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WINE AND GLOBAL WARMING: A LONG-RUN SIMULTANEOUS MODEL

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Abstract
This paper analyzes the impact of global warming on wine yields and wine prices in a time series model with simultaneous equations. Drawing on data from 1535 to 1875 for the French region of Alsace, we show that current temperatures maximize output. Further temperature increases will lead to a substantial decline in crop yield and revenue.

1 Introduction

The summer of 2003 was the warmest summer on record in many European countries. The heat wave resulted in about 30,000 deaths and a multi-billion dollar loss in agricultural production (UNEP, 2003). However, vintners, especially in France and Germany, harvested another “century vintage” (Smith, 2003). The *New York Times* even referred to the “paradox of global warming” (Asimov, 2003). While many sectors are suffering from global warming, European wine makers are facing a period of improving quality. Since it is widely assumed that higher wine quality translates into higher wine prices, global warming should be good news for winemakers. The positive relationship between temperature and wine prices was confirmed by several studies for Bordeaux (e.g., Ashenfelter et al., 1995; Jones and Storchmann, 2001) and Mosel wines (Ashenfelter and Storchmann, 2006).[1] However, all these studies employ the so-called production-function approach, are somewhat static, and do not account for climate-induced crop substitutions.

The hedonic or Ricardian approach, as employed in a cross-sectional analysis by Mendelsohn, Nordhaus, and Shaw (henceforth MNS) (1994 and 1996), on the other hand, examines the impact of climatic and other variables on land values. It assumes that farmers try to optimize the usage of their land and may introduce new crops or change from farming to livestock or forestry when required. While this approach is superior to the production-function approach in its accounting for crop substitutions, it nonetheless suffers from serious shortcomings (Cline, 1996; Quiggin and Horowitz, 1999; Darwin, 1999; Schlenker et al., 2005, 2006; Timmins, 2006; Deschenes and Greenstone, 2006a). Specifically, MNS's hedonic approach (a) does not account for adjustment costs, (b) does not treat irrigation adequately, (c) produces results too sensitive to different weighting schemes (e.g., cropland versus crop-revenue weights), (d) omits county-fixed effects that may confuse climate with other factors (e.g., soil quality), and (e) assumes agricultural prices to remain constant.

Our analysis focuses on the latter issue and evaluates the effects of climatic changes employing a dynamic time series model for a particular region, the French Alsace. The model draws on long-run historical data and was estimated for the time period from 1525 to 1875. Relying on times series data for one geographical point purges the model of problems (c) and (d) mentioned above. In addition, since Alsatian vineyards have never been irrigated, issue (b) can be discarded as well. The model considers the complex relationship between crop yield and price simultaneously. However, it deals with wine only and other crops are disregarded. As such, this analysis is not aimed at calculating the costs or benefits of global warming with respect to the entire economy but will focus instead on grape growers' and vintners' changes in crop price and yield as well as in their revenue due to changing temperatures.

Historical prices of agricultural goods have been examined by several authors in the past. While some authors attribute price changes to monetary policy (e.g., Fisher, 1989), Abel (1980), in an influential work, describes the ups and downs of grain prices as mainly driven by population growth. Bauernfeind and Woitek (1999), on the other hand, include climatic variables for the 16th century and conclude that grain prices are mainly determined by weather. Wine prices seem to be particularly sensitive to temperature and rainfall. Especially Ashenfelter and collaborators (e.g., Ashenfelter et al., 1995; Byron and Ashenfelter, 1995) have published an array of empirical studies for different regions

[1] For warmer wine producing regions, such as Australia and California, quadratic relationships were found, indicating a beneficial effect of rising temperatures only up to a certain point and negative effects beyond this point (Ashenfelter and Byron, 1995; Haeger and Storchmann, 2005).

that confirm the crucial role of weather. However, these empirical studies on wine prices are short-run analyses for small market segments (e.g., Bordeaux Crus Classés) in which weather-induced quality improvements directly translate into price increases. Quantity effects and their feedback-impact on prices are considered only implicitly.

There is a rich agronomic literature on weather effects on crop yields including winegrapes. Almost all studies draw on *ceteris paribus* experimental field trials which deliberately control behavioral adaptations by winegrowers. An extensive literature survey is provided by Gladstones (1992).[2] Economists, however, consider crop yields as a result of a complex production process that explicitly includes behavioral elements in response to climatic variables as well as to prices. In that regard, observed yield data are superior to experimental data.

Merging observed price and crop yield data for the Alsace region of France from 1525 to 1875 into a simultaneous model shows that present temperatures are optimal for professional viticulture. However, a temperature increase by 1^{o}C will lower revenue by 2% to 9%. Further warming will lead to dramatic losses in quantity and revenue.[3]

This paper is arranged as follows: Section 2 outlines the model. Section 3 describes the database and other statistical sources. After presenting and discussing the empirical results in Section 4, we simulate the impact of temperature increases on prices, crop yields and revenue in Section 5. Section 6 summarizes the main findings.

2 Model

We consider a simultaneous two-equation model with a price (equation 1) and a quantity component (equation 2). Assuming no inventories, i.e., a perfect market mechanism due to price adjustments, quantities supplied and demanded are equal and equations (1) and (2) can be interpreted as the wine demand and supply curves, respectively.

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[2] For more recent studies see also Bramley and Hamilton (2004).

[3] Applying different methods and referring to U.S. wines, a recent study found that global warming might reduce potential premium winegrape production area by 80% by the end of the 21st century (White et al., 2006).

The price equation is given as

$$(1)\quad P_t = \beta_0 + \beta_1 P_{t-1} + \beta_2 Q_t + \beta_3 \Delta W_t + \beta_4 Y_t + \sum_k \gamma_k X_t + \varepsilon_t \ .$$

First, wine prices in year t (P_t) are assumed to have an inherent sticky component and to some degree depend on last year's prices. Under *ceteris paribus* conditions, quantity (Q_t) is inversely related to price, i.e., increasing crop yields will lead to falling prices and vice versa. Hence we hypothesize that β_1 is positive and β_2 is negative.

