milk production and the use of legumes and (ii) wheat production and the use of variable rate application. We show that the economic value of reducing fertilizer increased over time in both grassland-based milk and wheat production. However, only in the case of wheat production was the reduction in fertilizer application observed as more risk-reducing over time. In contrast, in grassland-based milk production, the co-movement of fertilizer and milk prices canceled out the increase in risk reduction. We conclude that changes in market price, along with agri-environmental subsidies, can increasingly incentivize the reduction of fertilizer use.

KEYWORDS
farm management, fertilizer prices, legumes, precision farming, price risks, risk management, stochastic dominances

JEL CLASSIFICATION
Q11, Q12, Q15

1 | INTRODUCTION

The recent surge in synthetic fertilizer prices (starting in 2021) raised again concerns about farmers' exposure to the risk of market price changes. Rising and fluctuating synthetic fertilizer prices due to changes in energy prices, fertilizer demand, exchange rates, and politics significantly contribute to price risks (Brunelle et al., 2015; Ott, 2012; Rezitis, 2015; Vatsa et al., 2023). Furthermore, fertilizer and agricultural output price risks are expected to increase over time (e.g., due to climate change), causing growing challenges to farmers (e.g., Goodwin & Schnepf, 2000; Komarek et al., 2020; Schaub & Finger, 2020; Schlenker & Roberts, 2009; Schmitt et al., 2022; Ubilava, 2017).

Simultaneously, agricultural policies in Europe aim to increase the environmental sustainability of the

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agricultural sector (e.g., of the EU "Farm to Fork Strategy"), including the reduction of nitrogen runoffs into waterbodies and greenhouse gas emissions due to fertilizer applications (e.g., EU Commission, 2020; Gao & Cabrera Serrenho, 2023; Lüscher et al., 2014; Maaz et al., 2021). The fertilizer reduction potential per cropping system depends both on the reduction per area and the area the cropping system occupies, making both grasslands and wheat fields an important target for agricultural policies (FAO, 2022; FAOSTAT, 2023; Mottet et al., 2017; Sandström et al., 2022). Given that price risks often being the main concern of farmers (Komarek et al., 2020), the achievement of agricultural policy goals of reducing fertilizer application in both grassland and cropland interacts with input and output prices on the market. Changing to low-fertilizer cropping systems can, for example, be a valuable farm management strategy from an economic point of view in light of rising and more volatile fertilizer prices. However, whether the changes in price developments facilitate or hinder the use of new production methods that reduce synthetic fertilizer application by farmers (as required by agri-environmental policies) is poorly understood.

Our study aims to investigate how different market price conditions affect the economic value of changing fertilizer applications. Using input and output price data from 1991 to 2022, we investigate whether changes in market conditions hinder or facilitate farmers' uptake of measures to reduce synthetic fertilizer application and, thus, interact with agri-environmental policy efforts to reduce nutrient surpluses. Our analysis considers two different cropping systems: (i) grassland-based milk production and the use of legumes to (partly) substitute reduction in fertilizes application and (ii) wheat production and the use of precision farming technology, that is, variable rate application, to reduce fertilizer application.

Previous studies examining the relationship between fertilizer application and production risk have focused on grain crops or have been theoretical. Those studies often, but not always, found that high fertilizer applications increase risk and that risk-averse farmers apply less fertilizer (e.g., Babcock, 1992; Finger, 2012; Isik, 2002; Meyer-Aurich & Karatay, 2019; Möhring et al., 2020; Paulson & Babcock, 2010; Rajsic et al., 2009). In addition, the reduction in fertilizer application due to a fertilizer tax increase is higher among risk-averse farmers (e.g., Finger, 2012; Isik, 2002). Another line of study, mostly conducted in North America, assessed the profitability of using legumes in grasslands and showed mixed results (Adjesiwor & Islam, 2016; Adjesiwor et al., 2017; Biermacher et al., 2012; Humphreys et al., 2012). Studies that examined plant diversity in more general terms than in terms of legume proportions have shown that plant diversity increases revenues and reduces risk from grasslands (e.g., Binder et al., 2018; Schaub et al., 2020a, 2020b; Schläpfer et al., 2002). Studies investigating the effect of variable rate application in grain production have shown that it can reduce fertilizer application while maintaining yield (e.g., Argento et al., 2022; Späti et al., 2021). Moreover, Karatay and Meyer-Aurich (2020) showed that using a variable rate application can reduce the downside risk when producing wheat. Nevertheless, whether the cost-saving and the risk reduction justify investment into variable rate application is often questioned (e.g., Argento et al., 2022; Gandorfer & Meyer-Aurich, 2017; Karatay & Meyer-Aurich, 2020; Pannell, 2006; Späti et al., 2021). Therefore, existing studies have outlined that policy incentives, nitrogen taxes, and reductions in the costs of variable rate technologies are needed to make investments in these technologies economically more beneficial (e.g., Argento et al., 2022; Späti et al., 2021).

However, those strands of literature mentioned above, have not addressed so far the impacts of changes in fertilizer prices over time on farmers' decisions to reduce fertilizer application considering risk. Further, the risk management strategy to reduce fertilizer dependencies (e.g., by either using higher legume proportions in grasslands or variable rate application in wheat fields) to cope with price risk due to uncertain prices has not been studied so far. Yet, studying those aspects is particularly important given (i) the current turbulence in agricultural markets affects farmers' preferences with respect to fertilizer input use and (ii) changing input use influences the success of agri-environmental policy efforts. Moreover, because production decisions are determined by changes in input and output prices, it is important to consider not only fertilizer price development in isolation but also the comovement of output (e.g., milk or wheat) and input (e.g., fertilizer) prices, as it can reduce risks, given a natural hedge[1] (e.g., Neyhard et al., 2013).

Our study aims to close these gaps and investigate how changing market price conditions over time influence the economic value of reducing synthetic nitrogen fertilizer application. Thus, it informs whether price developments hinder or promote the adoption of systems with lower fertilizer inputs. Our contribution also shows how a reduction in the use of synthetic fertilizers affects the profits and risks (including downside risks) expected by farmers under different market price conditions. By studying both grassland-based milk and wheat production, we consider two different German market settings and the codevelopment of output prices of those markets with fertilizer prices. Our analysis shows whether reducing

[1] In the context of output and input prices, natural hedge describes the positive correlation between those prices. Natural hedge is often considered to be imperfect, that is, correlation <1.

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fertilizer dependency can be increasingly used as a risk-reducing instrument by farmers and whether current market price developments can influence the outcomes of agri-environmental policies.

For the analyses, we employ a stochastic dominance framework and use the consistent test for stochastic dominance proposed by Barrett and Donald (2003). Using the stochastic dominance framework allows us to model farmers' preferences for different production choices without making specific assumptions about farmers' risk preferences and consider downside risk. Moreover, the test proposed by Barrett and Donald (2003) allows us to overcome major restrictions of the framework, such as the binary state of dominance (yes/no) and uncertainty resulting from finite sample distributions. Furthermore, we combine price data for studying market trends and experimental field data for studying the relationship between fertilizer input and yields in grassland and wheat production considering the use of sustainable production techniques. The use of experimental data allows us to understand causal effects of sustainable production techniques on yields, as endogenous selection of management to fields (a common issue when using farm-level data) can be ruled out. We combine Swiss experimental data on grassland and wheat production, representing the environmental production conditions in mid-European lowlands such as found in Germany (Argento et al., 2021; Beck et al., 2018; Kirwan et al., 2007; Metzger, 2018; Metzger et al., 2012), with German price data, as German market conditions are more representative internationally and Switzerland does not produce synthetic fertilizer, but imports around 50% of its fertilizer from Germany (FOAG, 2023). Additionally, we conduct a sensitivity analysis to check whether our conclusions remain valid when using alternative price origins.

