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Climate change and extreme heat effects on output in Vietnamese agriculture

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Abstract:

Rising temperatures and heat waves can be very detrimental to crop yields in agriculture. In order to adjust to climate changes increased use of fertilizers and pesticides are often applied as observed also in Vietnamese agriculture. There are some temperature threshold values which will make agrochemicals decline in efficiency if exceeding the respective critical temperature levels. The present study analyses extreme heat effects of fertilizer and pesticides usage in Vietnam where extreme heat is quantified by the number of days with temperature exceeding thirty-five degrees Celsius, and the number of tropical nights. A modified Cobb-Douglas production function with climate variables is estimated in a FMOLS framework and allowing for interaction terms between heat and agrochemicals. The results show a declining efficiency of both fertilizers and pesticides with increasing heat during the last decades, and for fertilizers there may have been periods with negative marginal outcome from the increased use of fertilizer nutrients.

Keywords: Agricultural production, Climate change, Fertilizer, Pesticides, Extreme heat, Vietnam

Number of words: 6090

1. Introduction

The output from Vietnamese agriculture has been on the increase during the last decades but a likewise development has been the case for agrochemicals in form of plant protective products (pesticides), fertilizers and similarly the use of fossil fuels related to the mechanization of the sector. All of this will have detrimental impacts on the environment, human health and biodiversity. There is a trade-off especially between the growth in agricultural production and the use of fertilizers and pesticides and this connection has become more critical with the climate change developments. The ideal temperatures for applying agrochemicals are generally below thirty degrees and with more heat the products will lose efficiency and there is a risk for crop damage. According to a recent report from FAO the heat stress for livestock will start from twenty-five degrees Celsius and for the major crops the threshold level will be thirty degrees Celsius (FAO 2026). Thus, heat will have negative implications directly for activities related to both livestock and crop production and effects will be negatively influencing the effectiveness of agrochemicals.

According to a survey of 226 studies, the evidence is strongly in favor of higher temperatures reducing crop yields (Hu et al. 2024). There are as beforementioned most likely some temperature threshold values in relation to efficient applications of both fertilizers and pesticides, as e.g. evidenced for the use of fertilizer in China (Quan et al. 2014). The reactions to extreme heat in relation to agricultural activities may be manifold and may influence the use of several input factors, e.g. reduce the use of labor due to the hot working conditions and give incentives to increased use of pesticides to control for higher levels of pests and diseases (Tabe-Ojong et al. 2026).

The topic of the present analysis will be investigating the extreme heat effects on agricultural output via influencing the use of fertilizers and pesticides. There might be some temperature threshold values for the use of agrochemicals including nonlinear relationships, and therefore the analysis will include a variable quantifying the number of days with extreme heat. The interactions between agricultural output and climate conditions are very complex and quantifying the extreme heat might be useful for revealing any connections or effects from a hot climate. Traditionally, the mean temperatures are applied in studies investigating climate effects and this will also be included in the present analysis. The modelling approach will be based on a traditional production function, consistent with economic theory, and expanded to include relevant climate variables. There will be a focus on effects from extreme heat and as high temperatures will affect the function of agrochemicals there will be included interaction terms in the model between heat and fertilizers, and pesticides.

The analysis is structured with a survey of recent literature related to the topic in the next Section 2. Then, there will be a description of the data in Section 3, including the definition of the extreme heat variable, and further details on data are reported in Appendix A. Section 4 will be the model specification and with the details on the estimation methodology. The results from the analysis will be presented in Section 5, the conclusion will be in Section 6 and the last Section 7 deals with policy implications.

2. Literature review

Heatwaves have become more frequent and intense due to rising temperatures, which has a major negative influence on human health and productivity (Ruane 2024). Increased heat and water related stress driven by rising temperatures lowers agricultural productivity (Saleem et al. 2025). Crop yields in important food-producing regions worldwide are being impacted by the increased frequency of extreme heatwaves, droughts, and excessive rainfall occurring simultaneously within a single growing season (Lesk et al. 2022). Crop yields are projected to be hampered by shifting climate patterns, such as temperature and rainfall (Saleem et al. 2025). Depending on the particular crop, growing location, and fluctuations in these factors, the effects of rising temperatures, unpredictable rainfall, carbon dioxide fertilization, and irrigation vary (Nawaz et al. 2024). Because adaptation techniques effective for each climatic impact may prove insufficient under combined impacts, coupled extreme events will necessitate comprehensive agricultural adaptation strategies focused on multi-impact resilience (Lesk et al. 2022).

Agricultural production is commonly modeled through a production function framework in which output depends on land, labor, capital, and variable inputs such as fertilizers, pesticides, irrigation, and energy. In the context of climate change, however, this conventional specification needs to be extended because climatic conditions may affect output both directly and indirectly through the productivity of agricultural inputs. This issue is particularly relevant for Vietnam, where agricultural growth has been accompanied by intensive use of fertilizers and plant-protection chemicals.

Fertilizers contribute to plant growth by supplying nutrients, whereas pesticides are more appropriately conceptualized as damage-abatement inputs that reduce potential losses caused by insects, weeds, and pathogens. Tran et al. (2023), using data from Vietnamese rice and fruit farms, adopted a Cobb–Douglas production function in which pesticides are explicitly modeled as damage-abatement inputs. Their finding that approximately 95% of sampled farms overused pesticides suggests that higher pesticide application does not necessarily imply higher productive efficiency and

may instead reflect declining marginal returns, weak pest-management knowledge, or risk-averse behavior among farmers.

Climate change may further weaken the efficiency of these agrochemical inputs. For fertilizers, the main mechanism operates through nutrient-use efficiency. Penuelas et al. (2023) argue that the large-scale use of nitrogen, phosphorus, and potassium fertilizers has supported global food production but has also generated nutrient imbalances, pollution, and inefficient input allocation across countries. This study's discussion of the so-called 4R principle, right nutrient source, right rate, right time, and right place, implies that fertilizer productivity depends strongly on environmental and agronomic conditions. In tropical agricultural systems, this point is especially important because high temperatures and unstable moisture regimes may affect nitrogen volatilization, nutrient uptake, leaching, and soil biochemical processes. Thus, the same quantity of fertilizer may produce different yield effects under normal temperature conditions and under repeated extreme-heat exposure.