It is well-known that the quality of any fruit in general depends on the weather during its growing season. Several studies have examined the relationship between weather and wine prices and quality specifically for wine (e.g., Ashenfelter et al., 1995; Ashenfelter and Byron, 1995; Ashenfelter and Corsi, 2001; Jones and Storchmann, 2001). Most of these studies point to a correlation between warm, dry growing seasons and sufficient rainfall in the preceding dormant period on the one hand, and good quality and high prices on the other. "Great vintages for Bordeaux wines correspond to the years in which August and September are dry, the growing season is warm, and the previous winter has been wet" (Ashenfelter et al., 1995). We assume quality to be a relative term, assessable only in comparison to qualities in prior years. The 'relative weather' ΔW_t , therefore, denotes changes in weather in period *t* compared to prior periods and can, so our hypothesis, capture quality effects. For instance, an otherwise average vintage may be deemed "excellent" if many preceding vintages were of lower quality.[4] Therefore, a year with more beneficial weather than last year's will improve the quality rating of the wine and vice versa.

[4] Similarly, if prior vintages are to be assessed retroactively or old ratings are revised, the quality of succeeding vintages may be of importance as well.

Wine demand also depends on real income (Y_t). *Ceteris paribus*, income growth will increase the equilibrium price of wine and vice versa. Given that we can only draw on real GDP by centuries, which we interpolated using constant growth rates, (Y_t) does not account for sudden shocks or temporary variations. Therefore, X denotes a vector of exogenous demand shocks such as plague outbreaks or revolts.

Crop yield (quantity supplied) in year *t* (Q_t) is assumed to be a function of last year's crop yield, wine prices during prior periods ($P_{t-\tau}$), weather-related variables (W_t), and a vector of other variables (X_t). Here, the lagged dependent variable captures the 'capital stock effect', i.e., a certain acreage planted is associated with a particular 'base production'.

(2) $Q_t = \alpha_0 + \alpha_1 Q_{t-1} + \sum_i \pi_i W_t + \alpha_2 P_{t-\tau} + \sum_j \lambda_j X_t + \varphi_t$

Weather related variables W_t affect crop yields in two ways. In the short run, weather variables have an immediate effect on the crop yield in period *t*. In the long run, climatic changes will affect the area under vines and will, therefore, influence the 'base production'. For instance, long-term climate changes may shift the northern frontier of professional viticulture in Europe. Waldau (1977) and especially Weber (1980) give a detailed account of – possibly partly climate induced - shifts that occurred over the last 800 years.

On the other hand, weather induced quantity decreases lead to price increases which, in turn, induce future quantity increases (*hog –cycle*). Finally, we consider exogenous shocks that might affect crop yield such as wars, vine diseases (unrelated to weather), or different policy variables.

3 Data and Sources

The analysis requires four different sets of data: (1) data on wine prices, (2) data on crop yields (must supply), (3) climate data, and (4) income data.

We draw on Alsatian wine prices as provided by Hanauer (1878). Hanauer reports prices of young wines ('*vin noveau*') for different Alsatian towns and villages, such as Strasbourg, Colmar, and Châtenois, for the time from 1478 to 1875. Since it was the most complete time series, we referred to average quality wine ('vin ordinaire') price data reported for Châtenois, a small village located in the French Bas-Rhin department, approximately 30 miles south of Strasbourg (see Figure 1). Until 1799, prices are given in pfennig per ohm,[5] thereafter Hanauer reports French prices in francs per hectoliter. We transformed the latter and used pfennig per ohm for the entire time period. In addition, Hanauer accounts for changing metal values of the pfennig and the franc, respectively, and also reports real prices in terms of grams of silver per hectoliter. A few data gaps were filled referring to the growth rates of wine prices for the village of Steinbach in the German Baden region. Andermann (1997) reports average nominal market prices for Steinbach, which is located approximately 40 miles from Châtenois, from 1475 to 1803. Figure 2 shows the wide variation in Alsatian nominal and real wine prices from 1478 to 1875. For the following calculations we refer to real prices only.

A complete time series of four centuries of Alsatian wine grape yields[6] is not readily available. Muller (1991, 1993, 1997, 2005) reports wine must quantities produced for select time periods and vintners. However, for the purpose of this analysis the data are too patchy and diverse. We, therefore, referred to Swiss harvest data as reported by Pfister (1981, 1988). Drawing on tax registers, Pfister provides numerous local and regional grape yield data from 1529 to 1825. As the most comprehensive series we selected the regional series for Zurich and its environs. We then completed the series by referring to official wine harvest statistics of the state of Württemberg (from 1827

[5] The size of the ancient German measurement "ohm" differed from region to region. For Châtenois, one ohm is an equivalent of approximately 50 liters (Hanauer, 1878).

[6] Given the insignificance of domestic raisin production, all grapes were used for wine production. We, therefore, use the terms *wine harvest yields*, *crop yields* and *wine supply* synonymously.

onwards) (Württemberg, 1899). The gap, i.e., the year 1826, was interpolated using the growth rates of harvest data for the Alsatian town of Barr (Muller, 1991).

Since there are no instrumentally-gauged weather data for the high middle ages, climatic data pose a more difficult issue than prices or yields. In fact, the oldest instrumentally measured time series is the so-called Manley temperature series for middle England, which starts in 1659 (Manley, 1974). The world's oldest precipitation data series is the one for Kew Gardens in London and begins in 1697 (Wales-Smith, 1971).[7] The longest instrumental temperature and rainfall data series for Alsace (Strasbourg) begins in 1801 and 1803, respectively (Oldenborgh, 2004), and is too short for our long-run analysis. Temperature data for the Swiss town of Basel date back to 1755. Precipitation data for Zurich start in 1708 (but exhibit many gaps especially in the 18th century).[8] We utilized the longest complete series of instrumentally measured weather data for the European continent which was measured in the Netherlands. Temperature data are for de Bilt (1706-2005) and precipitation data are for Hoofdorp (1735-2005). However, all instrumentally-measured weather data result in the omission of a large part of our observation period.

As an alternative to instrumental climate data we can also draw on climate time series data developed by paleoclimatologists. Historical climatology is aimed at broadening the understanding of weather and climate before the beginning of instrumental measurements. Drawing on non-instrumental man-made sources (e.g., records, documents, flood marks) and proxy variables (e.g., tree rings, ice core data), index data for temperature and precipitation back to the 15th century and before were computed (see e.g., Brázdil et al., 2005; Glaser et al., 1999, Bradley, 1998).

