THE IMPACT OF CLIMATE CHANGE ON THE PRODUCTION OF SPANISH WINES

by

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Abstract: Spain is the third largest producer and the largest exporter of wine in the world. Spanish wine, therefore, plays a vital role in both the global wine industry and the domestic Spanish economy. The most recent report of the Intergovernmental Panel on Climate Change (IPCC) documents increasingly convincing evidence of climate change and the potential damages a changing climate may have on important agricultural sectors. In this paper we examine the effects of climate change on the production of Spanish wines. We use hedonic regression techniques to tease out the relationship between wine yields and changing weather patterns (temperature and precipitation). This research may help better inform stakeholders in the wine industry on which areas in Spain may suffer the most and which areas are expected to thrive. Our results suggest substantial geographic differences across Spain in the effects of climate change on wine production. However, we show that increases in growing season temperature and precipitation have a negative effect on high quality wine yields in the most southern – and therefore most vulnerable – region of Spain.

1. Introduction

The most recent report by the IPCC concludes that the "warming of the climate system is unequivocal" (IPCC 2014). The IPCC warns that the impacts of a changing climate are far reaching, and include rising sea levels, an increase in the frequency and intensity of extreme weather patterns, changing ecosystems and wildlife habitats and an increase in the spread of infectious diseases. Climate change will also have a significant impact on agriculture. As solar radiation, temperature and precipitation are the driving factors of crop growth, agriculture is directly dependent on climate patterns and its variations (Rosenzweig and Parry 1994).

In this paper, we examine the effects of climate change on the production of Spanish wines - one of the most storied and commercially important wine regions in the world. Spain is the third largest producer by quantity of wine at 37.8 million hectoliters, they designate more hectares of land to wine production than any other country at 14% of total land under production, and they are the top exporter of wine in the world at 24 million hectoliters in 2015 (OIV 2015). According to the World Bank, Spain's agriculture sector, comprised mostly of wine, olive oil, and pork production, makes up 2.5% of the Spanish GDP in value added, or approximately $27.3 billion as of 2015, and employs 4.2% of the nation's workforce.

There are two bands of wine production spread across the world, one in each of the hemispheres, in which wine is optimally grown. The general hypothesis is that climate change will cause the wine bands to shift farther away from the equator toward the northernmost and southernmost frontiers. This may occur as temperatures generally increase in magnitude and variability. If this is the case, as evidence points to, there will be both winners and losers (Ashenfelter and Storchmann 2016). Regions on the frontiers of the wine bands will experience greater variability and quality in the varietals they can profitably grow while regions closer to the equator will experience greater adversity in their wine production once the loose threshold for quality wine yields is passed. This phenomenon is expected to occur slowly over time. Spain lies on the southern border of the northern hemisphere wine belt.

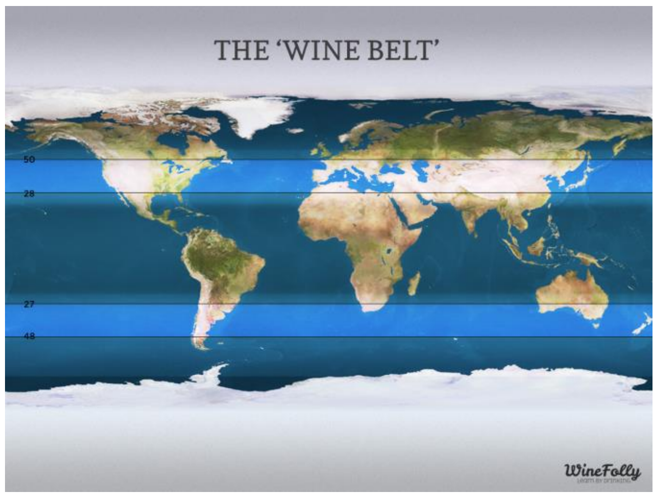


Figure 1: Map of World "Wine Belts"[1]

Because of this, the region's wine industry is potentially in danger over the long term if temperatures increase so much that Spain's southernmost regions are unable to produce wine profitably. Recent research predicts that while some regions of Spain may be better off in terms of grape production, the southernmost wine region in Spain (Andalucía) will suffer the most from increased average temperatures due to climate change (Resco 2015).