For grassland-based milk production, we find that changes in price regimes over time (i.e., 1991–2006 vs. 2007–2022) made the reduction of synthetic nitrogen fertilizer application more attractive. However, the reduction did not become more attractive over time for risk-averse farmers compared to risk-neutral farmers. In our analysis of wheat production, we also find that the reduction of synthetic nitrogen fertilizer application was more attractive under the more recent price regime, but in this production setting, even more so for risk-averse farmers. Our results highlight how developments in input and output prices can affect the achievement of agri-environmental policy goals and that considering the comovement of input and output prices remains important when assessing price risks and farmers' decisions.

The rest of the paper is structured as follows. Section 2 discusses the relevance of fertilizer reduction in grasslands and wheat fields. Section 3 presents the conceptual background of our analysis. Section 4 describes the data. Section 5 provides an overview of the price developments from 1991 to 2022 and motivates our price regime selection. Section 6 describes our empirical approach, and Section 7 presents our results. Finally, Section 8 summarizes and concludes the study.

2 | THE RELEVANCE OF REDUCING FERTILIZER APPLICATION IN GRASSLAND AND WHEAT PRODUCTION

Various options exist across cropping systems to reduce synthetic fertilizer application, such as keeping the same crop but using less fertilizer (e.g., by accepting lower yields or using precision farming technologies), planting cover crops, changing to less fertilizer demanding crops (e.g., soybeans or peas instead of winter wheat or rapeseed), or using plant diversity to supply the required nutrients (e.g., legume–grass swards instead of pure grass swards) (e.g., Argento et al., 2022; Blanco-Canqui et al., 2012; Lüscher et al., 2014; Sinaj et al., 2017; Smith et al., 1987). In our paper, we focus on (i) grassland-based milk production and the use of legumes to (partly) substitute reduction in fertilize application and (ii) wheat production and the use of variable rate application to reduce fertilizer application.

2.1 | Grassland production

Grasslands cover large shares of the agricultural area, contributing considerably to the provision of feed to ruminants (FAO, 2022; Mottet et al., 2017; Sandström et al., 2022). These grasslands, especially less intensively managed grasslands, not only provide forage but also are important for providing a range of other ecosystem services (Bengtsson et al., 2019; Buisson et al., 2022; Le Clec'h et al., 2019). In Germany and Switzerland, for example, grasslands cover about 28% and 70%, respectively, of the agricultural area (DeStatis, 2022a, 2023; FOAG, 2022), of which, temporary grasslands are about 15% and 16%, respectively (DeStatis, 2022a, 2023; FOAG, 2022). Therefore, the extent of grassland area makes grassland an important target for fertilizer reduction. Moreover, studying price risk originating from fertilizer price uncertainty in grassland production is also highly important, as farmers use synthetic nitrogen fertilizer across the globe in grasslands to increase yields (often to complement organic fertilizer), and the expenses for synthetic fertilizer can considerably contribute to farmers' variable production costs (Bouwman et al., 2002; Dangal et al., 2019; Einarsson et al., 2021; KTBL, 2023; LfL, 2023; Li et al., 2013; Pilgrim et al., 2010; Schils et al., 2005; Xu et al., 2019). The recommended

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N fertilization of grasslands varies depending on the number of cuts, ranging for intensively managed grasslands between 180 and 330 kg N per ha (Agrarheute, 2011; Galler, 2010; Huguenin-Elie et al., 2017).

Reducing synthetic nitrogen fertilizer use, for example, by substituting it with higher legume proportions in grasslands (e.g., Lüscher et al., 2014; Nyfeler et al., 2009; Suter et al., 2015), can be an option to partly offset the yield losses. Therefore, it can be a price risk mitigation strategy against rising and volatile fertilizer prices and reducing environmental pollution.[2] Moreover, a positive effect of legumes on yields is observed across a range of environmental conditions (e.g., Suter et al., 2015). While including legumes was found to have a positive effect on yields in grasslands with varying levels of fertilizer application, high application levels reduce legumes in grasslands over time and, in turn, the effect of legumes on yield (Finn et al., 2013; Lüscher et al., 2014; Nyfeler et al., 2009).

2.2 | Wheat production

Wheat is the most important cereal produced in Europe (FAOSTAT, 2023). In Germany and Switzerland, for example, wheat fields cover about half of the total area of cereal production (FAOSTAT, 2023). In the production of arable crops, including wheat, farmers globally use synthetic nitrogen fertilizer to increase yields (e.g., Bouwman et al., 2002; Einarsson et al., 2021). Therefore, the fertilizer management of wheat fields significantly contributes to the sustainability of agricultural production and, thus, to the interest of agri-environmental policy. Next to this, understanding how changes in prices influence profits and price risk is important for farmers' risk management, given its significant contribution to the variable costs of producing wheat (e.g., KTBL, 2023; LfL, 2023). The recommended application of nitrogen in Germany and Switzerland is around 140–172 kg N per ha (KTBL, 2023; Sinaj et al., 2017).[3]

The use of variable rate application of synthetic nitrogen fertilizer as a precision farming technology is frequently discussed in the literature to reduce the amount of fertilizer in the production of cereals, such as wheat, while maintaining yields (e.g., Finger, 2023; Finger et al., 2019). When using variable rate application technologies, fertilizer is not uniformly applied across areas (i.e., fields or subfields); however, information about plant and environmental conditions is used to customize fertilizer application within an area. For example, multispectral images of plants taken by drones can be used to assess the nitrogen status of a plant, or soil samples can be taken to assess the soil's mineral nitrogen status (Argento et al., 2022; for an overview about variable rate application technologies, see Späti et al., 2021). In general, the reduction potential of fertilizer due to variable rate application increases with the heterogeneity of the areas (e.g., Späti et al., 2021).

3 | CONCEPTUAL BACKGROUND

In this section, we present a conceptual model to describe how changes in (fertilizer) prices over time can influence farmers' preferences when risk is considered. We use this conceptual model as a basis for the empirical analysis (see *Section 6*) of two cropping systems that use sustainable production techniques to (partly) replace fertilizer applications. First, we assess grassland-based milk production and the substitution potential of synthetic fertilizers with legumes. Second, we assess wheat production and the substitution potential of synthetic fertilizer by using a variable rate application. Following the production systems to be analyzed, we focus on milk or wheat prices as output prices.

3.1 | The model setup

Farmer's profit, π, from agricultural production, depends on revenues, R, (from selling agricultural outputs) and costs, C (for inputs such as fertilizer, seeds, pesticides, or technology):

$$\pi = R(q_Y, p_Y) - C(q_X, p_X) \tag{1}$$

where q_Y and p_Y indicate the output quantities and prices, respectively, and q_X and p_X the input quantities and prices, respectively. Thus, revenues of output Y are given by $r_Y = q_Y p_Y$ and costs of input X are given by $c_X = q_X p_X$.

Given our focus on synthetic fertilizer as input price and milk and wheat prices as output prices, we assume that synthetic fertilizer, milk, and wheat prices are stochastic, while yields and other costs (such as machinery costs) are deterministic.[4] This stochasticity of prices represents price

[2] Including legumes in grasslands can increase yields as they fix nitrogen from the air, and including different plant species in grasslands can result in resource partitioning effects because different plants need different resources and take them from different resource pools (e.g., Lüscher et al., 2014; Loreau & Hector, 2001; Carlsson & Huss-Danell, 2003).

[3] 172 kg N per ha is based on fields with medium potential wheat yields (KTBL, 2023).

[4] Focusing on stochastic prices allows us to isolate the effect of price uncertainty on costs, revenues, and risks. This setup is compared to other studies that investigated the influence of stochastic yields on production risk, keeping prices deterministic (e.g., Baumgärtner & Quaas 2010; Paulson & Babcock, 2010; Rajsic et al., 2009; Schaub et al., 2020a).

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risks to farmers.[5] In line with the focus of our analysis, we can simplify our profit of interest to the following:

$$\pi_m = r_m(q_m, p_m) - c_f(q_f, p_f) \quad (2)$$

$$\pi_w = r_w(q_w, p_w) - c_f(q_f, p_f) \quad (3)$$

where subscript m indicates milk, f fertilizer, and w wheat. For simplicity, we refer in this paper to π_m and π_w as profits even if they do not comprise all sources of revenues and costs.