Pfister (1988, 1998, 1999) provides monthly index data for temperature and precipitation in Switzerland starting with the year 1525. The data do not refer to a particular location but denote the average climate for all of Switzerland. Temperature and precipitation data

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[7] Updated data for both series are downloadable from the database of the Royal Meteorological Institute of the Netherlands, the Koninklijk Nederlands Meteorologisch Instituut KNMI (Oldenborgh, 2006).
[8] Both data series are downloadable from the KNMI server (Oldenborgh, 2006).

are defined as standard deviations from the 1901-1960 average. They are provided as monthly indices and can take on three values (+1, 0, -1), where 0 represents the 1901-1960 average. An index of +1 denotes a warmer or wetter month, respectively. Similarly, an index of –1 stands for a cold or dry month. For the entire growing season from April to October the indices can, therefore, take on 15 values ranging from -7 to +7. Since the indices are generated as standard deviations of measured temperature data (Pfister, 1988) we do not interpret them as qualitative but as quantitative variables. Henceforth, the model employing these indices will be called CH-1. Pfister also provides more refined monthly indices ranging from -3 to +3 leading to a growing season range from -21 to +21. The model that refers to these indices is denoted CH-3. Similar index data for Germany are provided by Glaser (1997, 2001) (GER-3). For the estimates, all temperature index data were transformed into positive numbers so that the lowest monthly value is equal to one.

Figure 3 shows the development of temperature indices over the last 500 years. For the sake of comparability, the figure also shows instrumentally-measured temperature data for the city of Basel (for 1755-2006), which closely follow the index data. Both data series show the steady temperature increase of the last 100 year to their peak today.

Income data were taken from Maddison (2003), who provides real GDP for several countries for the end of each century. Since Alsace was part of the Holy Roman Empire (mostly Germany) until the late 17th century and became part of France thereafter, we can refer to income data for either country. Whereas France's income had grown slightly faster between 1600 and 1700, Germany's GDP grew substantially more dynamically in the 19th and 20th century. Given the dominant role of the German Empire as market for Alsatian wines (Barth, 1958), we refer to German income data. This procedure was also corroborated by better regression results, i.e., a higher significance for the German over the French data. We interpolated the data with intra-century constant growth rates.

Between the 15th and 17th century all of Europe went through a multitude of plague outbreaks. All outbreaks (worldwide) by city are reported in Biraben (1975). We were, therefore, able to compute a dummy variable that takes on the value one for a plague outbreak in Alsace[9] and a value of zero otherwise. A disadvantage of this approach is that a dummy variable cannot account for the severity of each outbreak. Hatje (1992), however, reports detailed plague mortality rates for the city of Basel in Switzerland. Given the close proximity of Basel to Châtenois (55 miles),[10] these data appear to be a good proxy variable for Alsatian fatalities. In addition, due to its role as an important emporium and trade hub for Alsatian wines (Barth, 1958), plague outbreaks in Basel may have directly affected the wine demand.

Between 1500 and 1875, several wars, rebellions and uprisings haunted Alsace and the adjacent regions. The Thirty Year's War (1618-1648) in particular caused major devastation. Barth (1958) and Muller (1991, 1995, 1997, 2005) provide a detailed account of these events and their impact on infrastructure, viticulture, and society. We considered major disturbances by including dummy variables that take on the value one in the year of the event and zero otherwise.

Table 1 summarizes the descriptive statistics for both dependent and independent variables.

4. Results

We specified equation (1) as a log-log equation where the coefficient β_2 is the short-run price elasticity with respect to quantity.[11] Similarly, $\beta_2/(1-\beta_1)$ denotes the long-run elasticity. The 'relative weather' term, ΔW_t, was defined as the growing season temperature in year *t* minus the average growing season temperature over the preceding ten years. In contrast to Ashenfelter et. al (1995), we focused on temperatures only and disregarded rainfall. This procedure is corroborated by Jones at al. (2005), who explain wine quality in dependency on growing season temperatures only. To account for declining comparability opportunities over time due to the fact that older wines get

[9] The dummy variable accounts for outbreaks in Strasbourg, Colmar, Freiburg, and Basel.
[10] The distance between Basel and Steinbach in Baden (Germany) is approximately 95 miles.

consumed or spoiled we weighted the average by giving more weight to more recent vintages. The term was specified as

(3)

$$\Delta W_t = Temp_t - (0.19Temp_{t-1} + 0.17Temp_{t-2} + 0.15Temp_{t-3} + 0.13Temp_{t-4} + 0.11Temp_{t-5} + 0.09Temp_{t-6} + 0.07Temp_{t-7} + 0.05Temp_{t-8} + 0.03Temp_{t-9} + 0.01Temp_{t-10})$$

where *T* denotes growing season temperatures (May to October).[12] However, wine in the year 1500 was different from what it is now. It could not be stored for longer than one year (until the next vintage arrived) and most wines were 'enhanced' by adding spices and herbs, resin, high-percentage brandy or cooked wine (Unwin, 1991). It was not until the late seventeenth century that wine kept in bottles and sealed with shaped corks, lasted much longer than a single year while not easily oxidizing or assuming the taste of its container, which enabled the production of 'vintage wines.' The production of these 'new wines' began in Bordeaux and the first vintage wine was introduced to London in 1666 (Unwin, 1991). In France, the sale of wine in bottles was illegal before 1728 (Crestin-Billet, 2001). Along with the introduction of new production technologies (e.g., the usage of new oak barrels, sterilization with sulfur wicks, fining with egg whites) and the development of corkscrews in the late 18th century, wine bottles also became increasingly common outside of Bordeaux (May, 2003).

We hypothesize that the quality variable is not relevant for Alsatian wine before the late 18th century but gets increasingly more important afterwards. This assumption is implemented into the model by multiplying ΔW_t with a trend variable that becomes effective in the late 18th century and takes on the value zero beforehand (*trend1785*). The model generates the best results for the trend onset year of 1785.

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[11] Note that the elasticities derived from the equation differ markedly from those derived from the simultaneous model.
[12] We also tried geometric weights as well an unweighted average. All forms yield similar results.

We suppose that the temperature differential caused quality effect, i.e., the effect of ($trend1785 \cdot \Delta W_t$), becomes less important with increasing temperatures.[13] Hence, we divide ($trend1785 \cdot \Delta W_t$) by the natural logarithm of the growing season temperature and yield the variable $(trend1785 \cdot \Delta W_t)/\log(Temp)$.

