Spring Frost and Price Behaviour on the Apple Fruit Market

An investigation of prices in Europe and the US between 2001 and 2024.

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Independent project 15 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Natural Resources and Agricultural Sciences/Department of Economics
Agricultural Business and Economics
Degree project/SLU, Department of Economics 1751 • ISSN 1401-4084
Uppsala 2026

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Supervisor:	**Levi Soborowicz, Swedish University of Agricultural Sciences, Department of Economics**
Examiner:	Shon Ferguson, Swedish University of Agricultural Sciences, Department of Economics

Credits:	15 credits
Level:	First cycle, G2E
Course title:	Independent project in Economics
Course code:	EX0903
Program/education:	Agricultural Business and Economics
Course coordinating dept:	Department och Economics
Place of publication:	Uppsala
Cover picture:	The picture on the front page is from https://www.britannica.com/plant/apple-fruit-and-tree
Copyright:	All featured images are used with permission from the copyright owner.
Title of series:	Degree project/SLU, Department of Economics
Part number:	1751
ISSN:	1401-4084
Keywords:	Agricultural Economics, Panel Data Econometrics, Frost effects, Supply and demand mechanisms, Price dynamics, Panel Vector Autoregression.

Swedish University of Agricultural Sciences
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Abstract

Apples are an appealing healthy fruit, and, in this thesis, their price is investigated as a function of various factors. The main question pursued is how spring frost and economic dynamics interact with apple prices. Firstly, I examine spring frost and its possible correlation with farm-gate price, since frost during apple tree blossoming impacts apple development. This is done with Ordinary Least Squares (OLS). Secondly, supply and demand mechanisms are explored to further examine the potential relationship between weather and price. This is done using 2-Stage Least Squares (2SLS) regression, with price as the dependent variable, quantity as the independent variable, and spring frost as an instrumental variable. Both OLS and 2SLS models indicate a correlation between spring frost and price. Lastly, I develop a time-series model with lagged dependent variables in order to understand price behaviour, using price and quantity produced as endogenous variables, along with production costs (oil prices), macroeconomic indicators (GDP per capita, exchange rates, interest rates), and weather (spring frost) as exogenous variables. This model further supports the association between spring frost and prices. With these results, I contribute to agricultural economics research by discussing the economic effects of spring frost and highlighting possible interpretations of the developed time-series model.

Keywords: Agricultural Economics, Panel Data Econometrics, Frost effects, Supply and demand mechanisms, Price dynamics, Panel Vector Autoregression.

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1. Introduction

1.1. Background

An apple is the fruit of the apple tree, *Malus domestica*, a widely cultivated species belonging to the rose family, *Rosaceae*. Botanically, the apple is classified as a pome, which is a type of fleshy fruit. At harvest, apples are typically round and vary in colour, commonly appearing in shades of red, green, or yellow. Apples are primarily grown for sale as fresh fruit, although they are also used commercially to produce vinegar, juice, and other processed products (Britannica, 2026).

The market for apples was valued at around 112 billion US dollars in 2025. (GMI Research, 2026) World apple production amounted to 86 million tonnes in 2018. Daily consumption is expected to be 204 grammes per capita in 2025. (Vasilieva, 2021) This makes apples the second most-produced fruit in the world. Apples are nutritious, can be stored for up to 12 months, and they are easy to transport.

The exchange of goods and services in a market economy reflects a balance between consumer needs and wants and the availability of goods and services that meet those needs and wants. In the case of apples, availability depends on both natural conditions and producers' ability to grow fruit that meets consumer preferences. This relationship is evident in the declining value of apples when supply is abundant and, conversely, in the increasing value of apples when supply is limited.

This thesis investigates how weather shocks and market dynamics interact in determining apple prices using panel and time-series econometric methods. More specifically, it examines the correlation between spring frost and farm-gate prices. The research question is: *How do weather and economic dynamics influence apple prices?* The apple market is examined in order to better understand price behaviour. In particular, the price response to changes in quantity is tested using observational market data. In addition, key indicators of the global economy are incorporated into the economic models to better explain price behaviour.

Apples are nutritious fruits associated with positive health effects, and demand for them may be increasing as consumers become more health-conscious and place greater emphasis on sustainable food choices. (Vasylieva, 2021) Understanding apple prices is important because access to healthy fruit is relevant to public health, and understanding price movements can help ensure that policymakers and other key stakeholders are better aligned with supply chain developments.

Although numerous studies examine agricultural commodity prices, this thesis contributes to the literature by combining panel-data analysis of apple prices with macroeconomic variables and weather indicators. The focus is on major producing regions in Europe and the United States between 2001 and 2024.

The structure of this thesis is as follows. It addresses one main question about weather and price, followed by two questions about supply-and-demand mechanisms and macroeconomic influences. The first question is addressed throughout the thesis, while the latter two broaden the perspective and complement the discussion of the first. The literature review in chapter 1.2 will put this in a scientific context. In chapter 2, the mathematical framework, the models and the implementation of the methods are developed. Chapter 3 reports the results. In chapter 4, the results and the methodology are discussed, and in chapter 5 conclusions are drawn.

1.2. Literature Review

Agronomists have studied apple tree yield and growth in response to weather. In a study by Chen (2022), the impact of frost damage on yield is quantified using statistical methods in a typical apple-producing region in China. This study highlights the effects of spring frost using large-scale observational data. It is established that spring frost is correlated with reduced yield. The biological understanding is that frost during blossoming is an agro-meteorological problem for apple production. This is used to define the weather variable as the last day of spring when the temperature is below 0°C.

Apples are a common household staple. They have positive health effects, can serve as a substitute for snacks and candy, can be stored for up to 12 months, and are easy to transport. Apples are an appealing fruit as a consumption good. Supply-and-demand interactions are important for highlighting the fundamental market dynamic. With earlier studies on weather and its effects on yield in mind (Chen, 2022), we can outline a logical path that begins with apple production and supply and their interaction with demand. Economic theory holds that a reduction in supply should increase prices. With this in mind, we will assess the responsiveness of apple prices to changes in quantity supplied.

The dynamic price behaviour of apples is now said to be influenced by biological factors, weather, and supply-and-demand interactions. A general insight into agricultural commodity prices is that they are volatile and often unpredictable. Deaton (1992) discusses how well theories of price formation explain actual price behaviour. Price consistency and trending behaviour are important in his analysis. Rezitis (2013) develops a picture of price formation for food commodities that involves price expectations and shocks. These things highlight the dynamical properties of price behaviour. Cuaresma (2021) develops a model of agricultural commodity prices that incorporates non-linearities and macroeconomic indicators. His study is an example of a mathematical implementation that accounts for multiple potential influencing factors, providing a good statistical framework to follow. Concretely, Cuaresma's method of implementing Vector Autoregression is used in this thesis. Our analysis so far includes weather impacts and supply-and-demand mechanisms, and now we extend the picture to include trends, nonlinearity, and macroeconomic controls.

1.3. Hypotheses

We want to understand the relationship between weather and apple prices. The first question is whether there is a relationship between weather and apple prices.

H1: There is a correlation between weather and apple prices.

Frost during the blossoming phase of apple trees can disrupt the biological development of apples. Therefore, a longer duration of spring frost is hypothesised to decrease yield. Economic theory suggests that a lower supply leads to higher prices; in this case, spring frost is also hypothesised to raise prices.

Formally, we have the hypothesis:

H2: There is a positive correlation between spring frost and prices.

Prices of apples should be determined like all other food commodities, with the exception of apple trees' specific vulnerability to frost during their blossoming phase. Therefore, it is expected that weather is an important part of price formation and a model describing apple prices should include weather as a significant variable.

H3: A model of apple prices will include a significant weather variable.

2. Method

The goal is to understand the relationship between weather and prices. First, a direct model between weather and prices is developed. This is done statistically, with inspiration from Chen (2022).

Later, connections between weather and prices are highlighted and tested. This is done with supply-and-demand mechanisms in mind. The main target is apple price responsiveness to fluctuations in quantity induced by weather shocks.

Lastly, a general model for apple prices and their association with macroeconomic indicators is developed.