The pesticide channel operates through a different but related mechanism. Delcour et al. (2015) show that climate change can affect pesticide use through several pathways, including changes in crop-pest interactions, pest incidence, pesticide efficiency, environmental fate, and residue exposure. Their review indicates that temperature increases and altered precipitation patterns are among the main determinants of pest and pathogen pressure. At the same time, higher temperatures, moisture, and sunlight may accelerate pesticide degradation and volatilization, thereby reducing pesticide persistence in the field. Farmers may respond by changing application doses, frequencies, or product types, but such adaptation may increase environmental and human exposure if pesticide use becomes more intensive. This mechanism is consistent with the Vietnamese evidence on pesticide overuse and supports the argument that pesticide productivity should be modeled as climate-contingent rather than fixed.

Ma et al. (2025) review crop pest responses to climate and land-management change and report that warming can expand pest ranges, advance phenological events, and increase the number of reproductive generations per year. They also estimate that a 2° Celcius rise facilitates advanced phenological events and increases the number of reproductive generations per year, allowing pest populations to accumulate more rapidly and expand their geographic ranges into previously cooler regions. However, the response of pests to heat is not uniform. Pests in temperate regions may benefit from warming when temperatures remain below their physiological optima, whereas some tropical pests may already operate close to their thermal limits. Extreme heat may therefore intensify pest

pressure in some settings but suppress heat-sensitive pest populations in others. This supports the use of an empirical specification that distinguishes mean temperature from extreme heat days and allows for nonlinear or interaction effects.

A broader literature on climate change and agricultural productivity further indicates that crop output is sensitive to temperature, precipitation, soil conditions, and extreme events. Praveen and Sharma (2019) note that climate change affects agriculture through changes in rainfall, average temperature, extreme weather, pest and disease dynamics, soil erosion, and growing-season conditions. They also emphasize that changes in moisture and temperature can alter the absorption of fertilizers and minerals, which in turn affects yield formation. This argument is useful for the present study because it connects climate variables not only to crop physiology but also to input efficiency. In Vietnam, where rice, fruit crops, and other staple crops are produced under increasingly variable climatic conditions, a model that incorporates both average temperature and the number of extreme-heat days can therefore offer a more precise representation of climate-related production risks.

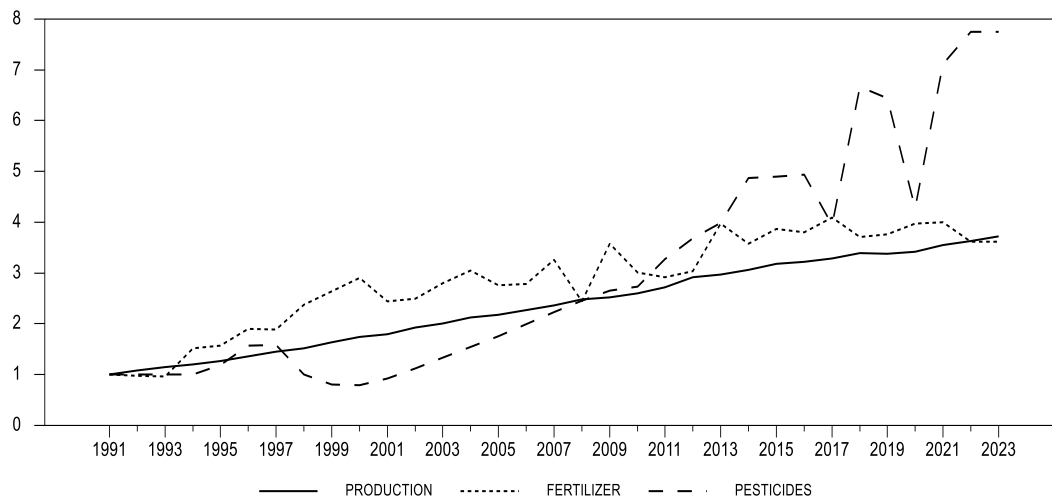
3. Data and descriptive statistics

The data applied in the present analysis are mainly from the *FAOSTAT* database (fao.org), which appears to include the most comprehensive and updated data in relation to Vietnamese agriculture. The data set covers both agricultural output as well as input resources and additional data in relation to the use of fertilizers and pesticides. The FAO data are compared to the data available from the *National Statistics Office* of Vietnam (nso.gov.org) to compare and check for consistency between the two data sources. Additional sources are also included, like the *WDI* database from the World Bank, and the climate data are extracted from the *Climate Change Knowledge Portal* (World Bank).

In line with the methodology and literature on the subject we have constructed a data set dealing with agricultural production in output volume terms but also output in value units are available. The data for agricultural output and inputs cover the Vietnamese agricultural sector in total and the data cover the time periods back to 1991. Thus, all variables will represent an average value for all the provinces in the country and thereby include heterogeneity with respect to local crops, cultivation practices, climate etc. Still, the intention with the analysis is from the methods and estimation techniques to extract valuable information from the data in relation to a macroeconomic analysis of Vietnamese agriculture. The data sources and definition of variables are further documented and described in Appendix A.

The total agricultural production appears with a strong increase since 1991 as exhibited in Figure 1. The data are in volumes, cf. Appendix A, and the total volumes of fertilizer and pesticides are also depicted.

Figure 1. Total volume of agricultural production and use of fertilizers and pesticides, 1991-2023 (Index, 1991=1).



Note: Fertilizers are N: Nitrogen, P: Phosphorus and K: Potassium. Data details to be found in Appendix A.