The vector of other variables (X_t) is comprised of mortality rates during plague outbreaks in the city of Basel, a trend variable, and some year specific dummy variables.

The price equation to be estimated is specified as

$$\begin{aligned} \log P_t = {} & \beta_0 + \beta_1 \log P_{t-1} + \beta_2 \log Q_t + \beta_3 (trend1785 \cdot \Delta W_t) / \log Temp_t + \\ & \beta_4 \log Y_t + \beta_5 PLAGUE_t + \sum_k \gamma_k D_t + \varepsilon_t \end{aligned} \tag{4}$$

In the crop yield equation (5), the weather vector is comprised of two temperature and two precipitation variables. In many studies growing season temperature was found to have a linearly positive relationship with European wine quality and price (e.g., Ashenfelter et al., 1995; Jones and Storchmann, 2001; Ashenfelter and Storchmann, 2006). However, recent analyses show that quadratic specifications might be more appropriate for warm climate wine regions. This approach suggests that increasing temperature improves the quantity (and quality) produced, but at a decreasing rate. Ultimately, if temperature is higher than a certain optimum, grape quality and quantity declines.[14] Wine related examples for quadratic specifications are the papers by

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[13] We do not find any indication for negative quality effects of above average temperatures. This is certainly not true for warm climate wine regions (see also Jones et al., 2005).

[14] Deschenes and Greenstone apply quadratic temperature functions in a large panel model for corn and soybeans (2006b). Schlenker and Roberts (2006) show that average temperature data that hide extreme events cloud the true relationship between temperature and crop yields. This is particularly true if the relationship is sharply nonlinear, i.e., if moderate temperatures are beneficial for yields but temperatures beyond a certain threshold cause yield to drop abruptly. As a remedy, they refer to hourly temperature exposure and show that for corn, soybeans, and cotton the 'true temperature-yield curve' is less smooth than a quadratic specification using average temperatures would suggest. Due to the lack of detailed weather data, we are unable to follow this approach.

Ashenfelter and Byron (1997) and Anderson and Woods (2006) for Australian Wine or Haeger and Storchmann's paper (2005) on Californian Pinot Noir. Jones et al. (2005) compare linear and quadratic specifications with respect to wine quality for all major wine regions in the world. It is shown that, except for the northernmost wine regions of Mosel and Rhine, quadratic specifications are superior.[15] We follow this approach.

With Ashenfelter et al. (1995) and Storchmann (2005), we assume that a wet winter prior to the growing season and a dry blossoming period are beneficial for grape quality and quantity.

The quantity of wine produced is a function of the wine price. However, due to the underlying production process, wine production exhibits a lagged response to price changes. Some adjustments can be made in a very short time period (e.g., pruning, determination of the harvest time and grape selection, fertilizing, pressing intensity), while others require considerably more time. The latter is particularly referring to changes in the area planted with vines. Since a newly planted vineyard does not provide grapes before the third year, we expect the quantity response to a price increase to grow in a quadratic pattern with a peak between the 5th and 10th year after initial impulse. This response pattern is best addressed by employing a lag scheme that follows a quadratic polynomial (*Almon lag*),[16] where the lag length is determined in a trial and error process (see also Davidson and McKinnon, 1993). Based on Schwarz and Akaike information criteria we choose an eleven year period and impose restrictions at both the near and the far end. The estimated crop yield equation is

$$\begin{aligned}\log(Q)_t = \alpha_0 + \alpha_1 \log(Q_{t-1}) + \pi_1 Temp_t + \pi_2 Temp_t^2 + \pi_3 RainW_t + \pi_4 RainB_t + \\ \alpha_2 PDL(\log P_t) + \sum_j \lambda_j D_t + \varphi_t\end{aligned} \tag{5}$$

where *PDL(P_t)* represents the polynomial distributed lag function of the natural logarithm of the wine price. *RainW* denotes winter rainfall prior to the growing season and *RainB*

[15] This is supported by viticultural research for Italy. Bindi et al. (1996) show that the yields (dry matter per hectare) of Cabernet Sauvignon and Sangiovese will decrease significantly with further warming.

stands for rainfall during the blossoming period. The vector *D* denotes annual dummy variables.

Given the simultaneity between the price and quantity equations (4) and (5) is estimated applying 2SLS. We estimate the model for different climate data – the index data CH-1, and CH-3, and instrumentally measured weather data for the Netherlands and Basel-Zurich (Table 2). Note that the time period covered differs substantially from CH-1 starting in 1535 to Basel/Zurich beginning in 1770. In addition, some data series are fairly incomplete. In fact, almost a third of the CH-3 and the Basel-Zurich series is missing.

With R^2 values between 0.56 and 0.73 all price models exhibit a reasonably high goodness to fit (Table 2). All variables show the correct sign and most of them are highly significant. Both the quantity and the quality variable are significant in all models. The plague mortality variable is significant (at the 9% level) only for the CH-1 model and insignificant in the other models using index data. This may be due to the long distance between Basel and Châtenois or the existence of exports markets that are further away. Since the last plague outbreak in Basel occurred in 1667/68 this variable is not included in the models using instrumentally-measured weather data.

As shown in Table 3, the wine yield models exhibit a similarly satisfactory goodness to fit. All variables show the correct sign and most of them are highly significant. The only exception are the Dutch rainfall variables suggesting that rainfall exhibits lower spatial correlation and is more locally concentrated than temperature.[17] All models show that the influence of temperature on wine yields follows a quadratic specification. Taking the partial derivative and setting it equal to zero enables us to calculate the optimal growing season temperature as

$$\frac{\partial Q}{\partial T} = \pi_1 + 2\pi_2 T = 0$$

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[16] Distributed lags are widely used in agricultural economics (see e.g., Chen et al., 1972).
[17] Note that the distance between Hoofdorp and Zurich is approximately 450 miles.

For the NLD model, for instance, this results in an optimum cumulative growing season temperature of 102.18 ^{o}C, which equals 14.59 ^{o}C per month. During the 158 years between 1718 and 1875, this threshold was exceeded seven times. However, between 1995 and 2006 alone, this was the case six times.

The distributed lag function is statistically significant at the 2% level for all but the CH-3 model (significance level 7.9%). It appears that a price change within any given time period has little immediate impact on wine production. According to Figure 4, which shows the b_i coefficients for the CH-1 and NLD model, a price change exhibits its maximum effect five to six years later, with the NLD model exhibiting a stronger price-quantity feedback than the CH-1 model.