2.1. Weather and price

We want to understand the relationship between weather and apple prices. Since prices generally follow an exponential trend, they are transformed with a logarithm. The logarithm of price shows a constant trend over time; therefore, a time trend is added.

The study by Chen (2022) indicates that spring frost is a weather phenomenon that influences apple trees. To model spring frost, the period from March to May is selected, and a frost day is defined as a day when the minimum temperature is below 0°C. Based on the available data, we can extract temperature data, create variables indicating days with spring frost, and determine the last day with spring frost.

Also, a fixed-effects control δ_i is added to account for the heterogeneity across countries. Prices are converted to real prices using the Food Consumer Price Index.

This gives the estimate of prices as the equation:

$$Log(RealPrice) = \beta_0 + \beta_1 * LastFrostDay + \beta_2 * t + \delta_i + \epsilon \tag{1}$$

If the hypotheses are true (there is a correlation between price and weather, and spring frost is positively correlated with price), then β_1 will be significant (H1) and positive (H2).

Implementation

Using these equations, an Ordinary Least Squares (OLS) regression model is implemented in R. Linear regression is a suitable method in this case because it provides a way to analyse the behaviour of the variables.

The regression model is tested on an aggregated dataset across all countries. To assess its robustness, two additional analyses are conducted: one excluding France and one excluding the US.

2.2. Supply and demand mechanisms

The logic is that weather affects yield, and this variation in yield should influence prices. The first stage is to estimate yield as a function of spring frost. Then prices will be estimated as a function of the estimated yield. The 2-stage least squares (2SLS) method is suitable because it accounts for the simultaneity of supply and demand. Wooldridge (2018) illustrates a methodology that I follow in the chapter on 2SLS and simultaneous equations. The yearly trend, β_2, of prices is taken into account, as is the heterogeneity across countries with δ_i.

Yield estimation:

$$Yield = \beta_0 + \beta_1 * LastFrostDay + \delta_i + \epsilon \qquad (2)$$

Price estimation as a function of the estimated yield:

$$Log(RealPrice) = \gamma_0 + \gamma_1 * estimated(Yield) + \gamma_2 * t + \delta_i + \epsilon \qquad (3)$$

Implementation

The first stage is a simple linear regression with yield as the dependent variable and spring frost as the independent variable.

A 2SLS method is implemented in R, with the log of prices as the dependent variable, yield as the independent variable, the last day of frost as the exogenous instrument, and time as an exogenous control. Because of heterogeneity across countries, a fixed-effects control is added to account for country differences.

2.3. Price analysis

To further our understanding, macroeconomic indicators are added to our price model, and an initial framework for analysing price can look like this:

$$Price = Quantity + OilPrices + GDPperCapita + ExchangeRates + InterestRate + Weather$$

Econometric insights provide ways to appropriately transform these variables. Logarithms are used to stabilise exponential trends and linearise relationships. Country-specific attributes are accounted for using real prices.

A possible econometric model can look like this:

$$log(RealPrice) = log(Quantity) + log(OilPrices) + log(GDPperCapita)$$
$$+log(ExchangeRate) + InterestRates + Weather + \epsilon$$

Time series properties

Time series analysis is appropriate because past prices are expected to be correlated with current prices, especially given possible storage dynamics (Deaton, A., 1992). Autocorrelation Function (ACF) test, Partial Autocorrelation Function (PACF) test and Augmented Dickey-Fuller (ADF) test are performed on all variables. The ACF test suggests that the interest rate and the log of Oil Price have a moving average (MA(2)) and that all other variables have a non-stationary trend. PACF indicates that the interest rate, log of Oil Price, and log of Quantity might be autoregressive (AR(1)). The ADF test indicates that only the log of Oil Price is stationary.

Panel Vector Autoregression

Given the data setup and the variables in this thesis, Vector Autoregression is an appropriate statistical model. We have multiple time series of variables that influence each other. VAR is a good method for showing the dynamics among these variables.

To account for the non-stationary features of these variables and to develop a model with a time-series perspective, Cuaresma (2021) provides a good example. Cuaresma, J., Obersteiner, M., & Hlouskova, J. developed a comprehensive econometric approach to agricultural commodity prices. The key framework of their approach is a time-series model with autoregressive features, in which today's price depends on historical prices. Their specification of a multivariate time series looks like this:

$$Y_t = C_0 + \sum_{l=1}^{p} C_l Y_{t-l} + \epsilon \qquad (4)$$

Where Y is the vector of the dependent variable, assumed to be dependent on its past values. C_0 is a vector of the intercept, and C_l with $l = 1,2,\ldots,p$ are coefficient matrices for the different lags l, and ε is the error. In our case, we use prices and quantities as endogenous variables because these are jointly determined. The non-stationary variables are differenced in order to make the equation stationary.

$y_t = x_t - x_{t-1}$

Differencing the non-stationary variables also changes the economic interpretation of what we are analysing; we are now analysing the growth of the differenced variables.

With a lag of one, which in equation (4) means that $l = 1$, the system of equations will look like this in the developed form:

$\Delta log(RealPrice_t) = c_0 + c_1 \Delta log(RealPrice_{t-1}) + c_2 \Delta log(Quantity_{t-1}) + \epsilon_P$

$\Delta log(Quantity_t) = d_0 + d_1 \Delta log(RealPrice_{t-1}) + d_2 \Delta log(Quantity_{t-1}) + \epsilon_Q$

A typical variation of (4) is a Vector Autoregression with exogenous variables (VARX) structure, which allows the variables in Y to be a function of exogenous variables (Canova, 2013). This is a good extension in our case because it allows us to include macroeconomic indicators and weather as exogenous variables that influence the endogenous system but are not influenced themselves. This is a meaningful model extension because apple price equilibrium mechanisms should not influence macroeconomic indicators and the weather, but prices can be expected to be influenced by these variables. Equation (4) becomes:

$$Y_t = C_0 + \sum_{l=1}^{p} C_l Y_{t-l} + FW_t + \epsilon \qquad (5)$$

Where Y_t is linearly dependent on the exogenous variables in the vector W_t with the coefficients F. F being a matrix of coefficients. Writing this out as an equation system with differenced log of price and differenced log of quantity as endogenous variables and log of oil price, differenced log of exchange rates, differenced log of GDP per capita, interest rates, and weather as exogenous variables, we get the equations:

$\Delta log(RealPrice_t) = c_0 + c_1 \Delta log(RealPrice_{t-1}) + c_2 \Delta log(Quantity_{t-1}) +$

$+ f_1 log(OilPrice_t) + f_2 \Delta log(ExchangeRate_t) + f_3 \Delta log(GDPperCapita_t) +$

$f_4 InterestRate_t + f_5 Weather_t + \epsilon_P$

And,

$\Delta log(Quantity_t) = d_0 + d_1 \Delta log(RealPrice_{t-1}) + d_2 \Delta log(Quantity_{t-1}) +$

$+ k_1 log(OilPrice_t) + k_2 \Delta log(ExchangeRate_t) + k_3 \Delta log(GDPperCapita_t) +$

$+ k_4 InterestRate_t + k_5 Weather_t + \epsilon_Q$

Since we have different countries with the same time series, Panel Vector Autoregression (PVAR) is the proper method, as illustrated by Canova, F., Ciccarelli, M. (2013) in chapter 2. Panel VAR have the same structure as VAR models, in the sense that all variables are interdependent, but a cross-sectional dimension is added. In our case, we have 5 different countries, and, in equation

(5), the dependent variable, $Y_t = (y_{1,t}, y_{2,t}, \ldots, y_{5,t})$, can be viewed as a stacked vector with one entry per country. Equation (5) will be analysed by examining its coefficients, stability conditions, and impulse response function.

The coefficients will tell us about the growth rate of prices. The stability condition is important for establishing whether the model is appropriate. The General Impulse Response (GIRF) shows how this model responds to a shock.

Implementation

As noted in the section about time series properties, the logarithm of prices is non-stationary, as are the logarithms of quantity, GDP per capita, and the Exchange rate. This means that they need to be differenced.