Wine grape varieties are sensitive agricultural products and economic commodities, with premium production occurring in very narrow climate ranges (Mozell and Thach 2014). Climate change poses risk to grapes as minor changes in climate variability disproportionately affect premium quality wine grapes, as opposed to other crops (Furer

[1] Map sourced from winefolly.com.

2006; Hannah et al. 2013; Tate 2001). Tate (2001) finds that wine grapes, *Vitis vinifera*, will begin to occupy areas closer to the poles as temperatures warm. Some climates growing grapes successfully that are closer to the equator will be unable to do so as temperatures warm. Climates closer to poles will have greater ability to grow more varieties and at greater qualities (Mozell and Thach 2014). Some examples of these changes as predicted by Furer (2006) include complete identity changes to the world-famous Burgundy and Bordeaux regions of France, a loss of grape growing viability on Mediterranean coastline, and Spain's mainland rising in temperature and decreasing in fresh water to a point of absent grape growth. In an extreme climate change scenario, Spain could lose its ability to grow wine grapes of quality along its Mediterranean coastline and central plateau, leaving the northern river valleys and northwest Spain more hospitable environments for warmer grape varieties. The northern Spanish regions experiencing warmer temperatures may adapt to grow more red varieties of low acid, high sugar, and high alcohol (Santisi 2011).

Our purpose in this paper is to estimate the impact changes in climate have on the production of Spanish wines. Following the literature, climate is defined as average weather metrics and the changes in average weather over time is what is considered climate change (Ashenfelter and Storchmann 2016). The early literature on the effects of temperature on grape growing was focused on questions of regional suitability and optimal vineyard locations. Therefore, the link between climate and wine production has been well known for centuries (Amerine and Winkler 1944). More recently, data analysis techniques have been developed to investigate the impact of changing temperatures (and other climate variables) on wine production. The production of wine (quantity and quality) is a key element into the economic value of the wine industry in Spain. Of course climate change can be predicted to affect wine prices as well as harvests. In this sense our analysis should be considered one step in a broader research agenda that estimates the economic impact of a changing climate on the Spanish wine industry.

Following the literature, we use a hedonic approach to estimating the effects of climate change on wine production. The hedonic method applies regression techniques to historic data to isolate the impact changes in temperature and precipitation have on production levels while controlling for other factors. Although we are not aware of other studies that explore the formal link between Spanish wine production and climate change, the general approach used here has been applied to German wines (Ashenfelter and Storchmann 2010) and a variety of other agricultural products (Mendelsohn et al. 1994; Nemani 2001; Schlenker et al. 2005; 2006). Our research design accounts for the considerable heterogeneity in the expected effects of climate change throughout Spain by estimating separate hedonic regression models for each wine region and wine type (separating high quality wines from others). Our approach closely follows Ashenfelter and Storchmann (2010) in which production levels are regressed on average temperatures in the growing season, precipitation measures in the growing season and precipitation in the winter preceding the growing season. They find that for most German wine regions, the marginal effect of a temperature increase has a positive and significant effect on revenues. A warming climate is more conducive to wine production in the Northern Hemisphere and therefore climate change leads to an increase in the commercial value of the German industries. This occurs both because of a shift from lower to higher quality wine production and overall yields. However, there is substantial variation in the impact of climate change according to geographic area. Indeed, the southern most regions see insignificant (and in one region negative) effects of climate change on wine revenues.

With wine production data made available through Eurostat and weather data available for purchase through WeatherSpark, we use regression techniques to estimate a relationship between yield and climate in the Spanish wine growing regions over the eighteen-year time frame from 1990-2007.[2] The yield data is segmented into eight overarching wine regions representing thirty-six sub regions. It contains hectoliter yields that were regressed against various temperature parameters, measured in degrees Celsius, and precipitation counts, measured in the average number of hourly reports of positive precipitation per day. In isolating these variables, we hope to estimate the impact that temperature during the growing season and/or precipitation counts throughout the year have on the production levels of Spanish wine grapes, both in total quantity and segmented by high and low quality. Analyzing the data in this way will yield the marginal changes in wine production caused by changes in temperature and precipitation throughout all of the wine regions in Spain.