In order to compare the performance of the models in a simultaneous dynamic ex-post solution we drew on the usual measures mean error (MEAN), mean absolute error (MAE), root mean squared error (RMSE), and mean percentage error (MAPE). As reported in Table 4 all models yield similar results. Because of their slightly better performance, we choose the CH-1 (index data) and the NLD model (instrumentally measured data) for the following temperature simulations.

5. Model Simulations

To model the impact of global warming on crop yields and prices, we increase the monthly temperature values by increments of 0.5^{o}C up to a maximum change of 4^{o}C compared to the base period. While this procedure is straightforward for degree Celsius data of the NLD series, the CH-1 series needs to be transformed.

Since the indices are defined as standard deviations from the 1901-1960 average, it is generally possible to convert them into degree Celsius temperatures and millimeter rainfall values (Pfister, 1988). However, given the error margin for monthly values, the calculation of temperature, and the precipitation values, the transformation is to be interpreted with caution. A simple regression of growing season temperatures from May to October over the corresponding indices from 1755 to 1875 yields the following results:

(6)	Temp	= 0.296 * Index	+ 15.107
		(15.1)	(494.2)
	R^2=0.831	adj. R^2=0.830	F statistic = 567.4
			(t values in parenthesis)

where *Temp* denotes the average growing season temperature (May-Oct) and *Index* the cumulative growing season index of the CH-1 model. Thus, a change of one degree Celsius for the entire growing season corresponds to a variation of approximately 3.38 index points.

Table 5 reports the results of the model simulations separately for price, quantity, and revenue and shows that both model yield similar results. As expected, price and crop yield are moving in opposite directions, i.e., increasing quantities coincide with decreasing prices and vice versa. Both models exhibit nonlinear crop yield and price developments. Crop yields increase with rising temperatures up to a certain threshold and decrease thereafter. In the CH-1 model this turning point is reached at a temperature increase of 1.42°C; for the NLD model this is 1.23°C. Similarly, prices reach their trough at an additional warming of 1.49°C (CH-1) and 1.25°C (NLD), respectively.

The trade-off between quantities and prices is reflected in revenue. According to both models moderate warming has a beneficial effect on revenue. Revenue peaks at an additional temperature increase of 1.47°C in the CH-1 model and 1.28°C for the NLD model, respectively. Beyond this point revenues decrease rapidly reflecting the exponential decline in crop yields.

Figure 5 shows the impact of global warming on revenue and display surprising similarities between the model referring to index weather data and that one using instrumentally measured data. The curves suggest that (1) a further temperature increase is still beneficial in both models and (2) the turning point is slightly further away in the CH-1 model whereas (3) the exacerbation after the turning point is stronger in the NLD than in the CH-1 model.

These suggestions must be approached with caution since the starting point, i.e., the point from which temperature increases, is not referring to the present time but to the time period the model was solved. For the CH-1 model this is 1535-1875 and for the NLD this is 1736-1875. Since then, temperatures have increased already. The growing season temperature average for the time period from 2000 to 2006 is about 1.1^{o}C (CH-1) and 1.38^{o}C (NLD), respectively, higher than in the reference period.

The arrows in Figure 5 indicate the average growing season temperature from 2000 to 2006 and show that the beneficial part of temperature increases already belongs to the past. Current viticulture in Alsace already operates at its revenue maximizing temperature and further warming will cause crop yield and revenue losses. Compared to the average growing season temperature from 2000 to 2006, warming by 1^{o}C will lead to a decline in revenue of 2.0% (CH-1) and 8.9% (NLD), respectively. Warming by 2^{o}C will cause losses between 15.7% (CH-1) and 21.3% (NLD) compared to the average revenue between 2000 and 2006.

6. Summary

In this paper, a simultaneous two equation model for wine prices and crop yields is introduced. We refer to long-run data for the French region of Alsace covering a 450-year time period from 1525 to 1875. Since measured weather data for Alsace for the observed time period are not available we referred to index weather data for Switzerland, as well as instrumentally measured weather data for the Netherlands. Both data bases led to surprisingly similar results.

(1) Wine prices are determined by wine quantity (crop yield) and wine quality. While high quantity has a negative influence on the price, better quality raises the wine

price.

(2) Wine quality appears to be a relative term depending mainly on the quality of prior vintages and, therefore, on temperatures in preceding years. Above average temperatures will produce above average wine qualities. However, the logarithmic specification indicates that quality improvements do not grow linearly but slow down with rising temperatures.

(3) Crop yields crucially depend on weather conditions. Precipitation prior to the growing season has a beneficial effect on wine quantities whereas rain during the blossoming period will lead to lower crop yields. Increasing temperature is beneficial for wine quantity, but at a decreasing rate. Ultimately, if temperature is higher than a certain optimum crop yields will decline at an increasing rate.

(4) Crop yields also depend on wine prices in preceding years. With a time lag, high wine prices will induce higher crop yields and more plantings and vice versa.

(5) The model suggests that present temperatures are optimal for crop yields and close to optimal for wine quality. Any further warming will lead to a decline in wine quantities. The entailing price increase is too small to offset this effect. Thus, rising temperatures will result in revenue decreases. A warming by $2^{o}C$ is likely to lead to a fall in revenue between 16% and 21%.

However, results of a model that explained the wine market of centuries ago might not be readily applicable for current viticulture. There are two possible caveats.

First, vintners may be able to breed new heat resistant clones or substitute warm climate varietals for the current ones in order to minimize or even offset crop losses. That way, global warming would be less harmful than the model suggests. However, since the model relies on observed data -- rather than experimental data -- behavioral adaptations are already accounted for. There were major changes in training methods and varietals planted between 1535 and 1875. The presently predominant varietals Riesling, Pinot Blanc, Gewürztraminer, and Tokay d'Alsace (Pinot Gris) have not always been the leading Alsatian varietals. In fact, most of these varietals were introduced during the 17th and 18th century. Riesling was first mentioned in 1628; Gewürztraminer and Tokay d'Alsace were introduced around 1750 (Barth, 1958). In addition, the ability to adapt to rising temperatures may depend on the dynamics of temperature changes. Given the relatively quick temperature increases of the last 100 years, compared to the model's base period (see Figure3), current adaptation requirements are certainly higher than captured by the model.