The last frost day is used as a weather indicator because the first-stage regression shows a statistically significant relationship with yield.

When implementing PVAR, price and quantity are treated as dependent variables, while the others are treated as exogenous control variables.

We follow the method of Sigmund (2021), which describes how to implement PVAR in R with the "panelvar" package, but we replace the *generalised method of moments* with *fixed-effects ordinary least squares* because our data have small N and large T. The fixed effects estimator removes country-specific heterogeneity through the within transformation. Consequently, country-specific intercepts are eliminated, while the dynamic coefficients are assumed to be the same across countries.

2.4. Data description

Farm gate prices

Farm-gate prices were obtained from the FAO. Agricultural producer prices are the prices received by farmers for primary crops, live animals, and livestock products, collected at the point of initial sale (i.e., at the farm gate). It is annual data, and the value is in the local currency per tonne. Farm gate prices are converted to real prices using inflation. The data spans from 2001 to 2024 and covers the countries France, Germany, Italy, Poland, and the USA. The farm-gate prices for apples are shown in Figure 1.

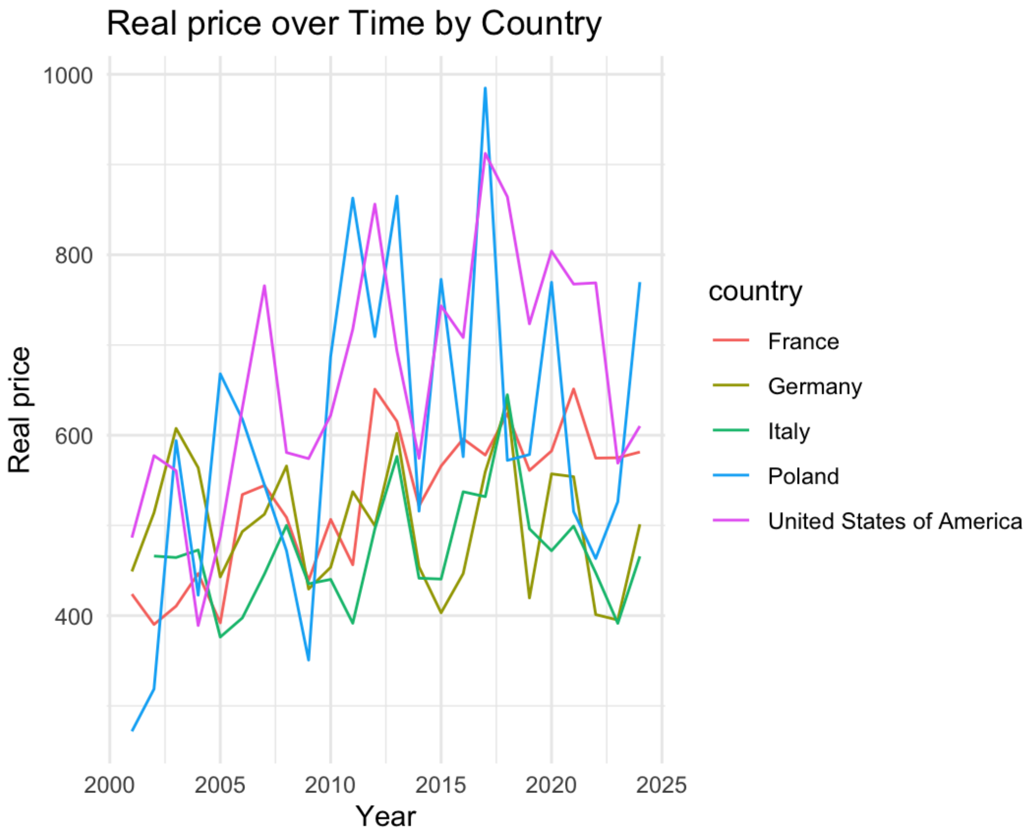

Figure 1. Real price over time.
Notes: The Y-axis is the real price in the local currency. The X-axis represents time. The colours are different for each country.

Quantity data

The quantity produced is an aggregate variable that measures a country's total output. The value is in tonnes. In this statistical variable, FAO indicates that it refers to all harvested crops, and includes on-holding losses and wastage, quantities consumed directly on the farm, and marketed quantities. The data spans from 2001 to 2024 and covers the countries France, Germany, Italy, Poland, and the USA. The quantity of apples produced is illustrated in Figure 2.

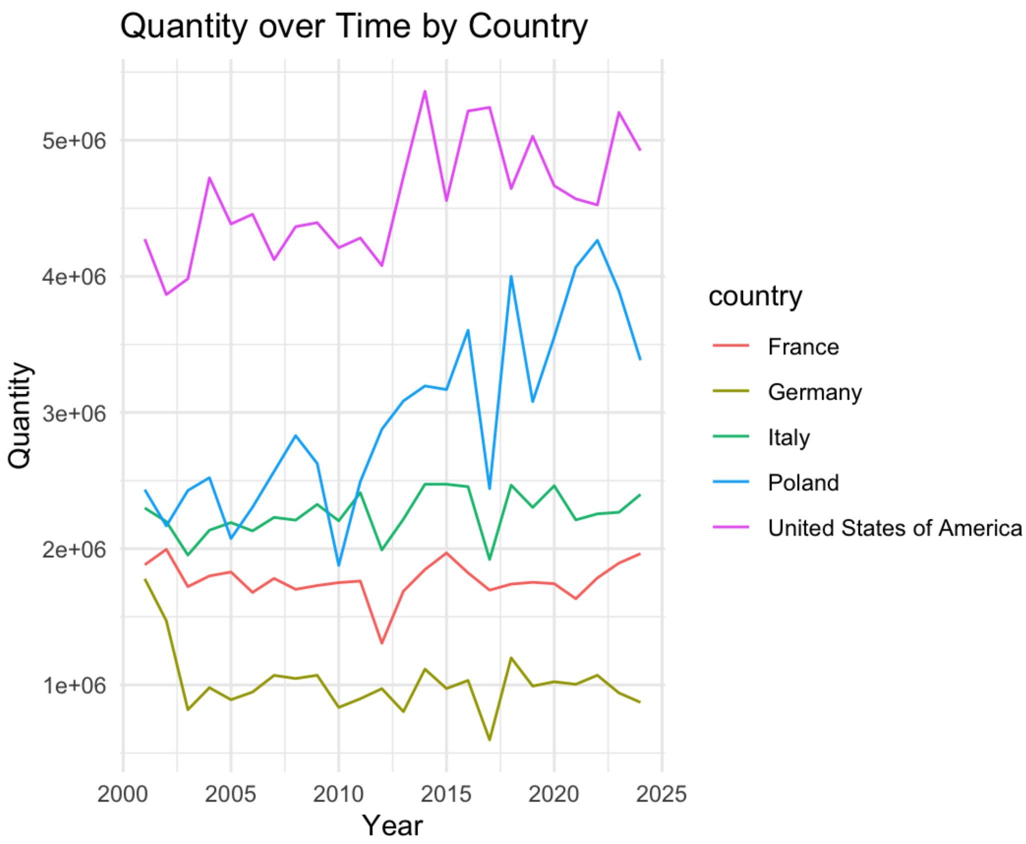

Figure 2. Quantity over time.
Notes: The Y-axis is the quantity in tonnes. The X-axis represents time. The colours are different for each country

Yield data

Yield data were acquired from FAOSTAT, a dataset in which the key value is yield per area, expressed in kilogrammes per hectare. It is annual data for the whole country. The data spans from 2001 to 2024 and covers the countries France, Germany, Italy, Poland, and the USA. The yield per hectare of apples is illustrated in Figure 3.