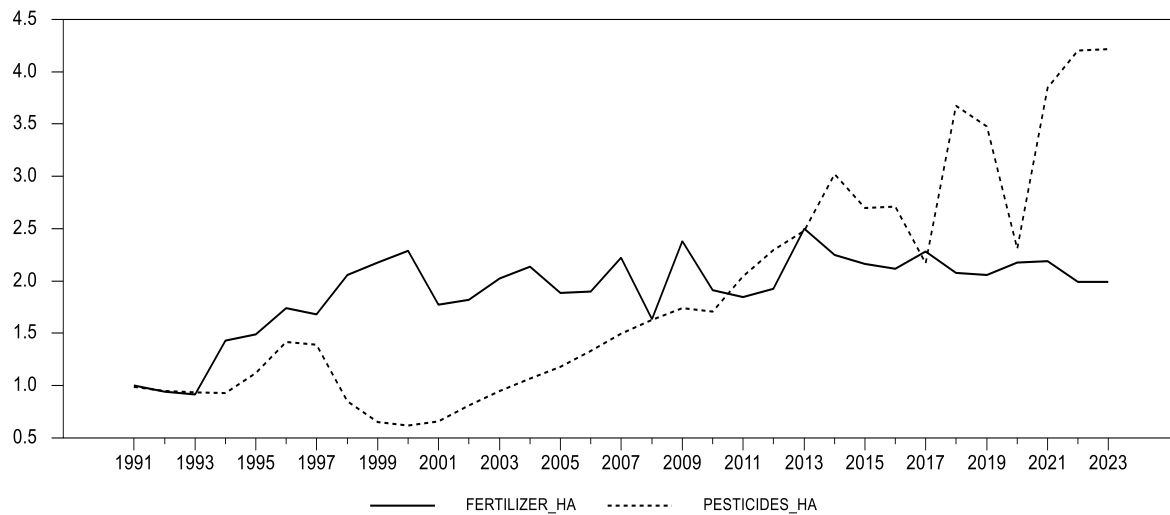
Source: FAOSTAT.

Agricultural production has more than tripled in the period and the use of fertilizer seems to follow the same kind of growth path, but the pesticides have increased a lot more during especially the last years. The latter may be caused by increased need for controlling infections due to higher temperatures during extreme heat periods. There is a drop in pesticide usage during the Covid period which also may be partly explained by economic causes as pesticides are considered relatively expensive and usage reduced in times of recession like the pandemic.

The area for agricultural production (cropland) has been of approximate the same size from the war time to the beginning of the 1990's whereafter the area increased during the next one and a half decade, but in recent years there is no increase in cropland and the overall increase is below the production as exhibited in Figure 1. The agricultural workforce has been declining for the whole period considered, but the capital stock, in real terms, has been increasing more than ten times since the mid 1990's. Thus, there is no doubt about large productivity increases in Vietnamese agriculture

and both fertilizers and pesticides seem to be important parts of this development. The intensity of the use of agrochemicals is depicted in Figure 2 with a unit of kg per hectare.

Figure 2. The use of fertilizers and pesticides, kg per hectare 1991-2023 (Indices, 1991 = 1).

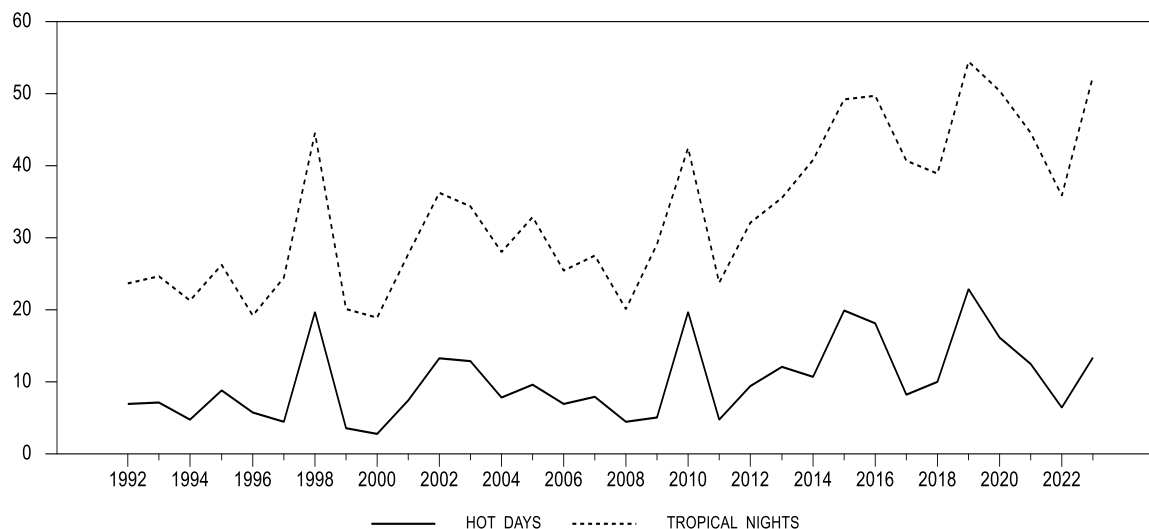


Notes: The volume (tons) of fertilizers are far beyond the use of pesticides and therefore data as indices.

Source: FAOSTAT.

The use of agrochemicals has been increasing in intensity as exhibited in Figure 2. The use of pesticides has been rather volatile, and for fertilizer there seems to be some leveling off during recent years. As stated in the introduction there is no doubt about the efficiency of both fertilizers and pesticides are declining with increasing temperatures. In this process with increasing heat in recent periods farmers will adopt the use of both agrochemical to the overall conditions and it may be difficult to quantify the effects between the latter chemicals and the climate developments. In the present analysis we have data measuring the more extreme heat periods compared to the development in mean temperatures and will try to model and quantify the climate effects on the efficiency of the agrochemicals. The data for the very hot periods are the number of days with temperatures above 35 degrees Celsius and the number of tropical nights where the temperature stays above 26 degrees Celsius. The nighttime temperature is also important as there will be no cooling off during the night and thereby make use of agrochemicals in the early mornings more efficient. Data for these two variables is exhibited in Figure 3.

Figure 3. The number of hot days and tropical nights.



Note: See the definitions in Appendix A.