Farmers' valuation of changing synthetic fertilizer and milk or wheat prices depends on their influence on farmers' utility. Thus, on the influence on the expected level of costs and revenues, and, if farmers are not risk-neutral, on its risk (Chavas, 2004). We assume that farmers' utility function, $U(\cdot)$, to be monotonic ($U' > 0$) and reflect risk aversion ($U'' < 0$) (e.g., Iyer et al., 2020). Thus, given our focus on the influence of changing input (i.e., synthetic fertilizer) and output (i.e., milk or wheat) prices on reducing synthetic fertilizer application, we can express the main units of interest in our analysis as $\frac{\partial U(\partial \pi_m/\partial f)}{\partial t}$ and $\frac{\partial U(\partial \pi_w/\partial f)}{\partial t}$, where t indicates the change in time.

3.2 | Stochastic dominance to assess scenarios

We use the stochastic dominance framework to evaluate the implications of changes in prices on farmers' choice to reduce fertilizer input in different time periods, considering both expected profits and price risks. Henceforth, farmers' choices in different periods are called "scenarios." Using stochastic dominance, we can model farmers' preferences for different scenarios without making specific assumptions about the degree of farmers' risk aversion (e.g., compared to using certainty equivalents) (Chavas, 2004).

Stochastic dominance builds on the dominance of one scenario, a, over another scenario, b, using their respective cumulative density function (CDF) (e.g., Chavas, 2004). Stochastic dominance includes different orders of dominance, most notably first- and second-order stochastic dominance. First-order dominance as an assessment tool only requires that farmers are nonsatiated (i.e., $U' > 0$), and second-order stochastic dominance only further assumes that farmers are risk averse (i.e., $U' > 0$ and $U'' < 0$). Using those two orders of stochastic dominance, farmers' preferences for different scenarios with respect to a quantity (here h) can be evaluated. Scenario a "first-order dominates" scenario b if its CDF, $F_a(h)$, is always right of or equal to the CDF of scenario b, $F_b(h)$ (Chavas, 2004):

$$F_a(h) \le F_b(h) \text{ for any } h \quad (4)$$

Scenario a "second-order dominates" scenario b if the total area under $F_a(h)$ is at any value of h^* smaller than or equal to the total area under $F_b(h)$ (Chavas, 2004):

$$\int_{-\infty}^{h^*} F_a(h)\, dh \le \int_{-\infty}^{h^*} F_b(h)\, dh \text{ for any } h^* \quad (5)$$

Thus, one scenario can second-order dominate another scenario only if the downside risk is also lower.

Both first- and second-order stochastic dominance are influenced by the difference in the expected mean of the scenarios. However, we are also interested in farmers' preferences between the two scenarios, depending only on their price risks. Thus, we modify the second-order stochastic dominance by centering each of the observations of the scenarios (i.e., $\bar{h} = h - E_j(h)$, where $E()$ is the expectation operator and j indicates the scenario). We call this "mean-independent second-order stochastic dominance":

$$\int_{-\infty}^{\bar{h}^*} F_a(\bar{h})\, d\bar{h} \le \int_{-\infty}^{\bar{h}^*} F_b(\bar{h})\, d\bar{h} \text{ for any } \bar{h}^* \quad (6)$$

4 | DATA

To understand how different price regimes influence farmers' preferences concerning changes in synthetic fertilizer application and the use of alternative sustainable production techniques, we utilize the following three main data sources for our analysis: (i) experimental grassland yield data from Switzerland, (ii) experimental wheat yield data from Switzerland, and (iii) price indices and real prices of synthetic fertilizer, milk, and wheat from Germany. The production and price data used reflects mid-European environmental lowland production and European market conditions. More precisely, German market prices for fertilizer represent the European market and are relevant for the Swiss market, as no synthetic fertilizer is produced in Switzerland and about 50% of Swiss fertilizer imports come from Germany (FOAG, 2023).[6] The experimental data

[5] The main risks in agriculture can be grouped into production, market, institutional, personal, and financial risks (Komarek et al., 2020). Market risks comprise price risks that originate from price uncertainty and cause uncertainty of costs and revenues.

[6] Additionally, we use Swiss import prices of fertilizer, milk, and wheat in a sensitivity analysis to verify the conclusions from our analysis using alternative price origins.

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represent environmental production conditions in mid-European lowlands, such as found in Germany (Argento et al., 2021; Beck et al., 2018; Kirwan et al., 2007; Metzger, 2018; Metzger et al., 2012 Figure S1). Using experimental data to understand the influence of fertilizer reduction and the use of sustainable production techniques on yields has the advantage that they allow for a causal assessment of those factors, which is hardly possible when using data from nonexperimental farm-level settings because of endogenous selection of management to fields.

4.1 | Grassland yield data

We use forage yields (i.e., annual dry matter biomass ton per ha) and quality (i.e., annual metabolizable energy content MJ per kg, ME) data from 2004 to 2005 from a Swiss grassland experiment representing productive agricultural conditions in mid-European lowlands (Kirwan et al., 2007; Nyfeler et al., 2009; Suter et al., 2021). Intensively managed grasslands are usually resown every two to five years in practice (e.g., DAFA, 2015, Suter et al., 2017). The experiment consisted of 78 plots that included randomly assigned variations in the sown proportion of legumes[7] (between zero and one divided into five levels, i.e., 0, .2, .5, .8, and 1) and fertilizer application levels (i.e., 50, 150, and 450 kg N per ha and year) (Nyfeler et al., 2009, Suter et al., 2021). During the experiment, no weather shocks were observed (Nyfeler, 2009). For additional details about the experiment, see Text S1 or Nyfeler et al. (2009) and Suter et al. (2021).

We assume that farmers consider quality-adjusted yields (i.e., forage yields × forage quality) expressed in milk production potential yields as targets when choosing between different farming practices. We express the milk production potential yields as the marginal gain of using forage from sown grasslands. Thus, we focus on the extra marginal milk production resulting from feeding forage and consider that other feeds already cover the maintenance of cows. We compute the milk production potential kg per kg dry matter biomass, MPP, as (Huguenin et al., 2021; Jans et al., 2015; Tonn et al., 2021):

$$MPP = ME\ 0.30216/3.14 \tag{7}$$

where 0.30216 is the conversion of ME MJ per kg to net energy for lactation MJ per kg (Tonn et al., 2021) and 3.14 conversation rate of net energy for lactation MJ per kg to MPP kg per kg dry matter biomass (Huguenin et al., 2021; Jans et al., 2015).[8]

4.2 | Wheat yield data

We use data on yields of winter wheat (i.e., *Triticum aestivum*) under uniform standard rate fertilizer application and variable rate application from an experiment conducted in northeast Switzerland in the growing seasons 2017–2018, 2018–2019, and 2019–2020 in Switzerland (see Argento et al., 2021, 2022). The experiment was set up within a farm setting that considers a crop rotation typical of mid-European agriculture, including cereals, sugar beet, rapeseed, and grassland. The environmental condition at the experimental site also represents a typical agricultural condition in the mid-European lowlands (Argento et al., 2021; Beck et al., 2018; Metzger, 2018; Metzger et al., 2012). In all growing seasons, wheat grain dry matter biomass (kg per ha) was measured, and in the last two growing seasons, grain protein content (%) was also measured. The total number of observations was 24, 42, and 40 for the growing seasons 2017–2018, 2018–2019, and 2019–2020, respectively. Lastly, during the growing seasons 2017–2018 and 2019–2020, spring droughts occurred (Argento et al., 2021, 2022).

The uniform standard rate application of N fertilizer in the first growing season (2017–2018) of the experiment was 116 kg N per ha, and in the second (2018–2019) and third growing seasons (2019–2020), it was 154–155 kg N per ha (Argento et al., 2022). The fertilization recommendations in Switzerland and Germany are similar, with 140 and 172 kg N per ha, respectively (KTBL, 2023; Sinaj et al., 2017).[9] Under the variable rate application, N fertilizer in the range of 80–155 N per ha was applied to each plot based on multispectral images and soil data. Thus, under variable rate application, the fertilizer application varied across plots. In both the standard and the variable rate appli-

[7] The legume and grass species considered here are red clover (*Trifolium pratense*), white clover (*Trifolium repens*), perennial ryegrass (*Lolium perenne*), and cock's-foot (*Dactylis glomerata*). These species are commonly used in mixtures for intensively managed grasslands, and they were shown to have no or very negligible differences in their prices (Schaub et al., 2021). Moreover, we are primarily interested in how the profit changes due to fertilizer reduction over time. Thus, differences in costs—as long as they are relatively constant—are not important for our results.