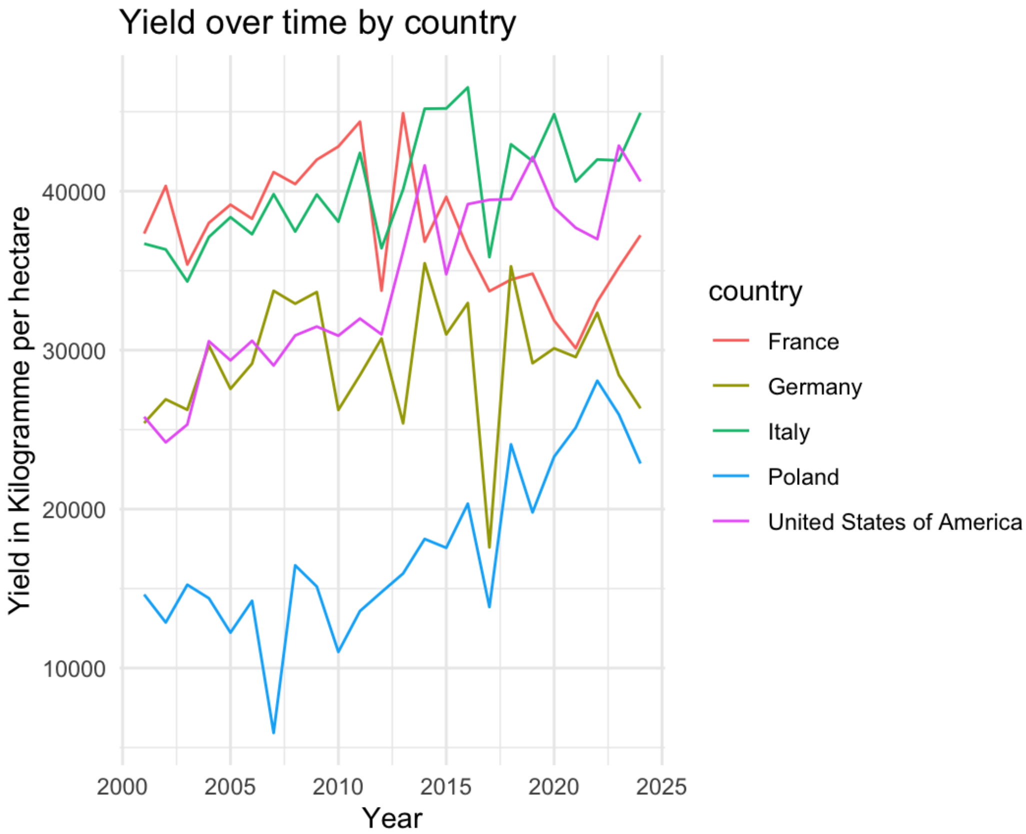

Figure 3. Yield over time.
Notes: The Y-axis is the quantity kilogramme per hectare. The X-axis represents time. The colours are different for each country

Food Consumer Price Index inflation rates

These indices measure price changes between the current and reference periods for the average basket of goods and services purchased by households. The FAOSTAT monthly Food CPI inflation rates are annual year-over-year inflation rates or percentage changes for the corresponding month of the previous year. This is used to make prices real prices. The data spans from 2001 to 2024 and covers the countries France, Germany, Italy, Poland, and the USA.

Weather data

Weather data were acquired from the Copernicus Climate Data Store. It was a Reanalysis product that provided hourly temperature data for the chosen coordinates. The places chosen were each country's highest-producing areas for apple production. For France it was Avignon in Provence-Alpes-Côte d'Azur (Latitude: 43.95, Longitude: 4.81), for Germany it was Friedrichshafen in Baden-Wurttemberg (Latitude: 47.67, Longitude: 9.51), for Italy it was Bolzano in South Tyrol (Latitude: 46.50, Longitude: 11.35), for Poland it was Grójec in the Mazovia region (Latitude: 51.87, Longitude: 20.87) and for the US it was Yakima in Washington state (Latitude: 46.60, Longitude: -120.51). The last day of spring with frost at the chosen locations is shown in Figure 4.

Frost days are the number of days in spring (March-May) when temperatures fall below 0°C. Last frost day is the last day in spring with a temperature below 0°C, where 0°C is before March, 1 is March the first, and so on.

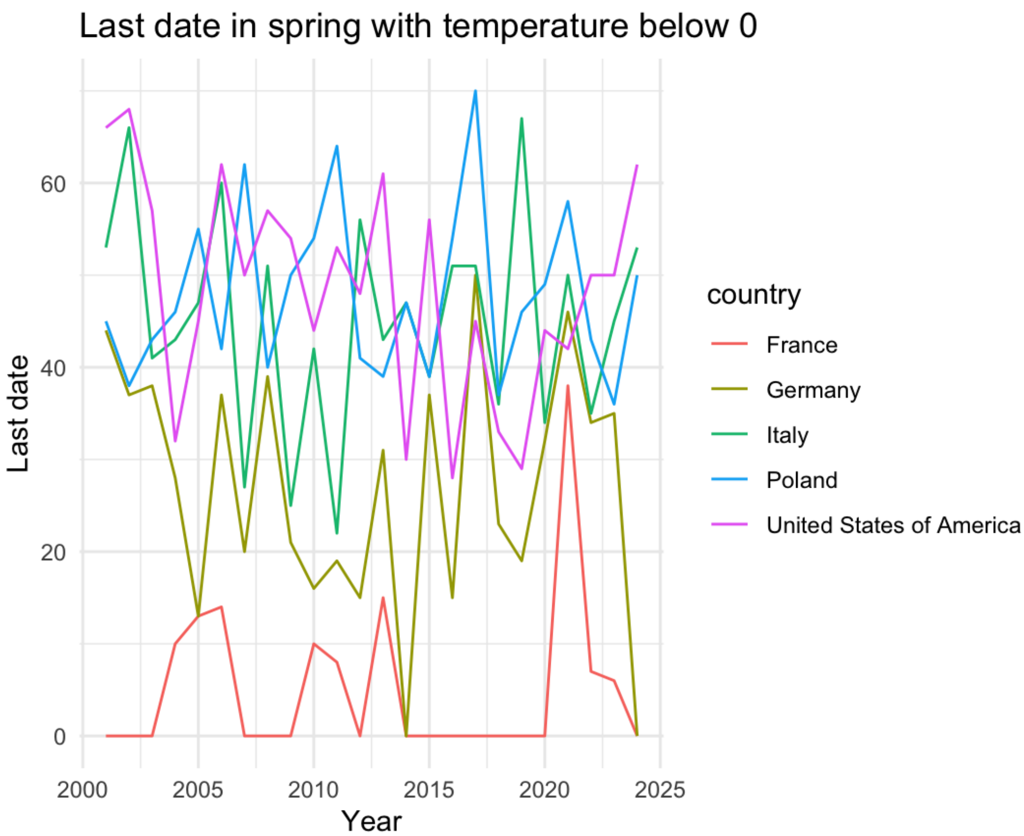

Figure 4. Weather data.
Notes: The Y-axis is the number of days with frost in the spring. The X-axis represents time. The colours are different for each country

Exchange rate

Exchange rates are defined as the price of one country's currency in relation to another. Exchange rates are provided as annual exchange rates of the Standard Local Currency (SLC) per US dollar, where SLC refers to the currency used in the most recent reference year of the statistical reference period covered. Exchange rates were acquired from FAO. The exchange rates are illustrated in Figure 5.