Before moving forward with a description of the Spanish wine industry, we want to discuss some important caveats and limitations to our study. We do not account for changes of vineyard practices or regulatory/trade conditions over the timeframe of this study. In this way, we cannot verify whether vineyard owners began adapting their practices over the eighteen-year span as more information and data was released on climate change. We also do not account in the data for any periods of extreme weather conditions such as extreme droughts or blizzards. The data is not adjusted for these outlying events. Additionally, we were limited in our resources in that we were unable to obtain reliable pricing data. We

[2] Weather data purchased from www.weatherspark.com.

cannot therefore regress climate factors against pricing data from Spanish wine to estimate revenues. However, prices can be influenced by many factors other than climate, such as consumer preferences, trade agreements, and regulatory changes.

2. Spanish Wine

We collected data from thirty-six wine growing sub regions, encapsulating the sixty-nine Designations of Origin, making up eight broad wine growing regions of Spain. The eight regions are Andalucía, Central Plateau, Duero River Valley, Ebro River Valley, Spanish Islands, Mediterranean Coast-North, Mediterranean Coast-South, and Northwestern Spain. These regions are shown in Figure 2 below. Note that in contrast to the map in Figure 2 we further divided the Mediterranean Coast into Northern and Southern regions (the areas north of Valencia comprise Mediterranean Cost-North).

Figure 2: Map of Spain Wine Regions[3]

[3] Source: adapted from map provided by www.winefolly.com.

The Spanish put emphasis on identifying wines by the Designation of Origin (DO) as opposed to the grape varietals. Spanish wine regulations put restrictions on regions so that understanding a given Spanish wine is more focused on the understanding the origin with less emphasis on the varietal. Nonetheless, we discuss some of the more common varietals grown in Spain and the regions in which they are most prominent.

As mentioned, the Spanish wine industry is a key player in the scope of the global wine industry. They are the third largest producer in hectoliters, the largest exporter, and the largest percentage of hectares under production is in Spain. A significant impact to their wine production would vastly change the global industry landscape. Spain serves as a low cost, bulk producer of wine, exporting much of their table wine produced to other countries for rebranding and export. While the Spanish wine industry makes up only a portion of the 2.5% agricultural sector of Spain's GDP, the sector employs 4.2% of the population in a growing services economy. If wine production jobs were to be lost, the condition of 24.7% Spanish unemployment would worsen, especially in rural areas. It is vital that producers are vigilant in adjusting growing practices and grape varietals to climate change.

Of the red grape varieties, Tempranillo is the best-known quality of native grapes. La Rioja is its home but it is also cultivated across Spain including Ribera del Duero, La Mancha, and Catalonia. Tempranillo tends to bring forward a particularly young, fresh, and fruity taste, as its name suggests. Garnacha, or Grenache, tends to be blended with Tempranillo in La Rioja but is also found in northeastern regions as well as Navarra, Aragón, and Catalonia. Common varietals such as Cabernet Sauvignon, Merlot, and Syrah are also relatively popular in Spain. These grapes are grown all over the world and Spain is no exception. Merlot and Cabernet are spread across the country's regions while Syrah is more focused in La Mancha and the Mediterranean areas. Of the white grape varieties, Verdejo, Albarino, and Godello are found in the northwest regions of Spain. These are considered to be high quality grapes producing very aromatic wines.

Spanish wine is subject to six levels of quality and three levels of aging. Vino de Mesa and Vinos de la Tierra are the lowest two quality levels representing blends of low quality grapes of somewhat unknown, or vague origin. Vinos de Calidad con Indicación Geográfica are wines that are from a region in the process of taking the next step up to Denominación de Origen (DO). DO wines are considered the most widely sold quality wines. They are marketed heavily and appeal to the masses. The next step up is DO Calificada, indicating a DO that has provided consistent high quality wines. Lastly, the Vino de Pago designation is meant for internationally recognized single estate vineyards.