[8] The values represent milk production potential under optimal conditions for cows with a live weight of 630 kg, 7000 kg energy-corrected milk production potential, and after the second lactation (Huguenin et al., 2021). We note that we use a conversation rate of net energy for lactation MJ per kg to milk production potential of 3.14, following Jans et al. (2015) and AGFF (2021); while Tonn et al. (2021) use a conversation rate of 3.284 as the energy requirement to produce 1 kg of milk. Furthermore, we note that the average metabolizable energy content is based on that of the second and fourth harvests (see Suter et al., 2021 for details). This should not affect our results, as we focus on comparing changes over time.

[9] 172 kg N per ha is based on fields with medium potential wheat yields (KTBL, 2023).

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cation, plots were fertilized three times in one growing season.

4.3 | Price data

We utilize 3-monthly price indices of synthetic fertilizer in Germany from January 1991 to July 2022 (DeStatis, 2022b, 2022c).[10] Next, we also use monthly price indices of milk, wheat, and consumer products for the same period (DeStatis, 2022b, 2022c).[11] Given that we focus on price developments over time, we consider that price indices reflect those well, particularly because milk and wheat are rather homogenous products (as compared to rather heterogeneous products, for example, horticultural goods).[12]

We used the consumer price index to convert the nominal real price indices of fertilizers, milk, and wheat into real price indices. Next, we applied linear interpolation to get from a 3-monthly to monthly synthetic fertilizer price index to obtain the same resolution for the fertilizer, milk, and wheat price index. We run a placebo test to check the influence of the interpolation. To this end, we used the same 3-monthly time resolution for the milk and wheat price index, as for the fertilizer price index, and interpolated them to a monthly resolution. The interpolated values are quite similar (Table S1).[13]

Furthermore, we used the January 2015 fertilizer price of calcium ammonium nitrate (27% N) of 27.9 euros per 100 kg to transform the real price index series into a monetary real price series.[14] Next, we used the milk and wheat prices of 29.8 and 17.0 euros per 100 kg, without taxes, for January 2015 to do the same transformation for the real milk and wheat price index (FAOSTAT, 2023; Federal Office for Agriculture and Food, 2022).

[10] The synthetic fertilizer price index comprises different synthetic fertilizers and but focuses to a very high degree on N-fertilizer (DeStatis, 2022b; Eurostat, 2002). Thus, we consider that the index is representative for the general price movements of N-fertilizer.

[11] Consumer prices are available only from 1991 onwards.

[12] Considering that price movements (and comovements) differ across space, one could expect that regional prices are more volatile than national price indices. Therefore, we estimate in our analysis below rather a lower bound of the risk-reducing effect of reducing fertilizer application.

[13] If the interpolation would affect the results of our scenario analysis, it might lead to estimating the lower bound of the risk-reducing effect of fertilizer reduction. However, next to the placebo tests we also observe that fertilizer prices generally show less intra-annual seasonal variation than wheat and milk prices (Figure 1), which would further reduce the potential effect of the interpolation on our results.

[14] The price is taken from the Rheinland-Pfalz Chamber of Agriculture (2015) and is without taxes and Ex Works for a purchasing quantity of 10 tons in Hesse.

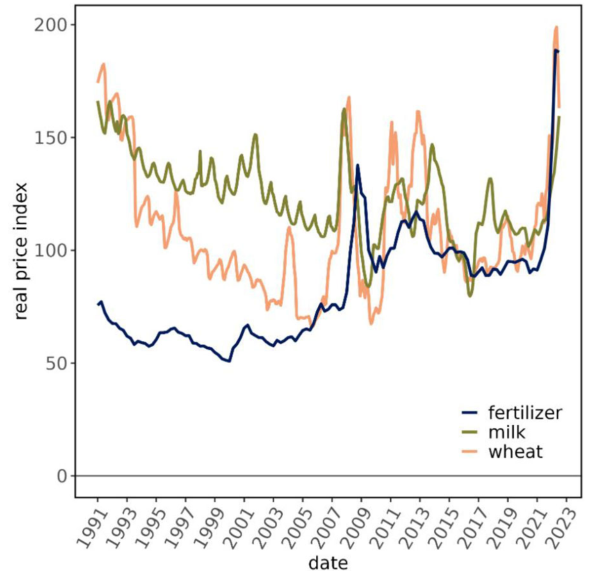

FIGURE 1 Price indices of synthetic fertilizer, milk, and wheat from 1991 to 2022.

5 | MARKET PRICE DEVELOPMENTS OVER TIME

In this section, we describe how market prices and price risk developed in Germany between 1991 and 2022 (Figure 1). Real fertilizer prices slightly decreased between 1991 and 2002 and have increased since then in Germany. Stronger increases have occurred, especially since 2006, with two spikes (2008–2010 and since late 2021). By contrast, real milk prices decreased between 1991 and 2006, and have stayed at a similar level since then. Real wheat prices also decreased in the 1990s until the beginning of the 2000s; however, the decrease in wheat prices was stronger than the decrease in real milk prices. Since then, the level of real wheat prices has not shown a particular trend.

The volatility of synthetic fertilizer prices increased over time: while the variance of the synthetic fertilizer prices index was 33 from 1991 to 2006, it was 365 from 2007 to 2022, representing a +1016% increase in the variance (Table S1). This change in the variance of synthetic fertilizer prices over time was higher than for the price index of milk, which was +29%. Moreover, for the wheat price index, the variance even decreased over time, that is, by −21%.[15] This development of the variance was characterized by a strong decrease in wheat prices over a long time. However, we still observe that the variance in wheat prices index in the period from 2007 to 2022 was with 706 higher than the variance of fertilizer and milk price index with 365 and 270, respectively. Furthermore, while synthetic fertilizer prices

[15] The coefficient of variation changed by +105%, +29%, and −16% for synthetic fertilizer, milk, and wheat price indices, respectively, over time.

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were correlated with both the price of milk and wheat, the comovements were not perfect (Table S2).

The development of fertilizer, milk, and wheat prices reflects developments in market and policy conditions. For instance, higher milk price volatility also reflects the liberalization of the milk market in Germany (e.g., BMEL, 2021; Philippidis & Waschik, 2019). The liberalization of the milk market was mapped out in 2003 at the European Union level and gradually implemented, with important liberalization steps in 2008 and 2009 (e.g., Philippidis & Waschik, 2019). Another example is the 2007–2008 world food price crisis that led to sharp price surges of agricultural commodities, such as wheat, in Germany (Figure 1; e.g., Headey & Fan, 2008).

Considering the development of prices over time, we split for our subsequent analysis the price time series into two periods of equal length based on the available price data (i.e., from 1991 to 2022) and a shift in fertilizer prices (i.e., from low and less volatile between 1991 and 2006 to high and more volatile between 2007 and 2022).

6 | EMPIRICAL APPROACH

Our empirical approach consists of two steps. In the first step, we estimate the effects of changing fertilizer application on yield in forage and wheat production, when sustainable production techniques are used. These estimates are used in a second step, where we model farmers' preferences about the reduction of synthetic fertilizer application when fertilizer and milk or wheat prices change in levels and volatility over time.