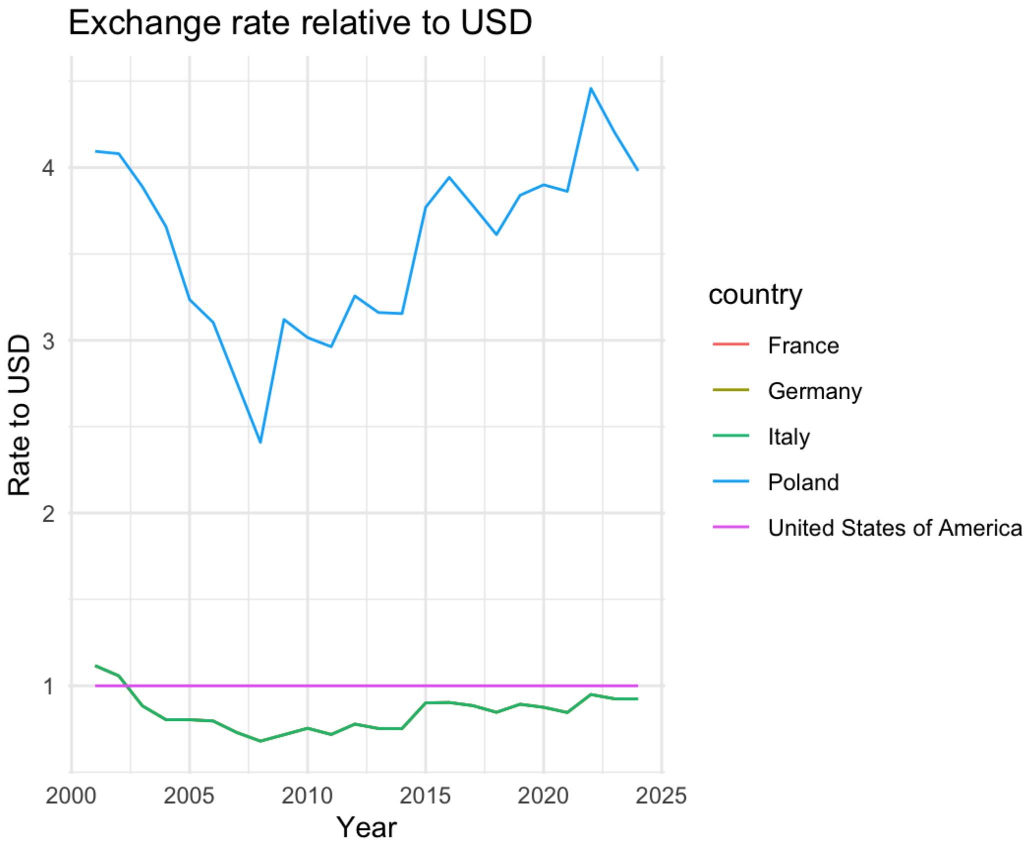

Figure 5. Exchange rate relative to USD over time.
Notes: The Y-axis is the exchange rate. The X-axis represents time. The colours differ by country: blue is the zloty, and green is the Euro.

GDP per Capita

Gross domestic product is the total income earned through the production of goods and services in an economic territory during an accounting period. It can be measured in three ways: the expenditure approach, the incomffe approach, or the production approach. The core indicator has been divided by the general population to achieve a per capita estimate. This indicator is expressed in current prices, meaning no adjustment has been made to account for price changes over time. This indicator is expressed in United States dollars and was acquired from FAO. The data spans from 2001 to 2024 and covers the countries France, Germany, Italy, Poland, and the USA. The GDP per capita for each country included in the analysis is illustrated in Figure 6.

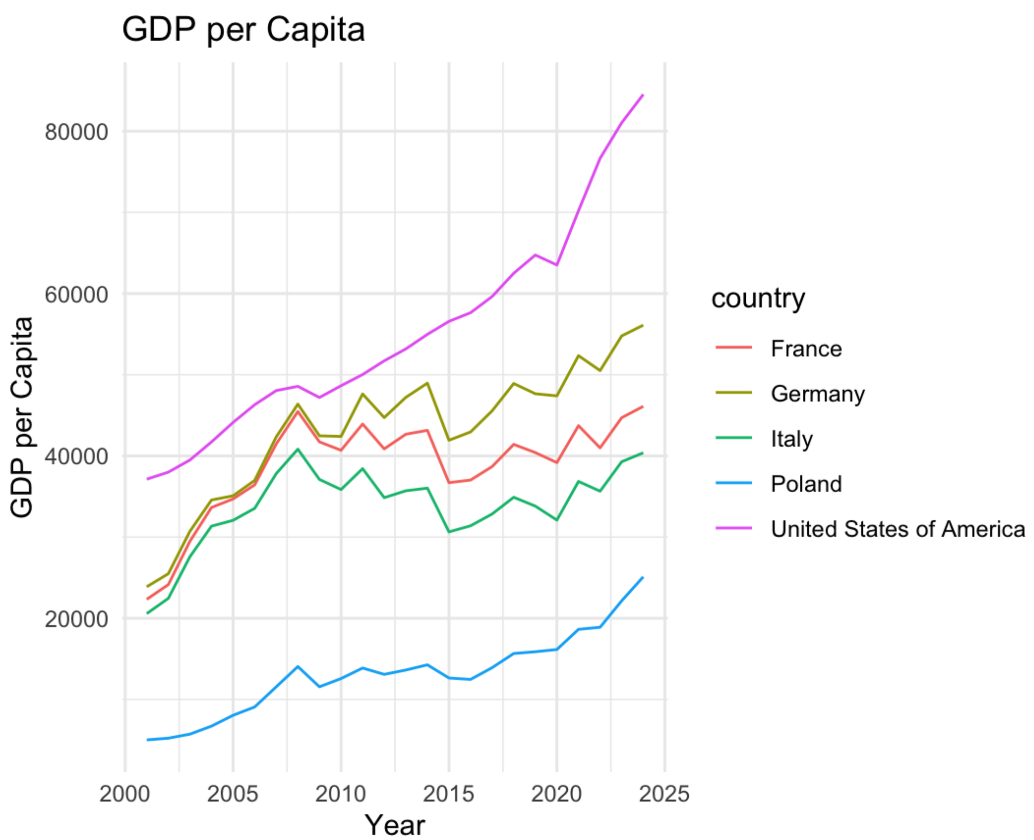

Figure 6. GDP per capita over time.
Notes: The Y-axis is the GDP per capita. The X-axis represents time. The colours differ by country.

Interest rates

The European Deposit Facility is the floor interest rate set by the European Central Bank. The deposit facility rate is the interest rate banks receive when they deposit money with the central bank overnight. This is the rate through which the Governing Council steers its monetary policy stance. Money market rates are expected to evolve around the deposit facility rate, with some tolerance for volatility, as long as it does not blur the signal about the intended monetary policy stance.

Federal Reserve data was used for the USA. The federal funds rate is the interest rate at which depository institutions trade federal funds (balances held at Federal Reserve Banks) with each other overnight. The different interest rates are illustrated in Figure 7.

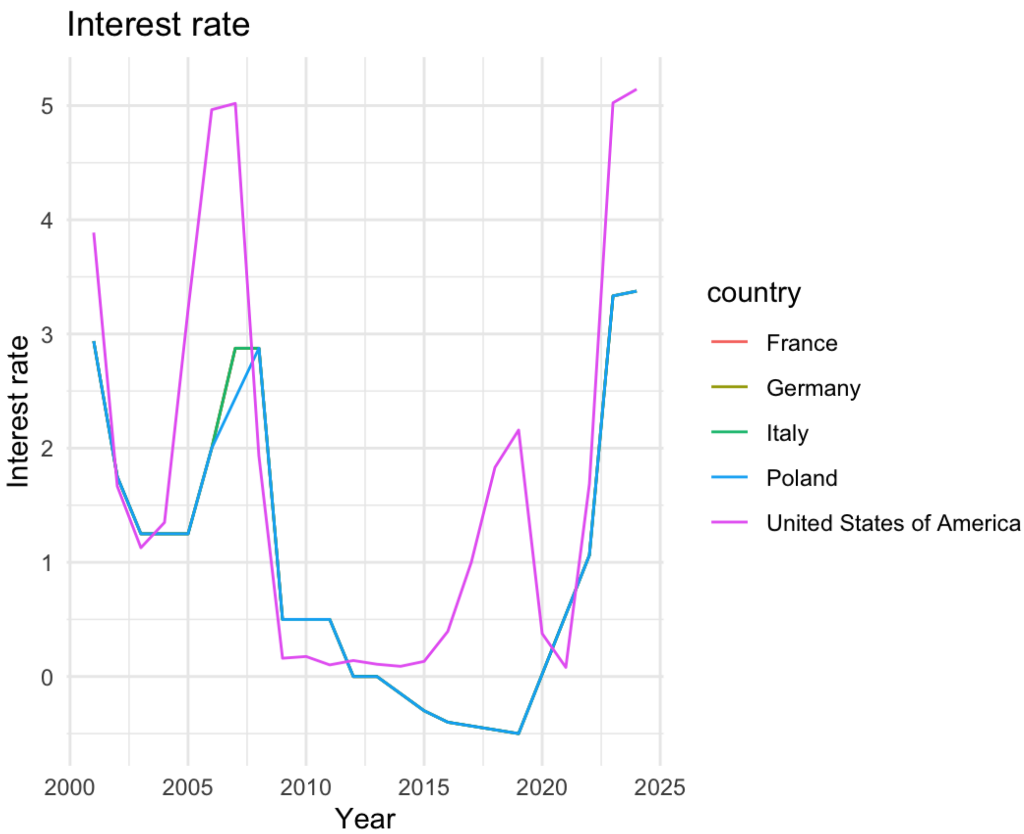

Figure 7. Interest rate over time.
Notes: The Y-axis is the interest rate. The X-axis represents time. The colours differ by country: pink represents the interest rate set by the ECB, and blue represents the interest rate set by the US Federal Reserve.