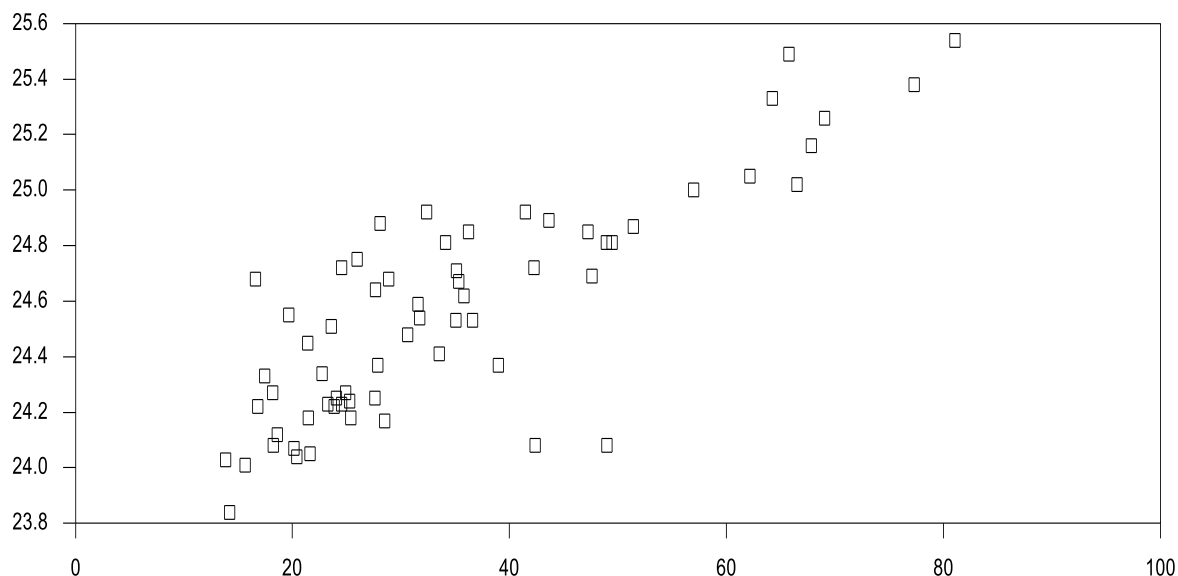
Source: *Climate Change Knowledge Portal* (World Bank).

Generally, there have been more days with extreme heat as defined by the sum of hot days and tropical nights during the last part of the period considered. The two parts of the heat variable are highly correlated as should be expected, but there does not seem to be any clear connection or correlation with the use of agrochemicals as exhibited in Figure 2 and Figure 3.

The heat variable to be included in the model estimations will be defined as the sum of hot days and tropical nights. This approach is in line with Tabe-Ojong et al. (2026) where a similar index of extreme heat degree days is constructed and measure the cumulated amount of time where a threshold value of temperature is exceeded. There might be temperature threshold values for the various crops in relation to declining yields as well as less efficient fertilizers and pesticides in case of extreme heat.

In most cases where the effects of agrochemicals are analyzed in relation to climate effects the mean temperature is applied. Figure 4 depicts a scatter plot between the heat variable and the annual mean temperature in Vietnam.

Figure 4. Scatter plot between the mean temperature og extreme heat.



Note: Annual mean temperature on the vertical axis and the horizontal axis with the number of days with extreme heat (number of hot days plus tropical nights, depicted in Figure 3).

Source: *Climate Change Knowledge Portal* (World Bank).

There is, as expected, a close correlation between the two variables in Figure 4, and both of these will be tested in the empirical modelling in the next Sections 4 and 5. The variations in the mean temperature are normally rather small – compared to the heat index here – and it might be difficult to test for an effect on e.g. fertilizer efficiency. As beforementioned, the heat variable is more extreme and probably more likely to reveal any connections to the use of fertilizers or pesticides. The hot days defined as periods with a maximum temperature above 35 degrees Celsius is directly linked to the fact that this threshold is critical for the efficiency of agrochemicals. Therefore, the heat variable may be a better choice in the model estimations compared to the mean temperature. Still, the heat is correlated with the mean temperature as revealed in Figure 4 and thereby indirectly also making eventual estimation results to be interpreted in relation to temperature.

The main hypothesis to test in the analysis will be investigating for any connection from climate effects as defined by the heat variable to the use of fertilizers and pesticides. Results from the analysis must correspond consistently with the data in Figure 3, i.e. reduced effects from agrochemicals must be expected to appear in years like 2010, 2015-16 and 2019 where the heat variable reaches maximum values.

Additional to the data for hot days and hot nights the climate data set also includes mean temperatures, precipitation and humidity which are often part of analyses as the case here. These variables will be included in the empirical tests of the model along the extreme heat variable.

4. Model specification

The purpose of the analysis is to ascertain the connection between climate change, especially the extreme heat, and the effects on total production in Vietnamese agriculture. High temperatures can have both positive and negative effects on agricultural activities, but especially the effectiveness of fertilizers and pesticides will be influenced by extreme heat. The *a priori* assumptions will be less usage of agrochemicals due to the declining effectiveness of both fertilizers and pesticides in periods of very hot temperatures.

The point of departure for the modelling procedure that is consistent with economics reasoning will be a full production function as mentioned in the last part of Section 2. Firstly, a Cobb-Douglas type of model including climate variables often referred to as a C-D-C model will be considered (Li 2023; Jin et al. 2025). The traditional input factors will be land, labor and capital, but also fertilizers and pesticides will be included as these chemicals are widely used in agriculture and influence significantly on output (Kahsay and Hansen 2016). It is a well-documented fact that especially high temperatures will interact with fertilizers and pesticides and therefore a model not allowing interaction terms between these variables may be mis-specified. The C-D-C model is not including interaction terms in the standard versions in contrast to e.g. the trans-log production function. The latter is a more flexible model that will include e.g. a fertilizer-temperature interaction term, but with at least five input factors, plus climate variables, this is not an option with a 32-periods time series data set. Therefore, the C-D-C modelling approach is applied with interaction terms and thereby giving a parsimonious model that will consider effects between input factors. The focus will be on extreme heat as presented in Section 3 and the effects on total output.

Estimating such a parsimonious model will be influenced by endogeneity problems as there may be causality issues and omitted variable bias with variables correlated with the error term. Additionally, the time series data might be non-stationary and to deal with these econometric challenges a fully modified OLS estimation procedure (FMOLS) will be applied (Zhang 2022). Thus, to deal with endogeneity and non-stationarity of variables all estimations performed with the parsimonious C-D-C model will be done with a FMOLS two-stage estimation method and done with the time-series software RATS (Estima.com).