6.1 | Estimating yield effects

6.1.1 | Yield effects in grassland-based milk production

We estimate the influence of reducing synthetic nitrogen fertilizer input on milk production potential yields and the substitution potentials between using synthetic fertilizer and legumes following the production function:

$$q_{gi} = \beta_0 + \beta_1 f_i + \beta_2 f_i^2 + \beta_3 k_i + \beta_4 k_i^2 + \beta_5 f_i k_i + \beta_6 f_i k_i^2 + \beta_7 d_i + \beta_8 v_i + e_i \quad (8)$$

where the index g indicates that q_g are milk production potential yield from grassland and the index i indicates the plot. Further, f is the synthetic fertilizer level, k is the sown legume proportion, d is a dummy variable indicating high compared to low sowing density, v indicates the year, and e is the robust error term. Our model specification considers that milk production potential yields can first increase and then decrease with increasing fertilizer levels, as well as legume proportions (e.g., Aghajanzadeh-Darzi et al., 2017; Nyfeler et al., 2009; Suter et al., 2015).[16] Moreover, it considers that the effects of fertilizer and legume depend on each other, as it was previously shown that the legume effect decreases with fertilizer level (e.g., Nyfeler et al., 2009; Suter et al., 2015).

Furthermore, we use the estimates to predict the milk production potential yields for a range of legume proportions and synthetic fertilizer applications to assess the implications of reducing synthetic fertilizer and the substitution potentials of the different legume proportions. We consider a range from 0 to 180 kg N per ha for the prediction. In particular, we consider the five equally distributed levels of 0, 45, 90, 135, and 180 kg N per ha. The upper limit follows the upper end of the recommendation for intensively managed grasslands by Huguenin-Elie et al. (2017), that is, 180 kg N per ha.[17] All application levels below 180 kg N per ha represent reduction scenarios.

6.1.2 | Yield effects in wheat production

We estimate the influence of using variable rate application on wheat yields and synthetic fertilizer application using a nonparametric Student's t-test. In particular, we compare the wheat yield, q_w, protein content, q_c, and fertilizer application, q_f, under uniform standard rate application, sr, and the use of variable rate application, vr, i.e.

$$\Delta q_w^{sr,vr} = q_w^{vr} - q_w^{sr} \quad (9)$$

$$\Delta q_c^{sr,vr} = q_c^{vr} - q_c^{sr} \quad (10)$$

and

$$\Delta q_f^{sr,vr} = q_f^{vr} - q_f^{sr} \quad (11)$$

respectively. Δ indicates the difference between uniform standard rate application and the use of variable rate application. As described in the data section, uniform standard

[16] Given that we use experimental data with two varying inputs (i.e., synthetic fertilizer and legume share), we tested different model specifications with respect to those two inputs (i.e., $f + f^2$, $f + \log(f)$, and $f + f^{0.5}$ and $k + k^2$ and $k + k^{0.5}$) using the Akaike information criterion.

[17] While we consider an upper limit of 180 kg N per ha higher recommended N applications in intensively managed grasslands still exist (Agrarheute, 2011; Galler, 2010).

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rate application and the use of variable rate application are the treatments of the experiment.

Furthermore, we split the data into two samples, as in the harvesting period 2018–2019, the fertilizer application of the uniform standard rate application was lower (i.e., 116 kg N per ha) compared to the higher fertilizer application levels in the harvesting periods 2019–2020 and 2020–2021 (i.e., 154–155 kg N per ha) (Argento et al., 2022).

6.2 | Scenario analysis—assessing the economic value of reducing fertilizer application

In this section, we first describe how we analyze the economic value of reducing synthetic fertilizer applications under different price regimes. In doing so, we show whether market price developments affect farmers' preferences with respect to input use and discuss whether these developments facilitate or hinder the achievement of agri-environmental policy goals. Second, we present the econometric approach that is used for the scenario analysis.

6.2.1 | Overview of the different scenarios

First, we start the overview of the scenarios by describing our analysis of grassland-based milk production (see Table 1). Second, we describe the analysis of wheat production. Third, we describe an analysis that is independent of output quantities and prices by focusing only on synthetic fertilizer costs instead of profits. The latter allows us to identify the effect of the comovement of prices on farmers' preferences.

Grassland-based milk production

In *Analysis 1*, we assess differences in the economic value of reducing synthetic fertilizer application between two price regimes by comparing changes in expected profits from grassland-based milk production and fertilizer price risks using (i) the price regime from 1991 to 2006 and (ii) the price regime from 2007 to 2022.[18] In other words, the two price regimes reflect changes in prices over time. Furthermore, in *Analysis 1*, we consider different degrees of fertilizer reductions, ranging from −180 to −45 kg N per ha based on recommended N-application in grasslands, as described in *Section 2.1*. Note that we always assume that farmers maximize their yields using the optimal legume proportion.

With *Sensitivity Analyses 1*, we test the sensitivity of the results of *Analyses 1* by considering an alternative development of milk prices. In particular, we assume that milk prices developed as wheat prices did over the same time period.

Wheat production

Analysis 2 refers to wheat production and is carried out in the same way as *Analysis 1* of grassland production. For wheat production, we assume either the use of uniform standard fertilizer application or variable rate application. Thus, we consider a reduction potential of −36.27 kg N per ha (see Section 7.1.2). Furthermore, by conducting *Sensitivity Analysis 2*, we analyze how profit and price risks would have changed over time if wheat prices had developed as milk prices did.

Cost perspective

Finally, in *Analysis 3*, we study how the economic value of reducing synthetic fertilizer application changed over time when only the synthetic fertilizer costs are considered, not revenues. Thus, the analysis provides insights into the importance of considering the comovement of prices (which is considered in *Analysis 1* and *2*). Moreover, given that this analysis does not include output prices and quantities, it is not specific to any production system (e.g., wheat or grassland-based milk production), and it only depends on the reduction potential. In *Analysis 3*, we use the same range of synthetic fertilizer reduction levels as in *Analysis 1* to capture a wide variety of reduction potentials.

6.2.2 | Statistical inference

For both cropping systems and across all scenarios, we estimate whether scenario *a* dominants *b* (and vice versa) following the consistent tests for stochastic dominance proposed by Barrett and Donald (2003). The test for stochastic dominance allows for statistical inference for the first- and second-order dominance of samples that are finite and have different sample sizes. Moreover, the test overcomes two major restrictions of stochastic dominance testing: a binary state of dominance (yes/no) and uncertainty resulting from observations of the sample distribution. In our main analysis, we estimate Barrett and Donald's (2003) Kolmogorov–Smirnov type tests based on "bootstrapping 2".[19] Additionally, we check the sensitivity

[18] We assume that farmers substitute only synthetic and not organic fertilizers. We note that assuming that farmers use both synthetic and organic fertilizers would not change the general results of our findings but the magnitude of the effects.

[19] We used a bootstrapped-based test as it is less restrictive in its application and requires fewer assumptions about the distribution to compute

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TABLE 1 Overview of the scenario analysis and its specifications.

Analysis	Specification: Scenario	Specification: Reduction levels	Specification: Price period	Research question
Grassland-based milk production[a]				
Analysis 1	Scenario a	Synthetic fertilizer reduction from −180 to −45 kg N per ha[b]	1991–2006	How did the economic value of reducing synthetic fertilizer change over time in grassland-based milk production considering the use of legumes to (partly) substitute fertilizer reduction?
	Scenario b		2007–2022	
Sensitivity Analysis 1	Same as *Analysis 1* but considering that milk prices had developed as wheat prices did.			How do the answer to *Analysis 1* change when we assume that milk prices had developed as wheat prices did?
Wheat production				
Analysis 2	Scenario a	Synthetic fertilizer reduction of −36.27 kg N per ha[c]	1991–2006	How did the economic value of reducing synthetic fertilizer change over time in wheat production considering the use of variable rate application?
	Scenario b		2007–2022	
Sensitivity Analysis 2	Same as *Analysis 2* but considering that wheat prices had developed as milk prices did.			How do the answer to *Analysis 2* change when we assume that wheat prices had developed as milk prices did?
Cost perspective				
Analysis 3	Scenario a	Synthetic fertilizer reduction from −180 to −45 kg N per ha	1991–2006	How did the economic value of reducing synthetic fertilizer change over time, considering only expected costs and fertilizer price risks (but not output price developments), and a range of synthetic fertilizer reduction scenarios?
	Scenario b		2007–2022	

[a]Note that we assume a legume proportion that maximizes milk production potential yields.
[b]Reduction compared to the baseline of 180 kg synthetic N per ha.
[c]Reduction compared to the baseline of 154.27 kg synthetic N per ha.