Fossil fuel price index

Brent prices are used as indicators of costs for the apple producer, since fuel is an important part of crop cultivation. Brent prices are also closely related to energy prices. The data is averaged annually and recorded in US dollars. The data was acquired from the website “Our World in Data”. The fossil fuel price is illustrated in Figure 8.

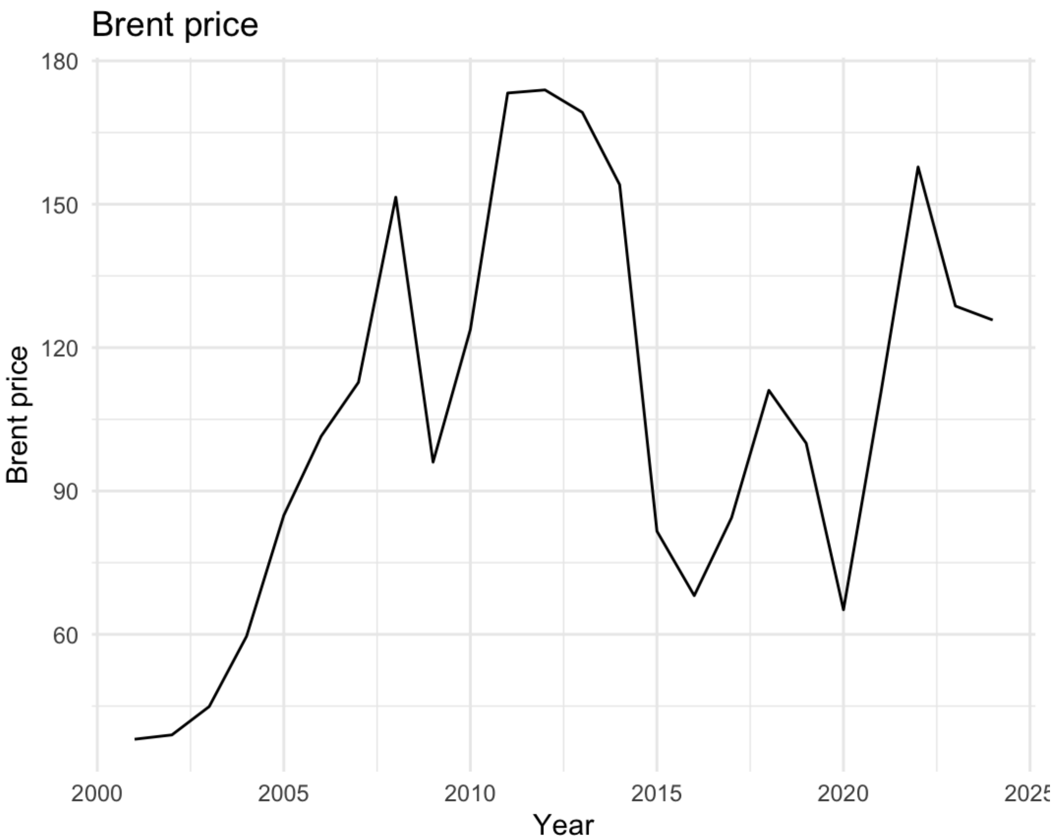

Figure 8. Oil price over time.
Notes: The Y-axis is the price of Brent Oil. The X-axis represents time.

3. Results

We wanted to understand the relationship between weather and apple prices. The results indicate a correlation between weather and prices. The results not only indicate a direct correlation between weather and prices but also show a correlation across multiple steps.

First, a direct correlation between spring frost and price is established. Then supply-and-demand mechanisms show that spring frost correlates with yield, which in turn correlates with prices. Lastly, the general model of price growth includes weather as a significant variable and emphasises the intertemporal dynamics of apple prices.

3.1 Weather and price

The first regression analysis of spring frost and price showed a positive correlation between spring frost and real prices, explaining 66.9% of the variation and supporting our hypotheses (p-value <2.2e-16, Table 1). The regression analysis, in which the logarithm of real prices is the dependent variable, suggests that if there is frost in the spring one day later, there is an associated 0.305% increase in the price (p-value < 0.059, Table 2). The logarithm of real farm-gate prices for apples with respect to spring frost is illustrated in Figure 9.

Table 1. Results of regression on last frost day and real prices.

Country	Coefficient for spring frost	Coefficient for yearly trend	Multiple R-squared	P-value of model	F-statistic
Aggregated	0.003051 .	0.034375 ***	0.6687	< 2.2e-16	37.35 on 6 and 111 DF
Without France	0.003373 .	0.034586 ***	0.64	< 2.2e-16	31.29 on 5 and 88 DF
Without US	0.003626 .	0.032730 ***	0.6302	< 2.2e-16	29.99 on 5 and 88 DF

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 2. Coefficient results of regression.

	Estimate	Std. Error	t-value	p-value
Intercept	-62.940698	5.096214	-12.350	< 2e-16
Last frost day	0.003051	0.001599	1.908	0.05895
Yearly trend	0.034375	0.002532	13.577	< 2e-16
Germany	-0.143992	0.064807	-2.222	0.02832
Italy	-0.277386	0.084192	-3.295	0.00132
Poland	-0.034537	0.087074	-0.397	0.69239
United States of America	0.021338	0.088374	0.241	0.80965

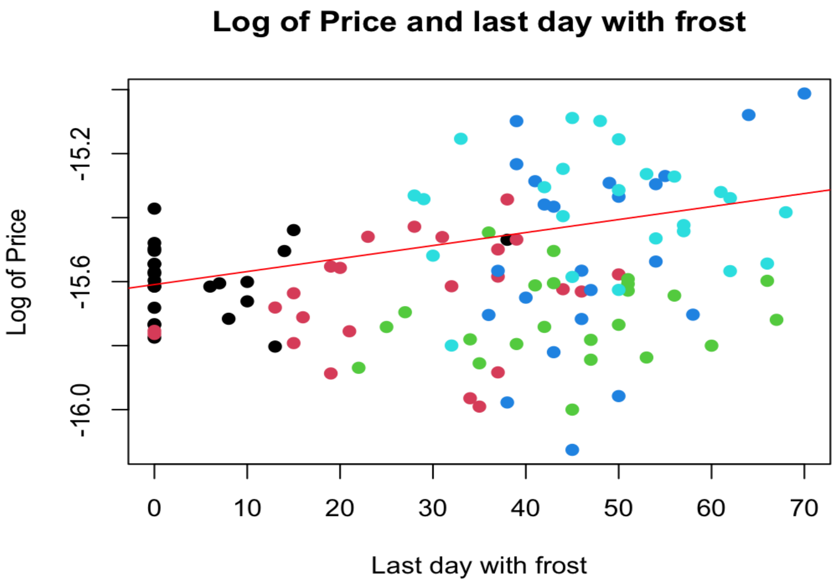

Figure 9. Log of price and last day with frost.
Notes: The Y-axis is the log of price untrended (the price trend has been removed). The X-axis represents the last day with frost, with March 1st set to one. The colours represent the different countries: black is France, red is Germany, green is Italy, blue is Poland, and cyan is the US.
Important note: The trend line is not the resulting model because it does not account for country-specific traits. This is a trend over the aggregated data.