In total, the C-D-C model will look like equation (1) in a log-linear form:

$$Y_t = \alpha_0 + \alpha_1 * L_t + \alpha_2 * W_t + \alpha_3 * C_t + \alpha_4 * F_t + \alpha_5 * P_t + \text{Climate variables} + \varepsilon_t \quad (1)$$

The variables are presented in the former Section 3 and the dependent variable (Y) is total output and therefore also the input factors are calculated in total quantities with total land (L), work force (W), capital stock (C), fertilizers (F) and pesticides (P). In all cases the variables are measured in natural logs, and the units of measurement will vary according to the respective variables. The core climate variables to be considered are temperature (including extreme heat), rain (and dry days) and humidity which will be tested sequentially in the model. In the estimations the focus will be on fertilizers and pesticides in relation to heat where a threshold value close to 35 degrees Celsius is acting in relation to these agrochemicals. With an interaction term between fertilizer and heat the parsimonious model will look like (2):

$$Y_t = \alpha_0 + \alpha_1 * L_t + \alpha_2 * W_t + \alpha_3 * C_t + \alpha_4 * F_t + \alpha_5 * P_t + \alpha_6 * \text{Heat}_t + \alpha_7 * (F_t * \text{Heat}_t) + \varepsilon_t \quad (2)$$

Additionally, a similar model is estimated with interaction between pesticides and heat:

$$Y_t = \alpha_0 + \alpha_1 * L_t + \alpha_2 * W_t + \alpha_3 * C_t + \alpha_4 * F_t + \alpha_5 * P_t + \alpha_6 * \text{Heat}_t + \alpha_7 * (P_t * \text{Heat}_t) + \varepsilon_t \quad (3)$$

Combining the two interaction terms in one model will be tested but it may also involve a multicollinearity issue additional to endogeneity, and therefore the estimations will be done for the two versions as presented in equations (2) and (3).

Especially fertilizers are influenced by high temperatures – which will be confirmed with the later parameters estimates – and the marginal effects of both fertilizer and pesticides in relation to heat will be varying with the actual level of these factors. For fertilizers the marginal effect will be $\alpha_4 + \alpha_7 * \text{Heat}$ based on parameter estimates from (2), and likewise $\alpha_5 + \alpha_7 * \text{Heat}$ with parameter estimates from (3) will indicate the marginal effect of increased use of pesticides.

The combined or total effect of fertilizer and heat on agricultural output will be the three terms with parameter coefficients α_4 , α_6 and α_7 in (2) and the signs and sizes of the parameter estimates will influence the result. For pesticides a similar calculation can be done based on equation (3). The expectations will be a negative sign for α_7 as this will indicate a decreasing effect of fertilizers, or pesticides, when heat is increasing in combination with more use of the agrochemicals.

5. Estimation results

The next step in the analysis will be to test various versions of the model (1) where the basic model is traditional input factors included in a log-linear version of the Cobb-Douglas production function. The result is reported as Model 1 in Table 1 and as expected the input factor land shows up with a coefficient close to unity and fertilizers and pesticides have positive overall impacts on production. The Augmented DF-test of residual stationarity is significant and the R^2 is very high, but with a low DW-test value. When climate influences the effectiveness of the agrochemicals the model is not well-specified and consequently the beforementioned climate variables, cf. Section 4 and the Appendix A, are added to the model estimations. In all cases the estimation procedure is FMOLS and the climate variables are added both individually one-by-one and in total, with subsequent deleting insignificant results. From this procedure only the heat variable shows up with significant parameter estimate and the expected (negative) sign as reported in Model 2. The effects on agricultural production from extreme heat seem to be strong enough to also appear in the estimations of Model 2, but with no influence on other parameter estimations from Model 1. Thus, one interpretation might be there is no effect from heat to agrochemicals, but the heat will still have negative effects on output. Climate conditions will also be implicit parts of Model 1 and Model 2 as farmers will adjust especially pesticides and fertilizers to the weather conditions, but this is of course not explicit results from the model estimates.

Normally, crops will need some heat to grow, and an overall negative effect is hard to believe although it's extreme heat in the present case. When the science evidence is strong heat will influence negatively on fertilizer and pesticide effectiveness there must be some interaction, and this is reported in Model 3 and Model 4 (Table 1). Models including other climate variables and interaction terms in the C-D-C framework have also been tested, but with no positive results.

Table 1. Parameter estimates of the C-D-C model (FMOLS).

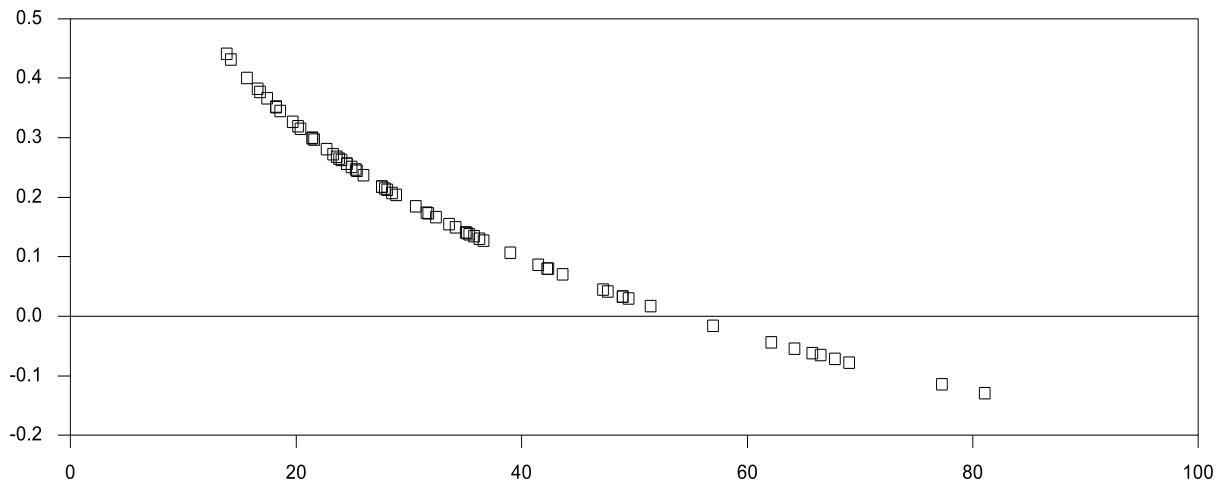
	Model 1	Model 2	Model 3	Model 4
Constant	-11.397*(1.145)	-11.769*(1.040)	-28.101*(2.286)	-14.458*(0.793)
Log L	1.033*(0.147)	1.089*(0.134)	1.006*(0.075)	0.959*(0.087)
Log W	0.054 (0.070)	0.059 (0.064)	0.085*(0.036)	0.065 (0.041)
Log C	0.061 (0.050)	0.069 (0.046)	0.110*(0.026)	0.130*(0.030)
Log F	0.225*(0.038)	0.215*(0.035)	1.287*(0.153)	0.193*(0.022)
Log P	0.080*(0.031)	0.081*(0.028)	0.096*(0.016)	0.355*(0.057)
Log H	-	-0.058*(0.020)	4.662*(0.650)	0.808*(0.167)
Log F*log H	-	-	-0.3223*(0.044)	-
Log P*log H	-	-	-	-0.081*(0.016)
DW	1.42	1.75	1.91	2.11
R ²	0.992	0.993	0.996	0.995
N	32	32	32	32
DF-test	3.93**	4.71**	5.15**	3.23*

Notes: The time period is 1991 to 2023 with N=32. Standard errors in parentheses and * for a parameter estimate significant at least the 5 per cent level. DW is the Durbin-Watson test for serial correlation. DF is a Dickey-Fuller test for stationarity of the residuals from the models with * indicating significant at the 5 per cent level, and ** for the 1 per cent level, respectively.