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of our results using the test based on "bootstrapping 1". We describe both tests in detail in Text S2. For both tests, we draw 100 samples in the bootstrapping procedures.[20]

The null hypothesis in both tests is that dominance cannot be rejected. Thus, we reject that a dominants b at the level z, where $p < z$. Given the null hypothesis, we always need to check both directions of dominance, that is, if a dominates b and if b dominates a (see Barrett & Donald, 2003 for details). We implemented the bootstrapped Kolmogorov–Smirnov type tests in the R package "stodom" (Schaub, 2024).

Furthermore, next to the consistent tests for stochastic dominance, we test for differences in the expected mean between scenarios a and b using a nonparametric test, that is, a Student's t-test.

7 | RESULTS

7.1 | Yield effects

7.1.1 | Yield effects in grassland-based milk production

Here, we present the effects of synthetic fertilizer use and legumes on milk production potential yields (Figure 2). For grasslands without legumes, that is, the legume proportion of zero in Figure 2, the results show that decreasing the input of synthetic nitrogen fertilizer from 180 (yellow line) to 135 N per ha (light green line) and 180–45 N per ha (blue line) reduces yields by 9% and 27%, respectively. The differences between yields for different synthetic nitrogen levels become smaller with increasing legume proportions. This is because the N-fixating effect of legumes decreases with higher overall synthetic nitrogen levels. Thus, optimal levels of legume proportions in grassland with respect to milk production potential yields vary with synthetic nitrogen level (black dots in Figure 2 and Table S3; note that higher synthetic nitrogen levels reduce the legume proportion in grasslands over time, which would further reduce the effect of legumes; e.g., Finn et al., 2013; Lüscher et al., 2014; Nyfeler et al., 2009).

Furthermore, the results show that increasing the legume proportion can substitute for synthetic fertilizer application levels when considering milk production potential yields. Figure 2 shows three substitution possibilities (dashed lines). For example, increasing the legume proportion to .12 in grasslands with a synthetic fertilization level of 45 kg N per ha can lead to the same yields as pure grass swards with a synthetic fertilization of 180 kg N per ha and year.

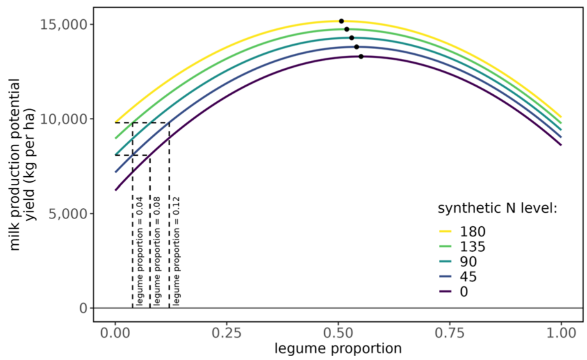

FIGURE 2 Predicted milk production potential yields depending on legume proportion and synthetic fertilizer application.

Note: The dashed lines indicate three examples of substitution potentials. The black dots indicate the legume proportion per synthetic nitrogen (N) level with the maximum milk production potential yields. Predictions are based on the model results of Equation (8), considering high sowing density and the year 2004 (see Table S4).

7.1.2 | Yield effects in wheat production

Here, we present our estimation results of how using variable rate application instead of uniform standard application changes wheat yield, protein content, and synthetic fertilizer use (see also results in Argento et al., 2022). We find that when the uniform standard application rate is low (i.e., 116 kg N per ha), using variable rate application reduces the total amount of fertilizer applied on average by 9% (i.e., 10.67 kg N per ha; Table S5). However, the reduction potential remains uncertain, given a p-value of .34 when considering the low uniform standard application rate. In contrast, given a higher uniform standard rate application (i.e., 154–155 kg N per ha), we find a clear effect of using variable rate application to reduce synthetic fertilizer input (Table S5). In particular, we find an average reduction potential of 24% (i.e., 36.27 kg N per ha). Considering this reduction potential, the results show no clear impact on the yield quantity and quality (Table S5; see also results in Argento et al., 2022). Consequently, in our scenario analysis in *Section 7.2.2*, we consider only the case in which uniform standard rate application was initially high and variable rate application offered a fertilizer reduction potential of −36 kg N per ha without affecting yield quantity and quality.

the test statistic than the Monte-Carlo methods proposed by Barrett and Donald (2003).

[20] We consider a bin size of one to compute the empirical CDFs, that is, steps of one Euro per ha, which provided us a good resolution given the range of our data.

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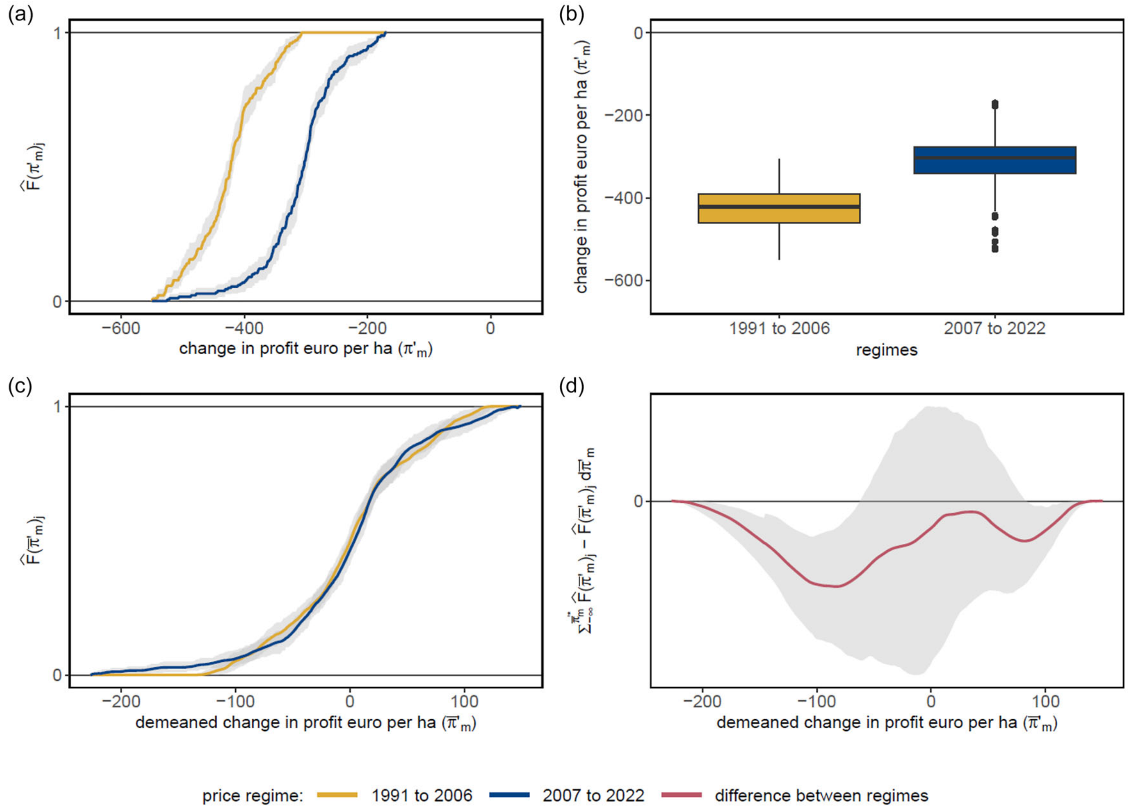

FIGURE 3 Profits of grassland-based milk production—Results of *Analysis 1* for a synthetic fertilizer reduction of −135 N per ha.

Note: π'_m indicates the change in milk profits (*sensu* Equation 2) when changing the fertilizer application. Panel a shows the empirical CDF (eCDF), and Panel b box plots of the change in expected profit. Panel c shows the eCDFs, and Panel d shows the difference in eCDFs of the changes in demeaned profits. Panel a relates to first-order stochastic dominance, and Panels c and d to mean-independent second-order stochastic dominance. The average changes in profits shown in Panel b are −424 and −309 euros per ha for the periods 1991–2006 and 2007–2022, respectively. The illustration is based on bootstrapped prices ($N = 100$). The gray ribbons indicate 95% quantiles.