The three labels of aging accompany the quality and origin designations. Crianza indicates a wine that has aged for 2 years and has aged at least 6 months in oak. Reserva is meant for wines aged for 3 years and at least 12 months in oak. Gran Reserva is the highest aging designation, indicating that the wine has aged for at least 5 years, 18 months in oak, and 36 months in the bottle.

Lower yields are often linked to higher quality wines. However, Robinson (2006) finds that there are examples of a direct relationship between yield and quality as seen in Bordeaux and Burgundy vintages. This understanding of quality is not universally accepted nor does it universally appear in evidence. The data we have chosen to utilize does however distinguish quality levels with the highest level identified as the lowest hl/ha yielded. It seems the majority of quality grape production is focused in the top two classes of quality with the third level of quality significantly lower. Lower quality grapes however do account for a greater proportion of total production than high quality, see Table 2.

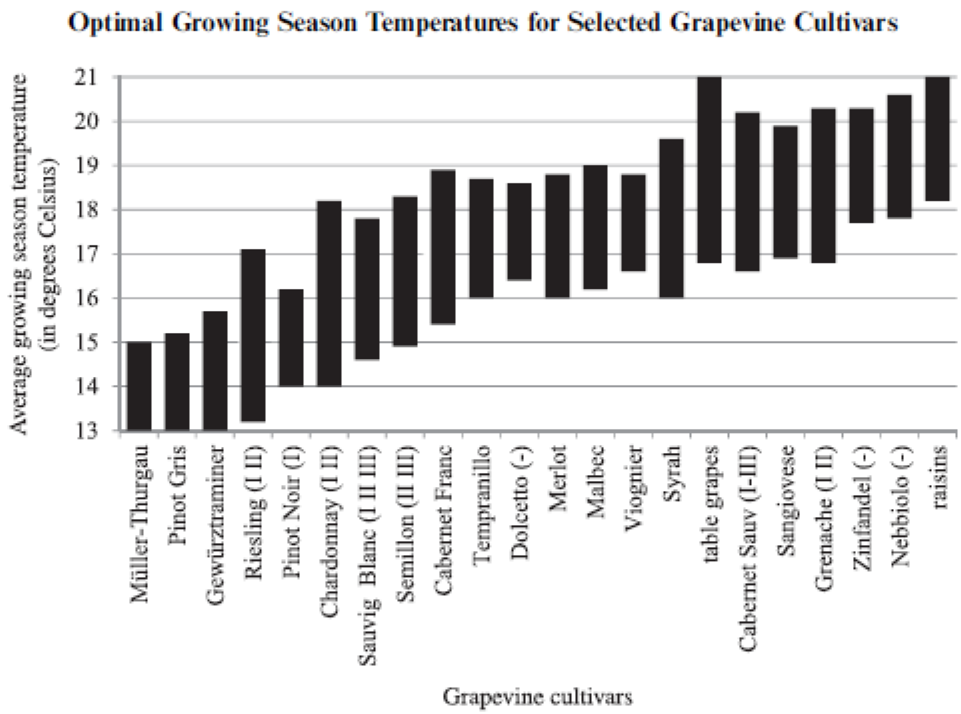


Figure 3: Optimal Growing Season Temperature Ranges[4]

Figure 3 depicts the optimal growing season temperature ranges for various grapevine cultivars. Jones et al. (2005) found that the suitability of grape varieties for various average growing season temperature ranges is fairly extensive. That is to say that the substitutability of varieties at any given temperature range is fairly high. For example, the Tempranillo grape varietal, the most prominent varietal native to Spain, if planted in southern regions that are experiencing warming, it could be partially substituted for Cabernet Sauvignon, Sangiovese, or Grenache to compensate for the increase in average high temperatures. These three substitutes would be optimal for handling any increase in average temperature relative to the Tempranillo grape but could also reasonably grow successfully alongside Tempranillo.

[4] Chart sourced from Jones et al. (2005)

Understanding substitutability of varietals is one method of defending against production losses from climate change.