Second, even if rising global temperatures impair crop yields in Alsace it will benefit cooler regions such as the German Mosel valley (Ashenfelter and Storchmann, 2006) or regions that have not been appropriate for viticulture in the past. Due to declining transportation cost, even wines from Australia or South America can replace European wines. Global trade is, therefore, likely to fill the void left by crop losses in Alsace and tend to offset the (small) positive price effect. This will enforce the negative impact of prospective temperature increases.

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Figure 1
Châtenois, Basel, and Steinbach

Figure 2

Wine Prices in Châtenois

1478-1498=100, moving 20-year averages

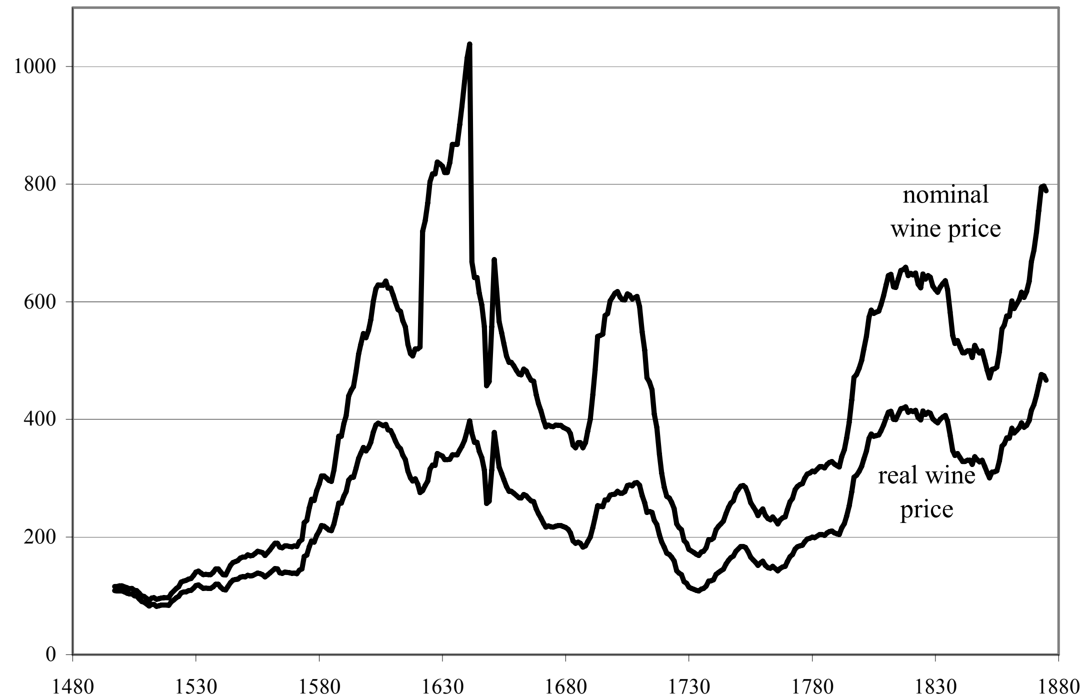

Figure 3

Annual Temperatures in Switzerland

CH-1 Index Data and Basel Degree Celsius 1525-2006

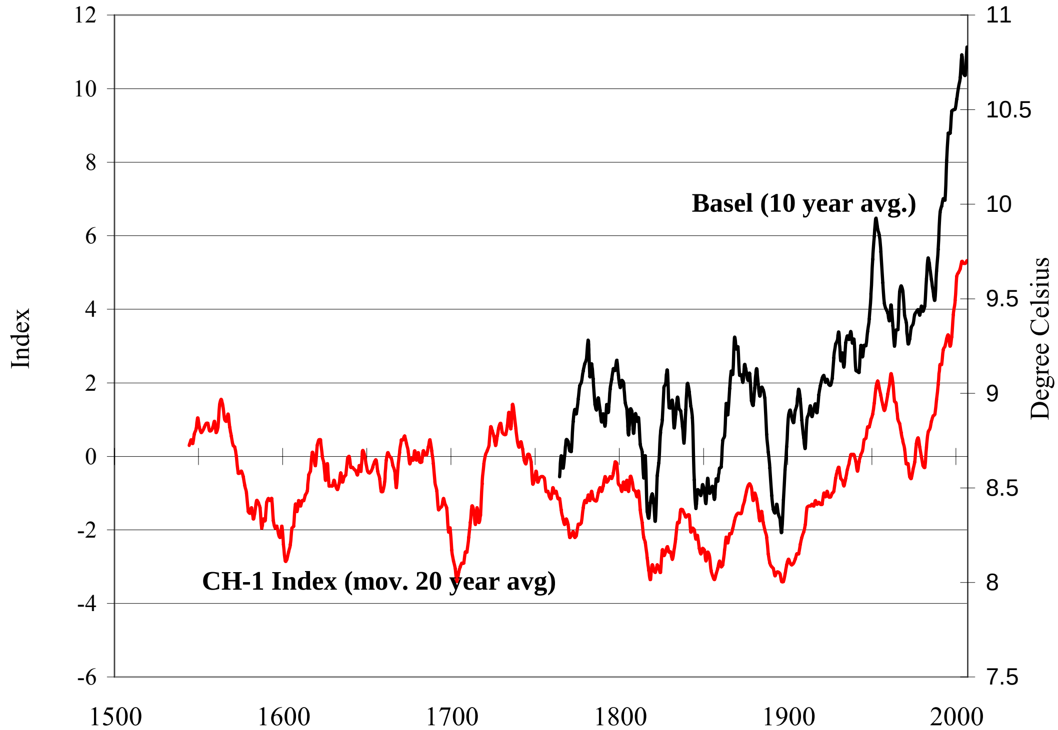

Figure 4
Polynomial Lags for Wine Production Response

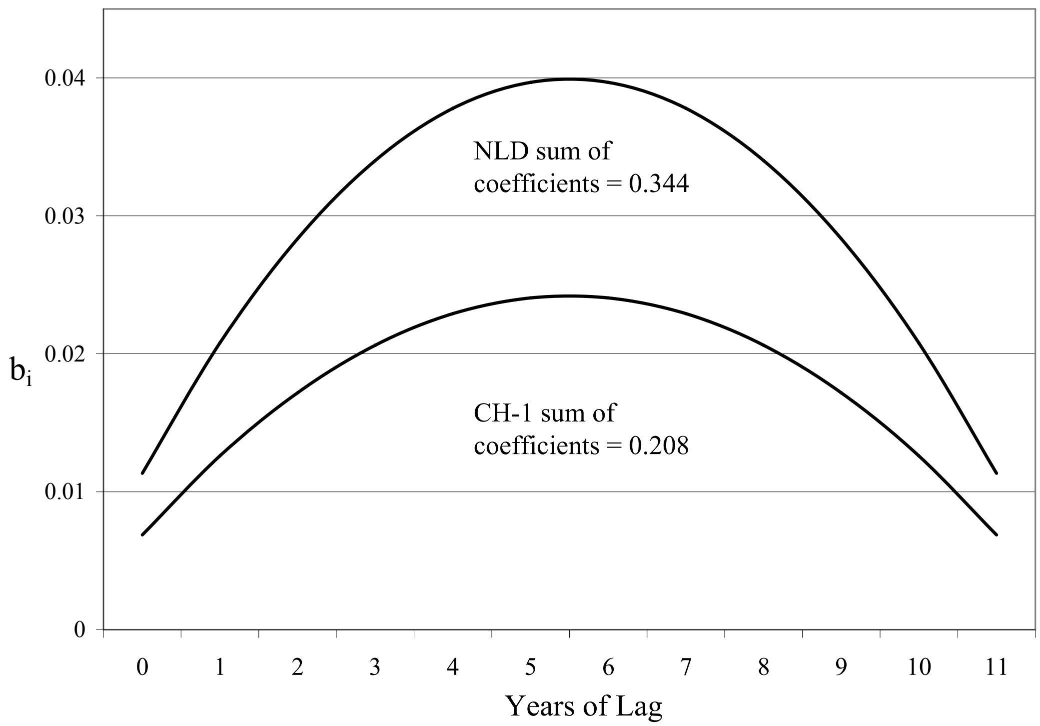

Figure 5
Impact of Global Warming on Revenue
Percentage Changes Compared to Model's Reference Time Period

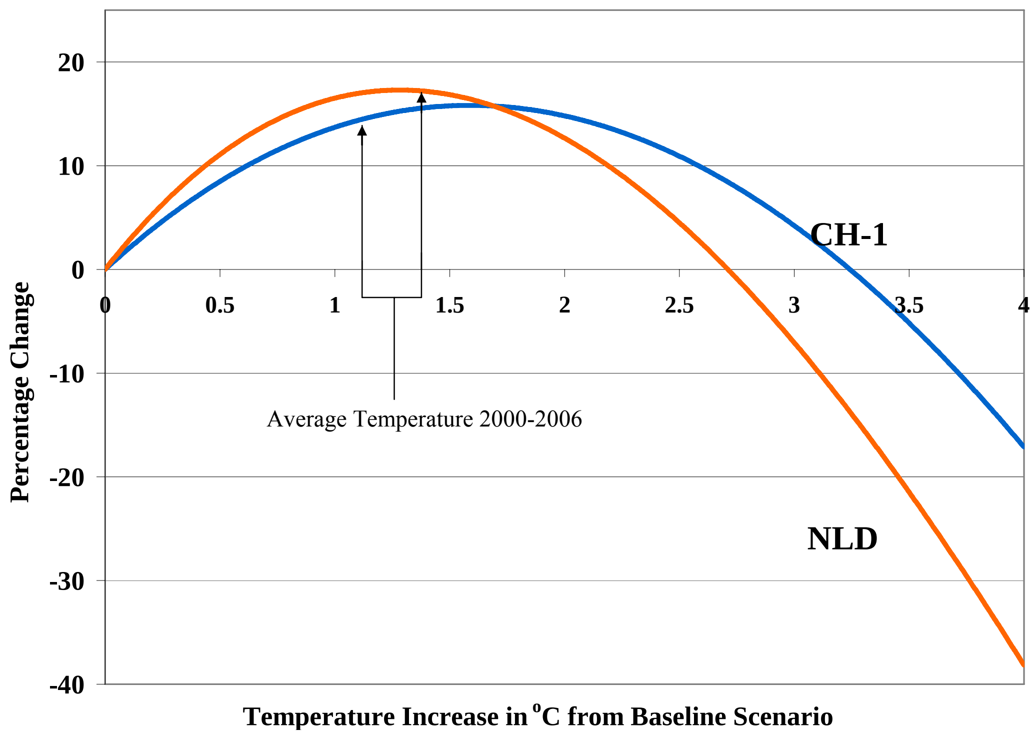

Table 1
Descriptive Statistics of Variables

