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How do inputs and weather drive wheat yield volatility? The example of Germany ☆

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ABSTRACT

Increases in cereals production risk are commonly related to increases in weather risk. We analyze weather-induced changes in wheat yield volatility as a systemic weather risk in Germany. We disentangle, however, the relative impacts of inputs and weather on regional yield volatility. For this purpose we augment a production function with phenologically aggregated weather variables. Increasing volatility can be traced back to weather changes only in some regions. On average, inputs explain 49% of the total actual wheat yield volatility, while weather explains 43%. Models with only weather variables deliver biased but reasonable approximations for climate impact research.

1. Introduction

Climate change and its consequences for agricultural production have been open to environmental, social and economic debate for years. This is not surprising since weather conditions considerably determine crop yield levels and their variability, which are of interest for food security reasons at the macro-level (Brown et al., 2015; Wheeler and von Braun, 2013). Yields are also interesting at the micro-level, where a low level of yearly crop yield variability reduces income risks and contributes to farm income stability, which in turn could be relevant at the macro-level in that it warrants resilient food production. Hence, it is vital to better understand what determines yield variability in the most important crop-producing regions. This may also help farmers adapt their agronomic strategy towards better-known risks, and help policy makers to prevent food-crises or improve crisis management.

Undisputedly, long-term climatic changes alter cropping conditions (Siebert and Ewert, 2012) and might already have affected crop yield variability, which is identified as a key production risk of the most economically important cereals (IPCC, 2014, p. 71). Extreme weather events like the European heat wave in 2003 were discussed as either indicating an increase in temperature variability or resulting from a shift of the temperature distribution (Luterbacher et al., 2004; Perkins, 2015; Schär et al., 2004). Consensus exists that in the future, extreme weather events are expected to occur with greater frequency and severity in both temperate and tropical regions (IPCC, 2014, pp. 69–73). This will likely make crop production more vulnerable, with potentially considerable impacts on farm incomes and food security, particularly in less developed regions.

Farmers can control inputs like fertilizer for a given natural production environment like soil quality but cannot control the weather, nor can they affect developments in markets, agricultural, or environmental policy. Weather[1] is exogenous to farmers and directly affects crop yields. Additionally, indirect effects entailing

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[1] We use the term "weather" to be consistent with the majority of papers we reviewed. The literature applies different definitions. Dell et al. (2014) refer to inter-annual weather variations as long as the aggregation period is less than one year. Another strand of literature favors using a year-to-year or inter-annual variation of "climate" (e.g., Ray et al., 2015).

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input adjustments exist. For instance, weed growth, pests and diseases vary depending on weather conditions and farmers usually adjust their inputs accordingly during the production period. Weather can be interpreted as the major driver of production risk in crop production, though the question remains, how much overall production risk can actually be traced back to changing weather conditions?

In this study we consider wheat—one of the most important cash crops worldwide—where considerable upward trends in both yield levels and variability have been observed. While in 1995/96, on average, about 2.5 metric tons per hectare (tons ha^{-1}) were harvested worldwide, in 2012/13 this increased to about 3.2 tons ha^{-1} (FAOstat, 2015). Our investigation concentrates on Germany, which produces 17% of the European Union's (EU) wheat output. In the period 1995/96 to 2012/13, German wheat yields increased from 7.1 to 7.7 tons ha^{-1}. Although a long period of relative yield stability existed in the 20th century (Calderini and Slafer, 1998), both absolute and relative wheat yield variability have increased in Germany since the 1990s (Krause, 2008; Osborne and Wheeler, 2013). Particularly concerning is the upward trend in relative yield variability, that is, an increased proportion of yield at risk relative to the expected mean.

Against this background, the research questions guiding our analysis are as follows: How to explain increasing relative yield variability? Particularly, can one really conjecture that production risk measured as relative yield variability has increased only through changes in weather conditions, as the climate change discussion implies?