3.2 Supply and demand mechanisms

The first-stage estimate of yield and spring frost shows a correlation between yield and spring frost, explaining 79% of the variation (p-value < 2.2e-16, Table 3). A 131.5 kg/ha decrease in yield is associated with frost occurring one day later in the spring. This regression also shows how the different countries impact the yield (Table 4). The yield for apples with respect to spring frost is shown in Figure 10.

The second-stage estimate of price as a function of yield suggests a correlation between yield and prices (p-value < 0.1, Table 5), with spring frost serving as a good instrument (Weak instruments Statistic > 10, p-value 0.00047, Table 6). It states that for every 1,000 kg increase in yield per hectare, there is a 2.61% associated decrease in prices (p-value = 0.09; Table 5).

In effect, these results imply that with last frost occurring one day later in the spring, yield is associated with a decrease of 131.5 kg/ha, which, in turn, is associated with a 0.34% increase in real prices (a 1000 kg/ha change is associated with a 2.61% change).

Table 3. Results of regression on last frost day and yield.

Country	Intercept	Coefficient for spring frost	Multiple R-squared	P-value of model	F-statistic
Aggregated	38212.2 ***	-131.5 ***	0.7891	< 2.2e-16	84.58 on 5 and 113 DF

Signif. codes: 0 ‘*** ’0.001 ‘** ’0.01 ‘* ’0.05 ‘. ’0.1 ’ ‘1

Table 4. Coefficient results of first stage linear regression of last frost day and yield.

	Estimate	Std. Error	t-value	p-value
Intercept	38212.2	880.0	43.421	< 2e-16
Last frost day	-131.5	35.6	-3.693	0.000343
Germany	-5284.0	1448.4	-3.648	0.000401
Italy	7981.1	1877.5	4.251	4.40e-05
Poland	-14196.9	1942.0	-7.311	4.08e-11
United States of America	2391.9	1971.7	1.213	0.227608

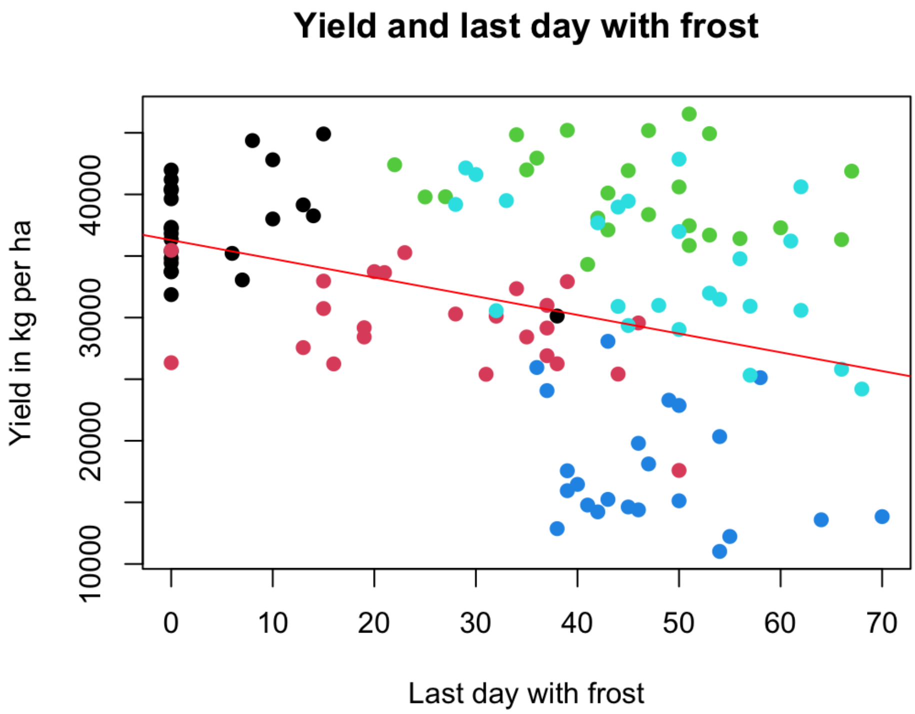

Figure 10. Yield and last day with frost.

Notes: The Y-axis is the yield. The X-axis is the last day with frost. The colours represent the different countries: black is France, red is Germany, green is Italy, blue is Poland, and cyan is the US. Also, the trend line is not the resulting model because it does not account for country-specific traits. This is a trend over the aggregated data.

Table 5. Coefficient results of 2-stage least squares regression.

	Estimate	Std. Error	t-value	p-value
Intercept	-7.572e+01	9.754e+00	-7.764	4.41e-12
Yield (kg/ha)	-2.610e-05	1.527e-05	-1.709	0.0902
Yearly trend	4.122e-02	5.081e-03	8.113	7.31e-13
Germany	-2.903e-01	1.388e-01	-2.091	0.0388
Italy	-8.477e-02	7.416e-02	-1.143	0.2555
Poland	-4.228e-01	3.086e-01	-1.370	0.1735
United States of America	6.720e-02	7.925e-02	0.848	0.3983

Table 6. Test Diagnostics of 2-Stage Least Squares.

	Df1	Df2	Statistic	P-value
Weak instruments	1	111	12.983	0.000472
Wu-Hausman	1	110	2.849	0.09426

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

3.3 Price analysis

Panel Vector Autoregression

The PVAR model gives us the resulting equation for prices (Table 7):

$$\Delta log(RealPrice_t) = -0.53\Delta log(RealPrice_{t-1}) - 0.43\Delta log(Quantity_{t-1}) +$$
$$-1.1\Delta log(GDPperCapita) + 0.0025InterestRate + 0.0062LastFrostDay +$$
$$+0.0001log(OilPrice) - 1.68\Delta log(ExchangeRate)$$

These results indicate that last year’s change in prices is correlated with this year's change in prices (p-value < 0.05, Table 7). It also shows that the exogenous control variables last frost day and changes in exchange rates are correlated with prices. The last frost day correlates with apple price growth in the model, supporting the hypothesis that weather is a significant variable in a model of apple prices. (p-value < 0.001, Table 7)

A stability test was performed, and since all eigenvalues lie inside the unit circle, the estimated PVAR satisfies the stability condition (Table 8). The eigenvalues of the estimated PVAR model are illustrated in Figure 11. This implies that shocks to the endogenous variables dissipate over time and the system converges back toward its long-run dynamic equilibrium. An impulse response function was also implemented and tried on the model. Figure 12, illustrating the Impulse Response Function, shows that the variables stabilise after an impulse within a few steps.

Table 7. The result of PVAR is the coefficients.

	Δlog_real_price	Δlog_quantity
Δlag1_log_real_price	-0.5293 ***	0.1918 **
Δlag1_log_quantity	-0.4314 ***	-0.4356 ***
Δlog_gdp_per_capita	-1.1067	0.2817
interest_rate	0.0025	0.0031
last_frost_day	0.0062 ***	-0.0049 ***
log_oil	0.0001	0.0644
Δlog_Exchange rate	-1.6819 *	0.6207

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Table 8. Eigenvalue stability condition.

	Eigenvalue	Modulus
1	-0.4824138+0.283825i	0.5597139
2	-0.4824138-0.283825i	0.5597139

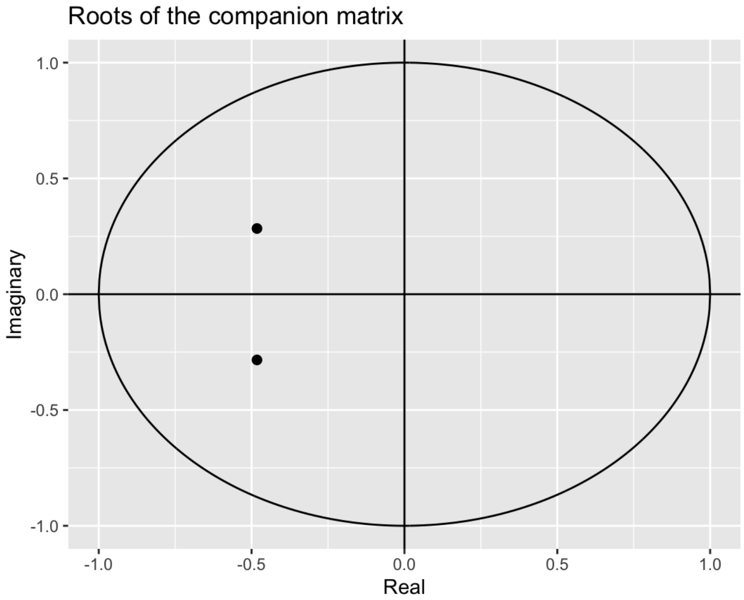

Figure 11. Eigenvalues of PVAR model.