7.2 | Results of scenario analysis

7.2.1 | Results of scenario analysis for grassland-based milk production

In this section, we present the results of how the economic value of reducing synthetic nitrogen fertilizer application and using legumes changed under different price regimes (thus, over time) for grassland-based milk production. For this purpose, we compare the change in profits (i.e., milk revenues minus synthetic fertilizer costs) over a range of synthetic fertilizer reduction levels,[21] considering prices from 1991 to 2006 versus 2007 to 2022 (*Analysis 1*).

In Figure 3, we visualize the results of the reduction scenario −135 kg N per ha, and in Table 2, we summarize the results of all reduction scenarios. As shown by the analysis of the first-order stochastic dominance, we find that farmers' economic value of synthetic fertilizer reduction increased over time independent of the risk preference (Figure 3, Table 2). When reducing the fertilizer application by 135 kg N per ha, the expected gain of doing it under the more recent price regime is 115 euros per ha, which is about 101% of the fertilizer costs when applying 180 kg N per ha for the time period 1991–2006 and 61% for the time period 2007–2022, respectively.

Furthermore, looking at the test results for the mean-independent second-order stochastic dominance, we do not find that the risk-reducing effect of lowering fertilizer application increased over time (Figure 3c,d, Table 2c).

Sensitivity Analysis 1 considers what would have happened if milk prices had developed as wheat prices did. The analysis shows that the economic value gains of reducing synthetic fertilizer applications would have become smaller over time (Table S6). This is because of the development of a strong natural hedge (i.e., a positive correlation) between wheat and synthetic fertilizer prices and a slightly higher wheat price level under the more recent compared to the earlier price regime.

[21] We consider that farmers select the yield-maximizing proportion of legumes depending on the fertilizer application.

TABLE 2 Profits of grassland-based milk production—Results of *Analysis 1*.[22]

Panel a: First-order stochastic dominance				
Scenario a: Prices of 1991–2006 and fertilizer reduction (kg per ha) of	**Scenario b: Prices of 2007–2022 and fertilizer reduction (kg per ha) of**	***p*-value$_{a,b}$**	***p*-value$_{b,a}$**	**Inference**
$N = -180$	$N = -180$	0	.99	b dominates a
$N = -135$	$N = -135$	0	.99	b dominates a
$N = -90$	$N = -90$	0	.99	b dominates a
$N = -45$	$N = -45$	0	.99	b dominates a
Panel b: Expected profits				
Scenario a: Prices of 1991–2006 and fertilizer reduction (kg per ha) of	**Scenario b: Prices of 2007–2022 and fertilizer reduction (kg per ha) of**	**Difference in profits (b—a) (Euro per ha)**	**Confidence interval**	***p*-value**
$N = -180$	$N = -180$	156	[139–172]	<.001
$N = -135$	$N = -135$	110	[98–122]	<.001
$N = -90$	$N = -90$	76	[68–83]	<.001
$N = -45$	$N = -45$	37	[33–41]	<.001
Panel c: Mean-independent second-order stochastic dominance				
Scenario a: Prices of 1991–2006 and fertilizer reduction (kg per ha) of	**Scenario b: Prices of 2007–2022 and fertilizer reduction (kg per ha) of**	***p*-value$_{a,b}$**	***p*-value$_{b,a}$**	**Inference**
$N = -180$	$N = -180$	.81	.42	no dominance
$N = -135$	$N = -135$	.81	.42	no dominance
$N = -90$	$N = -90$	.80	.41	no dominance
$N = -45$	$N = -45$	.76	.41	no dominance

Note: The test results of first-order stochastic dominance, mean comparison, and mean-independent second-order stochastic dominance are displayed in Panels a, b, and c, respectively. Profits refer to milk revenues minus synthetic fertilizer costs. Kolmogorov–Smirnov type tests based on “bootstrapping 2” were used for computing the *p*-values of the tests for stochastic dominance.

7.2.2 | Results of scenario analysis for wheat production

We now look at the results of reducing synthetic nitrogen fertilizer application due to variable rate application on the economic value of wheat production, that is, *Analysis 2*. Our test of first-order stochastic dominance shows an increase in economic value for wheat-producing farmers with all risk preferences from reducing fertilizer dependencies over time, that is the economic value of fertilizer reduction increased from the first (1991–2006) to the second (2007–2022) considered period (Figure 4a). The expected profit gain for farmers increased over time by 15 euros per ha (Figure 4b), which is about 15% of the fertilizer costs of the uniform standard rate application for the time period from 1991 to 2006 and 9% for the time period from 2007 to 2022, respectively.

Regarding the influence explicitly on risks using mean-independent second-order stochastic dominance, we find that the same synthetic fertilizer reductions became more risk-reducing over time (Figure 4c,d). This is in contrast to the results for grassland-based milk production. Thus, for wheat production, reducing synthetic fertilizer application via variable rate application under the condition of the recent price regime provides an additional utility gain for risk-averse farmers compared to risk-neutral farmers.

Furthermore, in *Sensitivity Analysis 2*, we repeat *Analysis 2*, however, we consider what would have happened if wheat prices had developed as wheat prices did. The results of the economic value of reducing fertilizer remained very similar (Table S9). Also, the risk remained the same in both analyses, as wheat yields remained the same with variable rate application and therefore no effect of the natural hedge exists that impacts risk.

[22] For our analysis of both grassland-based milk production and wheat production: The results remain very similar when excluding prices after the 2022 Russian invasion of Ukraine, starting in February 2022 (Tables S7 and S8). Furthermore, when using Swiss import prices to check whether our conclusions remain valid using alternative price origins, we find that while costs and profits differ in levels when using German and Swiss prices the inference about changes over time using first and mean-independent second-order stochastic dominance are the same (Text S3).

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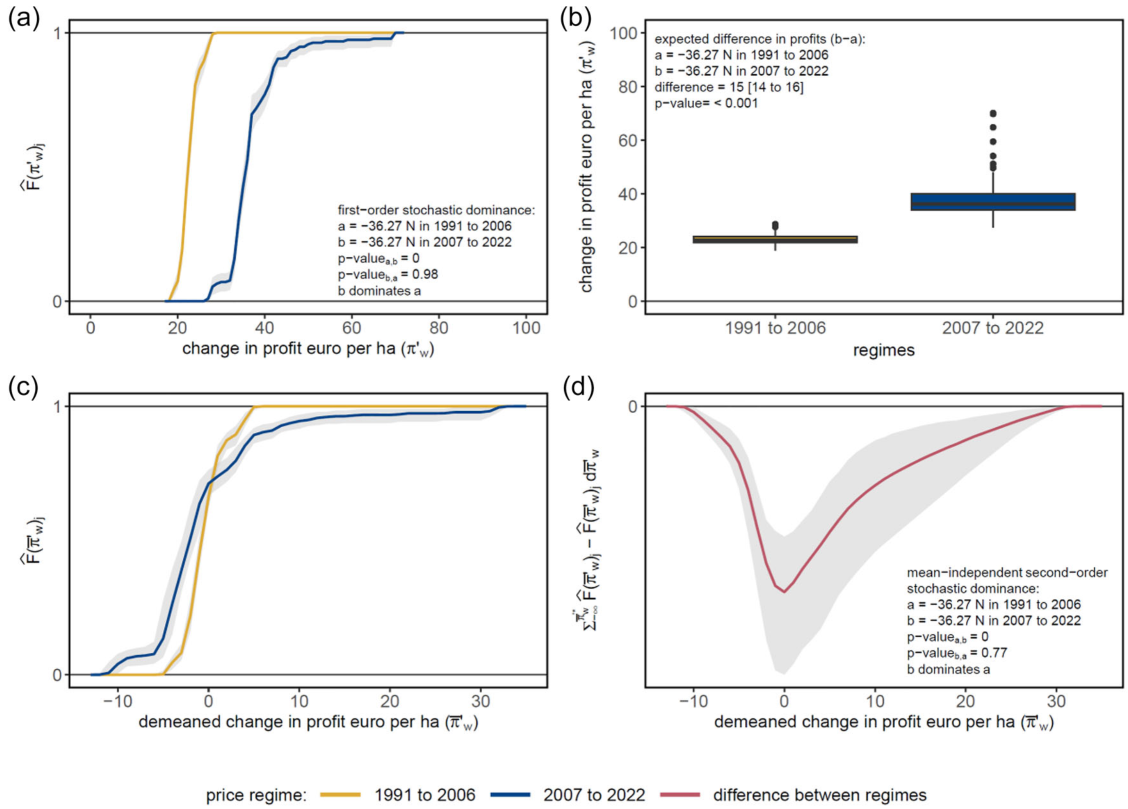

FIGURE 4 Profits of wheat production—Results of *Analysis 2* for a synthetic fertilizer reduction of −36.27 N per ha.