The interaction terms for both models in Table 1 are with a negative sign as expected and in accordance with basic knowledge about agrochemicals influenced by climate conditions. The adding of interaction terms does not seem to influence the other parameter estimates, e.g. the coefficient for pesticides in Model 3 is close to the result for pesticides in the first two models. The test statistics for the models are quite similar, apart from a better DW value for the last two models. Appendix B exhibits the residual plots for all models and the conclusion from there is that Model 3 (and Model 4) seems to fit the data best as the models without an interaction term show up with correlation in the residuals for the last decade.

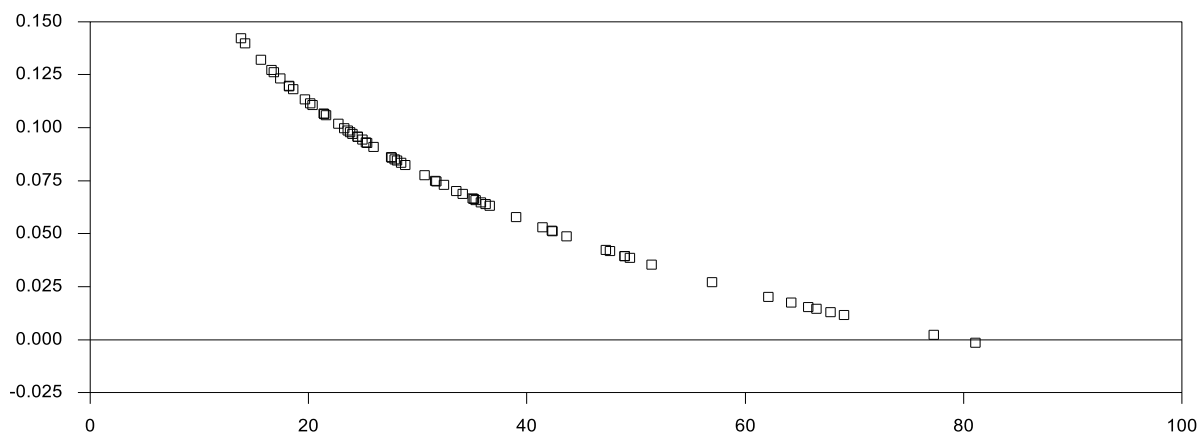
Due to the interaction term(s) the value of the coefficients is not directly or easily interpreted as the effect of e.g. fertilizers will vary with the value of the heat variable. The marginal effect of fertilizers and pesticides, respectively, can be calculated as explaining in Section 4, and with results depicted in Figure 5 and Figure 6.

Figure 5. Scatter plot between number of hot days/nights (horizontal axis) and the marginal effect of fertilizers on production.



The data plot in Figure 5 is done with the actual values of the heat variable and therefore each point represents an actual period (year). There are 8-9 years with high values for the heat variable, i.e. more than fifty days annually with extreme heat and a negative marginal effect, cf. Figure 3. This interpretation or conclusion must be interpreted with care as a year with periods of extreme heat may also have periods of more normal temperatures where fertilizers will work better. As stated in the introduction the test for effects from extreme heat is done partly to ascertain whether there is a fertilizer-heat connection or not – and in this connection the actual coefficient estimates may be treated with care. Therefore, one conclusion will be that extreme heat will influence effectiveness of fertilizers downwards and there may be periods with negative marginal effects. The total effect on agricultural production from fertilizers and heat will be determined from the three terms in (2) with the coefficients α_4 , α_6 and α_7 , but it will not be possible to use the model to calculate the effect of not using fertilizers at all in years with extreme heat. The only conclusion here is the marginal use of fertilizers may not be economically – and environmentally – beneficial in periods of extreme heat.

Figure 6. Scatter plot between number of hot days/nights (horizontal axis) and the marginal effect of pesticides on production.

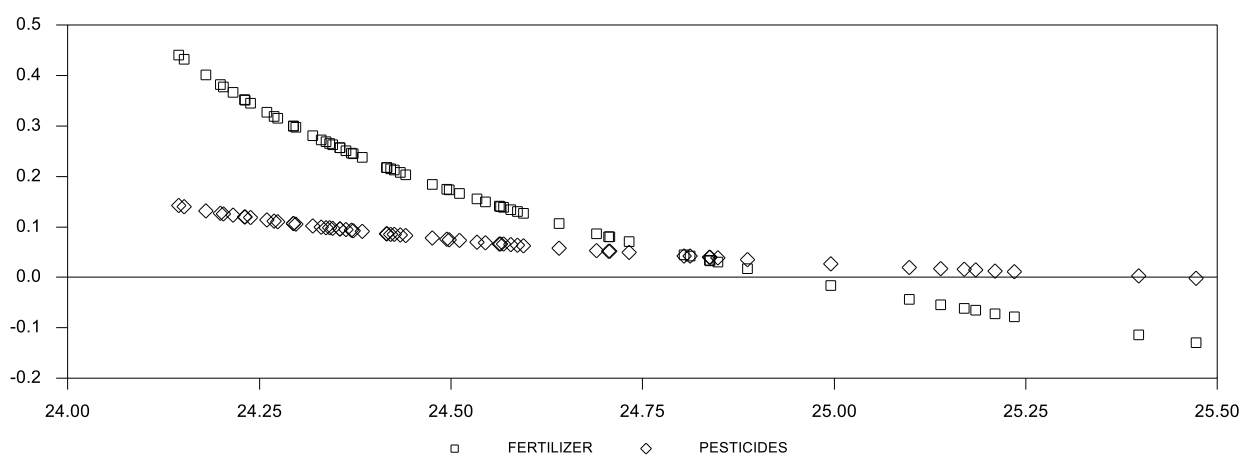


Notes: The horizontal axis is the heat variable, i.e. the total number of hot days and hot nights.