Several other reasons for this increase exist. First, farmers might adjust input levels because of changing input and output prices (Miao et al., 2016), while Finger (2010) discussed the importance of agricultural policy for yield analyses. Farmers in the EU have been exposed to rather radical changes in the Common Agricultural Policy (CAP) since 1992. Several reforms elevated the relative competitiveness of wheat, for instance, by removing price support, subsidies and compulsory set-asides (e.g., Gohin, 2006). Additionally, renewable energy policies have been proven to favor maize for silage (in Germany, increases of about 21% in the years 1990–2009 were reported, Statistisches Bundesamt, 2015). This might also have contributed to changes in the relative competitiveness of wheat production, which has consequences for input intensity and thus crop yield levels (Banse et al., 2008; Schulze Steinmann and Holm-Müller, 2010). Overall, these policy changes may have provided incentives for farmers to use lower quality (marginal) land for wheat production, likely with negative effects on average yield levels and increased variability. Crops planted on marginal soils with low water-holding capacity might be more sensitive to extreme temperature and precipitation changes compared to more favorable soils (Perkins, 2015, pp. 248–249). Moreover, yield can be interpreted as land productivity and may have increased due to scale and specialization effects (e.g., Yang et al., 1992; Kaufmann and Snell, 1997). Ongoing consolidation processes in the EU's agricultural sector (i.e., increased farm sizes) might enhance average yields per hectare despite the growing trend of planting marginal land with wheat.

While numerous studies consider how weather interacts with crop yield levels and their variance based on regression models (e.g., Chen et al., 2004), the relation between weather and relative yield variability of non-experimental yields has been analyzed by few researchers, for instance, Lobell (2007) or Ray et al. (2015). These authors, however, do not acknowledge any input adjustments that influence yield stability. To the best of our knowledge, thus far, the sources of yield volatility have not been disentangled into the major drivers of weather and inputs. Within this study we aim to close this gap and illustrate this idea using a case study for wheat yields in Germany.

While Iglesias and Quiroga (2007) assess the impact of weather variables on crop yields using time series regressions, we apply a panel data approach. We exploit the advantages of the panel structure to quantify whether and how weather- and input-induced risk has changed overall or only in some parts of Germany over time. Within our approach, we augment the contribution from Osborne and Wheeler (2013) and show that both inputs and weather matter for explaining yields and their relative variability. Our research contributes to the discussion of whether inputs need to be modeled when assessing climate change impacts on cereal yields. Further, understanding how weather drives observed relative yield variability today might be helpful for future adaptation challenges.

Our empirical analysis involves two major steps. First, we develop an empirical model of relative yield variability consistent with a production function approach. We consider major inputs, test for suitable functional forms and enhance this production function by a rich set of weather variables addressing phenological development. Second, we decompose the fitted values of this regression model to disentangle weather-induced compared to input- or policy-induced relative yield variability referring to the approach by You et al. (2009). To improve our understanding of whether to control for input adjustments while relating weather and yields, we present an alternative model that leaves out major inputs. Hypothesizing that the latter may suffer from omitted variables bias, our results show no considerable qualitative differences, though they do exhibit quantitative differences.

In what follows, we first unfold the conceptual framework and present related literature. After introducing the data, the presented framework leads us to our empirical strategy for disentangling crop yield volatility drivers. Following that, we report and discuss our results, and finally conclude.

2. Conceptual framework and related literature

Numerous studies deal with the impact of weather on yield levels by using either process-based crop simulation models (Müller and Robertson, 2014) or regression techniques.[2] The latter approach finds its roots in Oury (1965) and has two major strands. First, many studies exist that simply relate yield and weather within a regression model (e.g., Butler and Huybers, 2015; we refer here to the literature overview Tables S3–S5 in the supplementary appendix [SA]). In the second strand, weather impacts are analyzed within a production function framework including inputs. These models treat weather exogenously; however, a need to adjust inputs to changing weather might exist. For instance, the precipitation level will affect fertilizer intensity. Temperature instead affects length of the growing season and as such contributes to yield levels but rarely induces short-run adjustments to the input mix. While the first group of models takes this tacitly as a motive for leaving out inputs, the second strand of literature can also be criticized. While accounting for adjustments in the input mix in the short-run, production functions often fail to capture long-term adaptations to changes in climate such as altering crop rotation or alternative land-uses (e.g., Mendelsohn et al., 1994 or Deschênes and Greenstone, 2007).

When hypothesizing yield to be a function of inputs and weather, neglecting one group in the estimation of the impact of the other could result in biased parameter estimates as discussed by Kaufmann and Snell (1997), Reidsma et al. (2007, p. 417) or more recently by Miao et al. (2016, p. 201). In light of this debate, rather surprisingly only few recent studies include inputs or acknowledge other economic variables while analyzing weather impacts on yields (e.g., among others Schlenker and Lobell, 2010;

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[2] Literature reviews can be found in Dell et al. (2014), Schlenker and Roberts (2009), Tannura et al. (2008) and Ward et al. (2014).