Variable	Minimum	Maximum	Mean	Standard Deviation
Wine Price Real (gram silver/hectoliter)	9.1	205.8	61.5	36.3
Wine Quantity	1.0	245.6	51.7	38.7
Plague Mortality (%)	0.0	52.6	0.7	3.6
Real Income (million 1990 $)	8.3	155.7	25.3	26.4
Temperature				
CH-1 Growing Season (Apr-Oct)	7.0	21.0	13.4	2.9
CH-1 Growing Season (May-Oct)	6.0	18.0	11.6	2.6
CH-3 Growing Season (Apr-Oct)	10.0	45.0	27.6	5.5
CH-3 Growing Season (May-Oct)	9.0	38.0	23.9	4.8
GER-3 Growing Season (Apr-Oct)	13.0	41.0	27.1	4.3
GER-3 Growing Season (May-Oct)	12.0	36.0	23.5	3.8
NLD Growing Season (Apr-Oct)	76.7	106.0	93.1	5.0
NLD Growing Season (May-Oct)	71.2	96.1	85.0	4.4
Basel Growing Season (Apr-Oct)	83.9	109.6	97.4	4.9
Basel Growing Season (May-Oct)	75.8	99.0	88.5	4.4
Precipitation				
CH-1 Floraison (May-Jul)	1.0	7.0	4.2	1.4
CH-1 Winter (Dec-Mar)	1.0	9.0	4.4	1.5
CH-3 Floraison (May-Jul)	-9.0	8.0	0.5	2.8
CH-3 Winter (Dec-Mar)	-11.0	9.0	-0.9	3.2
GER-3 Floraison (May-Jul)	-9.0	7.0	-0.3	3.0
GER-3 Winter (Dec-Mar)	-8.0	7.0	0.1	3.1
NLD Floraison (May-Jul)	78.0	359.0	197.3	64.3
NLD Winter (Dec-Mar)	48.0	326.0	182.8	58.3
Zurich Floraison (May-Jul)	172.0	706.0	352.1	96.0
Zurich Winter (Dec-Mar)	79.0	530.6	276.0	97.6