The ranges displayed in Figure 3 are argued by van Leeuwen et al. to be underestimated. They argue that temperature suitability for high quality wines is more complex and it is no limited to exact limits. An alternative method to test the temperature suitability of grape varietals is the Huglin Heliothermal Index. For example, the index demonstrates that wine growth can't take place in areas with less than 1,500 degrees recorded during the vegetation period. This index is a measure of the total degrees Celsius during the vegetation period, April-October, counting only the days in which the average temperature is above 10 degrees Celsius (Tonietto and Carbonneau 2004). Unfortunately, the data used for this paper does not include production data on grape varieties but rather classes of quality level. Thus, we cannot attempt to test or qualify the suitability ranges of grape varietals given by Jones et al. (2005).

Aside from specific grape varietal suitability, generalizations can be made regarding the overall regions. As temperatures warm, we can expect climate conditions in the southern regions of Andalucía, Mediterranean Coast South, Islands, and the Central Plateau to restrict grape growth to lower quality production of red varietals and some parts of those regions to be without grape production. This is illustrated in the wine belt Figure 1. It shows us that temperature increases will push the southern regions to edge of the belt, if not out of the range completely. The northern regions however, could expect to see their suitable grape growing environments become more hospitable to a broader range of varietals. Northwest Spain, the Ebro and Duero River Valleys, and the Mediterranean North Coast would expect higher quality grape growth with increasing growing season length. Their average temperatures would increase to place them in more suitable ranges to continue to grow whites but also warmer reds. Overall, the southernmost regions will certainly bear the most impact of climate change. The southern regions produce the majority of Spanish wine, approximately 27,000,000 hectoliters of 37,000,000 for the entire country, Table 2.

3. Data and Methodology

Production data for thirty-six wine producing sub regions in Spain, over the time period 1990-2007, were acquired from the public database Eurostat.[5] The data was represented per 1,000 hectoliters for each year and for each sub region. The total production figures were given with four classes of quality as sub categories. Although, the fourth and lowest quality class never had any reported yield figures so it was excluded from data analysis. The remaining low quality figure was calculated by subtracting the total hl of quality yields from the total yield. Table 2 represents the descriptive statistics from the Eurostat production data. The table shows that the majority of wine produced in all of Spain, and in most regions, is considered low quality or "table wine." For our purposes, we consider all Class 1 – 3 wines as high quality wine and the rest as low quality wine.

Acquiring weather data on regions in Spain proved to be a difficult task. Weather data is not easily accessible in public records, thus, we acquired the data through a private weather database provider called WeatherSpark. Weather spark provided data from twenty-six weather stations across Spain. Some weather stations provided weather data covering multiple sub regions of wine production. Table 1 lists all wine producing sub regions and their weather station counterpart. We paired wine producing regions to weather stations by conducting searches in WeatherSpark for each specific region or city. WeatherSpark yielded

[5] Wine production regional data was extracted from http://ec.europa.eu/eurostat/data/database

the nearest weather station as a result. WeatherSpark was able to provide various climate factors such as average high and low temperatures, cloud variables, humidity, dew point and precipitation. However, precipitation data was not represented in mm of precipitation per day, week, or month. Instead, it was represented as the monthly mean number of hourly positive precipitation reports given in a day. For example, in Table 3 descriptive statistics of climate factors of Northwest Spain are shown to have an average 2.1 hourly reports of precipitation in a given day during the growing season. This would indicate that between 1990 and 2007 there would be an average of 2.1 precipitation reports on any given day during the growing season. Precipitation counts include any type of rainfall, thunderstorm, snowfall, etc.

In regards to precipitation's effects on vines and grape development, rainfall plays a more significant role in the cases of vines without irrigation, according to Ashenfelter and Storchmann 2016. This is the norm in most cases of "old world vines" or European wine growing regions. Most areas in Europe don't even allow irrigation. One exception in some areas is made for new vineyards, with vines younger than five years, to install irrigation systems. New world vines, such as those in California, tend to have irrigation systems to manage the water being supplied to the vines for optimal water distribution. The quantity and distribution of rainfall is less crucial to vine and grape development under circumstances of water management by irrigation systems. It is generally accepted that rainfall during the winter and early growing stages is optimal for crop development but rainfall during the grape growing season can be harmful to the quality and yield. High rainfall and humidity in the growing season can lead to incidences of disease or fungi forming on the vines and grapes. While we consider precipitation to be particularly significant in European wine growing regions, precipitation factors are much more uncertain than temperature factors, Bates et al. (2008), and there is no sound prediction as to how climate change will impact precipitation around the world.