The scatter plot for pesticides in Figure 6 has the same interpretation as already mentioned for fertilizers, but with the difference that the marginal effect may be positive up to 80 days with extreme heat. Thus, there appears to have been only 2 years with expected zero marginal effect for using pesticides which also – without evidence – seems in accordance with the data in Figure 2 where the use of fertilizers is slightly declining while the use of pesticides increases.

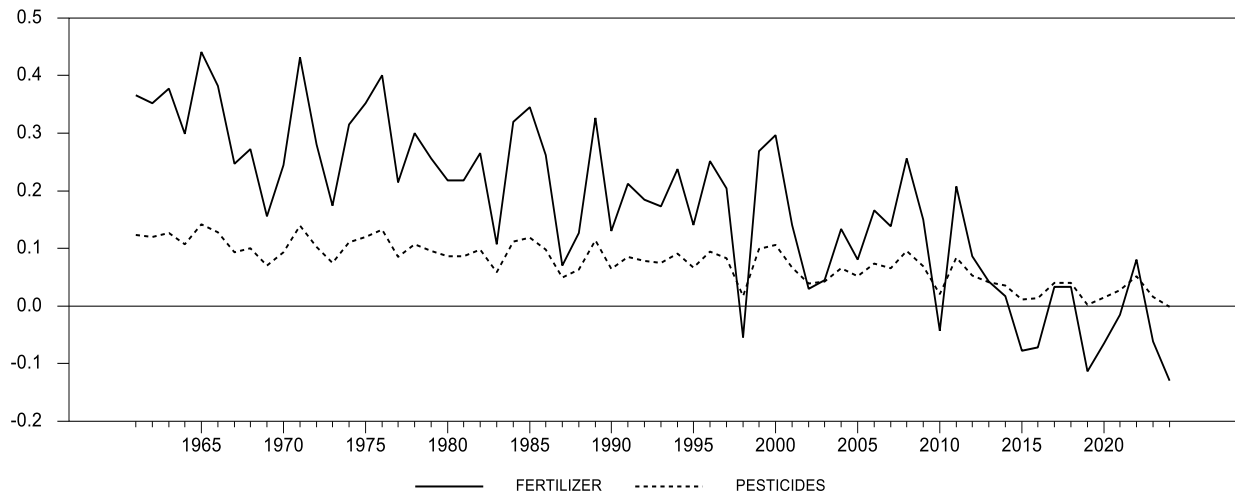
Figure 4 revealed a close correlation between the mean temperature and the heat variable, and estimating a linear relationship between the two variables can be applied to convert the heat values on the horizontal axis (Figure 5 and Figure 6) to mean temperatures, and the result exhibited in Figure 7.

Figure 7. Scatter plot between the annual mean temperature (horizontal axis) and the marginal effect of fertilizers and pesticides on production.



The marginal effects of the agrochemicals can also be exhibited in relation to the actual values of the extreme heat variable in the time span 1961-2023 as an alternative to a plot in relation to the heat variable (Figure 6 and Figure 7). The model parameter coefficients are estimated for the period 1991-2023, but data on the climate variables go back to 1961. Assuming the model estimates are valid back in time the marginal effects over the last sixty years can be calculated and presented in Figure 8.

Figure 8. The marginal effect of fertilizers and pesticides on production, 1961-2023.



Note: The marginal effects on production on the vertical axis and calculated from equations (2) and (3).

The conclusion from Figure 8 will be a declining marginal efficiency for especially fertilizers, and the climate effects from extreme heat have been mostly pronounced in recent years. Therefore, use of fertilizers should be carefully considered as the climate is not expected to be cooler – and if no efficiency of some agrochemicals, it's better to reduce the use, also due to the environment.

6. Conclusions

The first theoretical implication is in relation to the output elasticity of chemical inputs in the Cobb–Douglas production framework. The negative interaction coefficients in Models 3 and Model 4 imply that the estimated elasticity of agricultural output with respect to each chemical input is not constant but varies systematically with heat exposure. In the Vietnamese context, a proportional increase in fertilizer or pesticide use is associated with a smaller proportional increase in total output in years with a higher heat index. For fertilizers, the estimated elasticity $\partial \ln Y / \partial \ln F = 1.287 - 0.3223 \ln H$, becomes negative when the heat index exceeds approximately $H \approx 54.2$, indicating that the marginal contribution of additional fertilizer turns adverse under intense heat exposure. This pattern is broadly

consistent with agronomic mechanisms through which high temperatures and associated changes in humidity and soil moisture can alter nutrient uptake, volatilization, leaching, and key soil biochemical processes. As Peñuelas et al. (2023) likewise emphasize, fertilizer performance depends on using the appropriate nutrient source, rate, timing, and placement, implying that the same quantity of fertilizer may generate different yield effects under contrasting thermal regimes.

The second implication relates to the treatment of pesticides. In Model 4, the conditional output elasticity of pesticide use is given by $\partial \ln Y / \partial \ln P = 0.355 - 0.081 \ln H$, indicating that the estimated association between pesticide use and agricultural output weakens as extreme-heat exposure increases. This pattern is consistent with the proposition that the damage abatement contribution of pesticides is climate contingent. This result is particularly relevant for Vietnam. Tran et al. (2023) report pesticide overuse on approximately 95% of rice and fruit farms in their sample, suggesting that higher chemical intensity does not necessarily translate into higher productive efficiency. When viewed alongside the national-level time-series estimates in this study, that evidence indicates that input elasticities cannot be assumed stable as extreme heat exposure increases.