Table 2
Estimates for Wine Price Equation
2SLS estimates of equation (3)

Dependent variable: log(price)	Weather Data				
	Index Data			Instrumentally Measured Data	
	Swiss CH-1	Swiss CH-3	Germany GER-3	Netherlands NLD	Basel Zurich
time covered	1535-1875	1560-1875	1530-1875	1736-1875	1770-1875
Constant	-0.718 (-1.53)	-0.637^{+} (-1.91)	-0.657** (-2.43)	-0.341 (-0.63)	
lagged dependent	0.602** (14.48)	0.648** (13.02)	0.646** (16.90)	0.819** (7.66)	0.486** (3.05)
log (quantity)	-0.532** (-8.25)	-0.345** (-6.44)	-0.275** (-10.71)	-0.270** (-3.11)	-0.374* (-4.91)
(Δ Temp*trend 1785)/ log(Temp)	0.131** (4.38)	0.108** (3.82)	0.156** (5.08)	0.0001^{+} (1.92)	0.121** (3.52)
log income	0.483** (7.24)	0.351** (7.64)	0.321** (9.32)	0.224* (2.18)	0.392** (5.14)
plague mortality	-0.007^{+} (-1.70)	0.002 (0.54)	-0.004 (-0.76)		
annual dummy variables	YES (7)	YES (3)	YES (5)	YES (8)	YES (4)
R^2	0.731	0.703	0.722	0.708	0.559
adj. R^2	0.721	0.693	0.714	0.680	0.519
S.E.	0.296	0.314	0.295	0.314	0.334
n	341	236	346	140	86

heteroskedasticity and serial correlation consistent t-statistics in parenthesis. Significance level 2% (**), 5% (*) and 10% ($^{+}$).

Table 3

Estimates for Wine Quantity Equation
2SLS estimates of equation (4)

Dependent variable: log(quantity)	Weather Data				
	Index Data			Instrumental Data	
	Swiss CH-1	Swiss CH-3	Germany GER-3	Netherlands NLD	Basel Zurich
time covered	1535-1875	1560-1875	1530-1875	1736-1875	1770-1875
lagged dependent	0.203** (6.00)	0403** (5.06)	0.253** (5.90)	0.292** (3.86)	0.298** (4.10)
Temperature Growing Season	0.248** (6.39)	0.264** (3.98)	0.113** (4.57)	0.560** (4.29)	1.367** (5.08)
(Temperature Growing Season)^2	-0.006** (-4.30)	-0.004** (-3.58)	-0.001** (-2.95)	-0.003** (-3.94)	-0.007** (-4.78)
Precipitation Winter	0.050** (2.82)	0.025* (1.99)	0.021* (2.28)	-0.000 (-0.66)	0.002** (2.82)
Precipitation Blossom	-0.105** (-5.84)	-0.072** (-4.75)	-0.040** (-3.38)	-0.001 (-1.14)	-0.0003 (-0.37)
PDL log(price)	0.007** (2.79)	0.004$^+$ (1.95)	0.006** (2.07)	0.012** (3.28)	0.039** (4.04)
log (trend)	0.049** (5.52)		0.058** (6.31)		
annual dummy variables	YES (17)	YES (13)	YES (17)	YES (13)	YES (8)
R^2	0.688	0.594	0.598	0.671	0.693
adj. R^2	0.664	0.559	0.569	0.618	0.633
S.E.	0.450	0.501	0.479	0.449	0.480
AIC	-1.602	-1.300	-1.403	-1.470	-1.624
Schwarz criterion	-1.433	-1.006	-1.226	-1.050	-1.196
n	341	236	346	140	86

heteroskedasticity and serial correlation consistent t-statistics in parenthesis. Significance level 2% (**), 5% (*), 10% ($^+$)

Table 4
Evaluation Measures of Select Models

	time	n	MEAN[1]	MAE[1]	RMSE[1]	MAPE[1]
				Price		
Switzerland CH-1	1535-1875	341	-2.25	17.04	1.85	26.86
Switzerland CH-3	1560-1875	236	- 1.95	18.39	2.59	29.06
Germany GER-3	1530-1875	346	-2.41	17.32	1.28	27.51
Netherlands NLD	1736-1875	140	-1.44	19.14	2.47	25.84
Basel-Zurich	1770-1875	86	-4.19	26.15	3.52	31.82
				Quantity		
Switzerland CH-1	1535-1875	341	-4.44	17.56	2.08	36.68
Switzerland CH-3	1560-1875	236	-4.71	20.04	2.12	41.89
Germany GER-3	1530-1875	346	-5.70	19.32	1.60	41.53
Netherlands NLD	1736-1875	140	-6.06	23.95	3.26	35.08
Basel-Zurich	1770-1875	86	-3.91	26.33	4.48	37.20

[1] MEAN mean error, MAE mean absolute error, RMSE root mean squared error, MAPE mean absolute percentage error

Table 5
Impact of Global Warming on Price, Crop Yield, and Revenue
Model Simulations, Percentage Changes Compared to Base Scenario

	0.5 °C	1.0 °C	1.5 °C	2.0 °C	2.5 °C	3.0 °C	3.5°C	4.0 °C
				Price				
Switzerland CH-1 (n=341)	-4.05	-6.64	-7.71	-7.25	-5.26	-1.74	3.26	9.62
Netherlands NLD (n=140)	-2.97	-4.48	-4.53	-3.10	-0.02	4.20	10.02	17.13
				Crop Yield				
Switzerland CH-1 (n=341)	12.76	21.66	25.59	24.04	17.20	5.94	-8.42	-24.23
Netherlands NLD (n=140)	13.56	21.62	22.83	16.94	4.95	-11.22	-29.21	-46.79
				Revenue				
Switzerland CH-1	8.19	13.58	15.90	15.04	11.03	4.09	-5.43	-16.94
Netherlands NLD	10.18	16.18	17.27	13.32	4.74	-7.50	-22.12	-37.68

[1] the percentage change in revenue was calculated on average price and quantity values.

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