Note: π'_w indicates the change in wheat profits (*sensu* Equation 3) when changing the fertilizer application. Panel a shows the empirical CDF (eCDF), and Panel b box plots of the change in expected profit. Panel c shows the eCDFs, and Panel d shows the difference in eCDFs of the changes in demeaned profits. Panel a relates to first-order stochastic dominance, and Panels c and d to mean-independent second-order stochastic dominance. The average changes in profits shown in Panel b are 23.2 and 37.7 euros per ha for the period 1991–2006 and 2007–2022, respectively. The illustration is based on bootstrapped prices ($N = 100$). The gray ribbons indicate 95% quantiles. Kolmogorov–Smirnov type tests based on "bootstrapping 2" were used for computing the *p*-values of the tests for stochastic dominance. For details, see Table S10.

7.2.3 | Results of scenario analysis when taking a cost perspective

In this section, we assess the effect of reducing synthetic nitrogen fertilizer over time on expected costs and fertilizer price risks (i.e., *Analysis 3*). Thus, this analysis mainly differs from *Analysis 1* and *2* because we do not take into account the developments in output prices and, hence, revenues. Thus, we can analyze the impact of the natural hedge on our results.

Our test of first-order stochastic dominance shows an increase in economic value for farmers with all risk preferences from reducing fertilizer dependencies under the more recent price regime 2007–2022 (with higher and more volatile fertilizer prices) as compared to the price regime 1991–2006 (with lower and less volatile fertilizer prices) (Table S11). For example, the expected cost reduction when reducing fertilizer by 135 kg N per ha increased for farmers over time by 55 euros per ha, which is about 64% and 39% of the fertilizer costs under the earlier and later price regimes, respectively.

Following the test results of second-order stochastic dominance, we find that the same synthetic fertilizer reductions became more risk-reducing over time. Thus, reducing synthetic fertilizer application under the new price regime provides an additional utility gain for risk-averse farmers compared to risk-neutral farmers (Table S11). This finding aligns with the finding for wheat production (*Analysis 2*), but is in contrast to what we find when we consider grassland-based milk production (*Analysis 1*), where we find no mean-independent second-order stochastic dominance. There are two reasons for this. First, using variable rate application in wheat production does not change wheat yields; thus, the revenues from selling wheat are the same under uniform standard and variable rate application. Second, for grassland-based milk production, the comovement of milk and fertilizer prices increased over time (Table S2).

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The results of all stochastic dominance analyses are robust when using an alternative approach to compute the test, i.e., regardless of whether we use Kolmogorov–Smirnov type tests based on “bootstrapping 2” or “bootstrapping 1” (Tables S12–S16).

8 | SUMMARY AND CONCLUDING REMARKS

In this study, we analyze how different market price conditions affect the economic value of reducing fertilizer applications in grassland and wheat production. The results provide insights into farmers’ preferences regarding fertilizer use, given market price risks. Thus, the results provide insights into whether changes in market conditions facilitate or hinder fertilizer reduction measures and, therefore, agri-environmental policy efforts to reduce nutrient surpluses from agriculture.

For our analysis, we used the stochastic dominance framework and statistical tests for stochastic dominance proposed by Barrett and Donald (2003). The analysis uses German input and output price data from 1991 to 2022 to identify changes in market conditions. In addition, we use experimental field data from Swiss trials to causally identify the effect of fertilizer reduction and the use of sustainable production techniques on yields.

We find that the economic value of reducing fertilizer increased over time in both grassland-based milk production and wheat production. However, only in wheat production did reducing fertilizer application become more risk-reducing over time. In the case of grassland-based milk production, the risk-reducing effect of lower fertilizer application was cancelled out by the comovement of fertilizer and milk prices. We conclude that changes in market prices can affect farmers’ preference for reducing fertilizer use and that this change in preference can be, but not has to be, higher for risk-averse farmers. Therefore, the impact of market price developments, in terms of the level and volatility of input and output prices, on input use should be taken into account in the development and evaluation of agricultural policies.

Our analysis has some limitations. First, we use data from two countries, that is, German price data to study price trends, and Swiss experimental data to study the causal influence of fertilizer reduction and the use of sustainable production techniques on yields. Using experimental data allows for causal inference given certain environmental conditions. Even if, in the optimal case, all information would come from one country, our study presents generalizable results, namely how changes in market prices affect farmers’ preferences. The exact extent of these effects may vary over time, from farm to farm or region to region. Yet, with our analyses of two cropping systems, we show that the proposed method can be easily applied to the analysis of different case studies. Second, we considered that only fertilizer costs are stochastic, while other costs, such as machinery costs, are deterministic. While studying how, for example, the costs for variable rate application changed over time would be interesting, it is beyond the scope of this paper. In addition, the costs of such technologies might rather decrease over time, supporting the main conclusion of our analysis for wheat production and the use of variable rate application.

Our findings have three important implications for policymakers and farmers. First, our results highlight the importance of market price changes on farmers’ input use decisions. More precisely, stochastic input and output prices can contribute to the overall risk portfolio of farmers, next to other risks, such as production risks. Moreover, we also showed that output and input prices can naturally hedge with each other, resulting in lower price risks for farmers than when both are considered in isolation. It is therefore important to analyze the comovements of input and output price volatility to assess the risks to which farmers are exposed to, especially when risk mitigation policy interventions are planned. When considering risk-reducing policy measures, it is also important to bear in mind that reducing the price risk due to input reduction (e.g., fertilizer reduction, as in our case) can have different effects depending on the production systems and sustainable production techniques. Second, we show that changes in market conditions can facilitate the adoption of low-fertilizer production systems, thus achieving agri-environmental policy objectives. Here, for example, highlighting the cost- and risk-reducing effects of reducing fertilizer application in the conversation between policymakers and farmers, along with agri-environmental subsidies, can increasingly incentivize farmers to choose less fertilizer-intensive farming systems, such as legume-grass mixtures and variable rate application. Third, climate change and climate policies can cause fertilizer prices, as well as output prices, to increase and fluctuate in the future (e.g., Brown & Yucel, 2008; Komarek et al., 2020; Rezitis, 2015; Ubilava, 2017; Vatsa et al., 2023; Vielle & Viguier, 2007; Voisin, 2019). These future market price scenarios would further increase the mean and risk-reducing effects of low-fertilizer production systems, making them increasingly valuable management strategies for farmers to maintain competitiveness.

Our study highlights important avenues for future research. Future work could extend our conceptual model and test for the spatial heterogeneity of price risks due to volatile prices (e.g., different countries or regions within Germany), consider other farming systems, prices of differ-

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ent fertilizers (i.e., synthetic compound and straight as well as organic fertilizers), or price and production risks (e.g., from introducing legumes in grasslands) in combination. Furthermore, other drivers that alter farmers' decision-making and that can be linked to the reduction of synthetic fertilizer input could be considered in future work. These include, for example, payments for reducing fertilizer applications (e.g., via agri-environmental schemes).

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest

DATA APPENDIX AVAILABLE ONLINE

A data appendix to replicate the main results is available in the online version of this article. Please note: Wiley-Blackwell is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

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