In Model 2 the extreme heat index enters with a negative and statistically significant coefficient, whereas mean temperature, precipitation, and humidity do not remain in the final reported specification once the heat index is included. Moreover, Models 3 and 4 show that the output elasticities with respect to fertilizers and pesticides vary systematically with the extreme-heat index. These results suggest that annual mean temperature may not adequately capture the climate conditions relevant to Vietnamese agricultural production in the period studied. Such as two years with similar annual mean temperatures can differ substantially in the number of days above 35°C and nights above 26°C. When crop responses are nonlinear in temperature, such differences of the temperature distribution can generate materially different production outcomes even when mean temperatures remain similar. This interpretation is consistent with Schlenker and Roberts (2009) reporting a distinctly nonlinear crop yield response when temperatures exceed specific thresholds for each crop type, and Lesk et al. (2022) indicated that extreme temperatures and humidity can interact through plant physiological feedback mechanisms, climate systems, and plant atmospheres. The theoretical contribution of the present study is therefore not simply to add another climate control to a C-D-C model. Instead, the results suggest that climate should be considered holistically, encompassing the frequency, duration, and cumulative intensity of extreme weather events, rather than solely through annual or seasonal averages.

7. Policy implications

The complex nature of extreme weather events poses challenges for farmers in adapting to climate change and increasing agricultural productivity. Adaptation measures are implemented to cope with typical extreme weather events, such as rising temperatures, which trigger chain reactions in the climate that can reduce crop resilience as well as the effectiveness of fertilizers and pesticides. Based on empirical research, this paper finds that in Vietnam, rising temperatures and heatwaves can severely damage agricultural crop yields. A widely adopted adaptation strategy is for farmers in Vietnam to increase the use of fertilizers and pesticides. However, the effectiveness of both fertilizers and pesticides decreases with increasing heatwaves. Therefore, agricultural productivity growth policies should not focus on increasing the use of chemicals but rather prioritize improving the efficiency of fertilizer and pesticide use by supporting farmers in transitioning to smart and economical production methods.

First, farmers need to adjust fertilizer applications to suit soil temperature and moisture levels. Importantly, during extremely hot days, increased fertilization should be limited; applying too much fertilizer at this time not only reduces yield but also increases production costs. Support policies should prioritize accurate weather forecasting to detect climate changes and warn farmers about temperature trends promptly. Local authorities need strategies to help farmers better understand soil characteristics, analyze soil types, manage irrigation and moisture, and apply fertilizers at the right dosage and timing. Therefore, more agricultural engineers need to be deployed to farming households to introduce rational farming methods instead of subsidizing fertilizer quantities.

Furthermore, during periods of excessively high temperatures, farmers should not increase the quantity of pesticides to combat pests, as this measure does not generate a corresponding increase in yield and also causes environmental pollution. Policies should aim to develop pest management strategies to adapt to climate change. Specifically, research institutes, pesticide management agencies, and local authorities need to guide farmers on how to use pesticides according to temperature, season, crop type, and pest outbreak level, and support farmers in using the correct dosage and timing. Managers also need to strengthen scientific and technological research on pest forecasting linked to weather warnings and promote smart, timely pest detection and management measures.

Next, policies aimed at increasing agricultural production to adapt to extreme temperatures should shift the focus from monitoring average temperatures to monitoring extreme temperature thresholds that directly affect crop yields. Therefore, a scientific program for early warning of the number of

days with extreme heat and the number of nights exceeding dangerous temperature thresholds is necessary. More broadly, there should be specific dangerous temperature warning systems for each crop and production region. This strategy is essential to support farmers in adjusting planting schedules, irrigation regimes, and selecting appropriate fertilizer and pesticide dosages to suit extreme temperatures.

Finally, expanding cultivated land area and improving farmers' skills and methods are necessary. This, coupled with appropriate capital allocation, will help improve agricultural productivity and the rational use of chemical tools, thereby improving people's lives, protecting the environment, and moving towards sustainable development.

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Appendix A: Description of the data

The following is a list of variables applied in the analysis and with short comments (including sources) to the variables appearing in the analysis. In all cases *FAOSTAT* (April 2026) is the source, unless another data source is indicated, and the data will cover the period 1991-2023.

Total production (Y): An index of agricultural gross production (2014-2016=100) of crops and live-stock products. Volumes are aggregated using price weights.

Land (L): This is CropLand in FAO terms and total agricultural area (Unit: 1000 ha); corresponds to ‘Agricultural Production Land’ from the NSO database, Vietnam.

Employment in agriculture (W): data from WDI (World Bank). The NSO has data for agriculture since 2005, and these data corresponds approximately to the WDI data set. The data covers ‘agriculture, forestry and fisheries’ – which is the general case for many NSO data although not stated clearly in all cases. According to the *2011 Census Survey* from NSO (nso.gov.vn, published 2012) employment for agriculture is approximately 92 per cent of the total employment for the three above-mentioned sectors. Thus, this share of the WDI employment data is the estimate of the employment for all years in the sample.

Capital stock in agriculture (C): Data in *FAOSTAT* for the net capital stock, local currency in millions, 2015 prices. The data covers ‘agriculture, forestry and fisheries’ – which is the general case for many NSO data – and according to the *2011 Census Survey* from NSO the value added, in national account terms, for agriculture is approximately 78 per cent of the total value added for all three sectors. Thus, this share is the best available estimate of the capital stock for agriculture. The capital stock data from *FAOSTAT* must be partly acquired from using a stock-depreciation model as the time series of the data is increasing rather smoothly for the first part of the data sample starting in 1996. Therefore, the capital stock data are estimated backwards to 1991 (from a log-linear calculation) to make them correspond to the time span for all other variables in the analysis (1991-2023).

Fertilizer (F): the total amount of fertilizer consisting of nitrogen, phosphorus and potassium, measured in weight units (ton); *FAOSTAT*.

Pesticides (P): total amount measured in weight units (ton); *FAOSTAT*.

Fertilizer intensity: The FAOSTAT publishes data on the use of fertilizer and pesticides per area; unit: kg per hectare. The data on the use of fertilizer per hectare are consistent with the data published on total use of fertilizers and the agricultural area (CropLand).

Pesticide intensity: pesticides per area; unit: kg per hectare, and consistent with the overall data published.

Climate variables:

Temperature: Mean temperature, degrees Celsius.

Humidity: measured in per cent.

Precipitation: measure of total rainfall in mm.

Hot days: Number of days with max temperature above 35° C during the day.

Dry days: Consecutive number of dry days.

Tropical nights: Number of nights with minimum temperature above 26° C.

Heat: Adding hot days and tropical nights.

Data on total sunshine hours might be relevant for the analysis, but such data are only available back to 2006 and therefore not included in the data set.

Appendix B: Plot of residuals for Models 1, 2, 3 and 4.