Notes: X-axis is the real plane, and Y-axis is the imaginary plane.

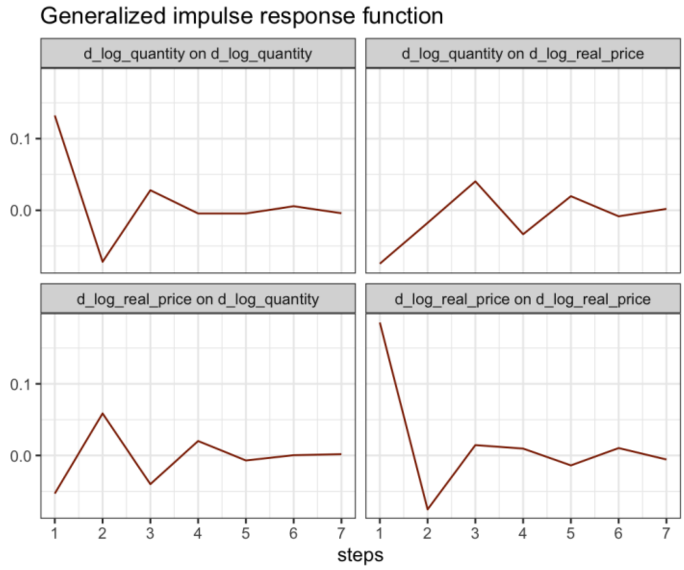

Figure 12. Impulse Response Function.

Notes: The X-axis is time steps, and the Y-axis is the percentage change from an impulse.

4. Discussion

4.1 Economic discussion of results

The results provide insight into the relationship between weather and apple prices. The direct regression between spring frost and price indicates a positive correlation. The 2-stage least squares method indicates that spring frost correlates with yield, which in turn correlates with prices. The model developed using Panel Vector Autoregression supports a correlation between spring frost and price growth while highlighting other dynamics important to understand prices. With this, we have support for all hypotheses.

The order of magnitude of the coefficients describing the correlation between weather and prices is interpreted as economically small. In the extreme case where the last frost day is one extra month later, the associated price increases by 9.153%, according to the regression that directly links spring frost and price. The regression of spring frost on yield indicates that when the last frost occurs a month later, the associated yield decreases by 4,000 kg per hectare. This is estimated to be a 12.5% decrease in yield (mean yield: 31957.83). This means that spring frost is associated with a bigger change in yield than in price. An economic interpretation of this is that the supply-chain transmission from supply to prices is not one-to-one. It could also be argued that apples are an inelastic commodity because when supply changes, the price does not change by as much.

The PVAR model indicates a 0.62% associated increase in price growth (p-value < 0.01) when spring frost occurs one day later. This is economically logical because spring frost is expected to reduce supply, and, in turn, prices should grow.

4.2 Price analysis

The model developed using Panel Vector Autoregression highlights the significance of storage dynamics. In the model, the growth of prices from the previous year negatively affects the current year's price growth (p-value < 0.001, Table 7). The negative sign on lagged prices can be interpreted as growth stabilisation, where a 1% price growth last year translates into -0.53% price growth this year.

The results from the Panel Vector Autoregression model indicate dynamic persistence and interdependence between last year's price growth and this year's price growth. In this model, lagged price growth is negatively correlated with current price growth, suggesting that higher price growth in a prior period may exert downward pressure on current price growth. Since this effect lies between zero and one, it also exhibits mean-reverting behaviour: over time, price growth stabilises at an equilibrium. Economically, this translates into price inertia, and growth tends to stabilise.

In Deaton's (1992) research, intertemporal price dynamics and the autoregressive features of prices are examined. One highlighted focus is storage dynamics and its contribution to price autocorrelation. In comparison, my results indicate that apple prices also contain autocorrelation, which can be used to argue for storage dynamics in the apple market. But with a word of Caution that the time series attribute of autocorrelation is not an implication of storage dynamics, but a feature in the data that storage dynamics can be a factor in explaining. One of Deaton's conclusions is that commodity prices generally move slowly, with high autocorrelation across time periods, but when a spike occurs and a high price is established, there is a possibility of further high prices. The results from the PVAR model are consistent with Deaton's arguments, given the mean-reverting growth rate. If the growth rate in the PVAR model spikes, prices will increase to a new level, while the growth rate will revert.

The exchange rate has a statistically significant correlation with prices in the PVAR model (p-value < 0.05), suggesting that trade-related dynamics are important for prices. But further analysis could take into account each country's specific trade relations. Trade effects related to supply-chain transmission in the apple market can be explained economically by the tendency of countries affected by a frost shock to increase imports from unaffected countries. This phenomenon is highly probable due to the localised nature of weather events within a global market, where disruptions in one region cause compensatory trade flows from unaffected regions.

4.3 Methodological discussion

Data

The weather data were collected at a single point, while price and yield statistics are at the national level. This could lead to a spatial mismatch. But I argue that the chosen places have the highest concentration of production and therefore provide a pretty good representation of each country's production. This representational argument is also used by Chen (2022).

In the time series analysis of the variables, the ADF test indicates that the last day with frost in spring contains non-stationary features (Dickey-Fuller = -2.23, p-value = 0.48), but this variable is never differenced. This is done because it is assumed that the last frost day in spring is a random process. The only reason not to accept that weather is bounded in this way would be if climate change were shifting spring temperatures.

Another thing with the data is that it would be appropriate to include a parameter to account for frost intensity. For example, Chen (2022) divided temperature into distinct thresholds, enabling analysis of whether frost severity correlates with price changes.

Regression models

The model explains 66.9% of the variation with a significant p-value, but the coefficient for last frost day is only marginally significant with a p-value of 0.059. This means the coefficient needs to be treated with caution. The same pattern is present in the 2SLS model, where the yield coefficient has a p-value of 0.09, indicating it is only marginally significant.

PVAR

Because of the non-stationarity found in the variables, this part is important for developing the mathematical dynamics underlying price formation. PVAR is a method that accounts for the cross-sectional influence of different variables, but it assumes a common slope for all countries. An easy way to question this model is then to ask if Poland should have the same growth rate as the US.

Test statistics indicate a stable, converging model, with price and quantity shocks stabilising after a few timesteps. The impulse response function exhibits oscillatory behaviour before convergence, which could be interpreted as a reactive market response.

5. Conclusion

Apples are biologically constrained commodities operating in a global economic system. In that respect, biological impacts and the economic dynamics have been studied using linear regression, and panel and time-series econometric methods.

The results imply that price is correlated with weather. The results show that later spring frost is associated with higher prices. The possible underlying relationship is studied by examining the correlation between spring frost and yield and, in turn, by highlighting associations in price changes using supply and demand mechanisms. The key contribution of this is a clear, simple line of reasoning linking weather and price behaviour. A possible further improvement would be to add frost intensity, which would provide a more advanced understanding of spring frost and its relationship with apple supply and demand.

The model of price growth using macroeconomic indicators showed that spring frost correlates positively with price growth. This is further evidence of the relationship between weather and prices. It also showed that lagged price growth correlates negatively with price growth. This result testifies to the intertemporal dynamics of price behaviour. Also, the exchange rate was a significant variable, and trade dynamics are understood to be an important influence on the apple fruit market.

In conclusion, the models do not establish any causal effects. However, they provide mutually consistent evidence that a later spring frost is associated with higher apple prices.

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