Table 3 also includes descriptive statistics of the average high and low temperature during both the growing season and the winter season, defined as April through October and November through March, respectively. However, it is acknowledged that the time frames for growing and winter seasons may differ over time and region. The association with calendar dates is loosely defined. Precipitation count data is listed in Table 3 as the average number of hourly reports of precipitation per day during the off season and growing season. As we would expect, the off season or winter precipitation counts are higher than the growing season counts. Higher counts in the winter are expected to produce higher quality and yield of wine due to vines receiving ample water, preparing them for a healthy growing season. Alternatively, lower counts in the growing season are favorable due to grape disease diminishing in drier conditions.

The descriptive statistics are meant to highlight relationships and trends in the data. In viewing the descriptive statistics, a picture of the conditions and production of each region is illustrated. We also include scatterplots (production vs temperature) and fitted trend lines for each of the eight wine producing regions. We then move to regression estimates. The log-linear regression results are intended to highlight any significance of the climate variables' impact on wine grape production. The Y variable production values were logged to normalize values. Thus, a change in any climate variable will result in a change in the log of production. We then estimate another set of models that allow for nonlinear changes in production caused by changes in weather variables.

4. Results

4.1 Descriptive Statistics

We begin with summary statistics of yields, weather variables and wine types by wine region. Data from thirty-six regions across eighteen years resulted in 648 observations. The average annual production yield from all of Spain was 37,248.4 (1,000 hl) with a standard deviation of 7,607.7. This indicates there was a wide variability of production yields over the eighteen-year period. Low quality wine production was the largest category on average across all regions with 19,260.1 while the Class 2 quality level was second largest at 9,965.8. Class 3 quality had the lowest average production yields with only three major regions producing any amount under Class 3. The large deviations may be the result of 1994 and 1995 production levels. A significant drought during these years produced extremely low yields and serve as the minimums of all observations in hl yield. This natural event is also directly reflected in the precipitation count data and somewhat noticeable in temperature variables.

Table 1: List of Weather Station and Producing Region Pairings

Wine Producing Region	Sub Region	Weather Data Station
Andalucía	Cádiz	Rota
Andalucía	Córdoba	Cordoba
Andalucía	Huelva	San Pablo Airport
Andalucía	Málaga	Malaga
Andalucía	Almería, Granada, Jaén, Sevilla	Granada
Central Plateau	Comunidad de Madrid	Madrid Barajas Airport
Central Plateau	Albacete	Albacete
Central Plateau	Ciudad Real	Madrid Barajas Airport
Central Plateau	Cuenca	Madrid Barajas Airport
Central Plateau	Guadalajara	Madrid Barajas Airport
Central Plateau	Toledo	Madrid Barajas Airport
Central Plateau	Badajoz	Badajoz
Central Plateau	Cáceres	Badajoz
Duero River Valley	Burgos	Burgos
Duero River Valley	León	Leon
Duero River Valley	Valladolid	Valladolid
Duero River Valley	Zamora	Matacan Airport
Duero River Valley	Ávila, Palencia, Salamanca, Segovia, Soria	Matacan Airport
Ebro River Valley	Araba/Álava	Vitoria-Gasteiz
Ebro River Valley	Gipuzkoa, Bizkaia	Bilbao
Ebro River Valley	Comunidad Foral de Navarra	Pamplona
Ebro River Valley	La Rioja	Agoncillo
Ebro River Valley	Huesca, Teruel	Zaragoza
Ebro River Valley	Zaragoza	Zaragoza
Islands	Illes Balears	Palma de Mallorca
Islands	Canarias (ES)	Gran Canaria
Mediterranean Coast North	Barcelona	Barcelona
Mediterranean Coast North	Girona, Lleida	Girona
Mediterranean Coast North	Tarragona	Reus
Mediterranean Coast North	Castellón / Castelló	Albacete
Mediterranean Coast South	Alicante / Alacant	Albacete
Mediterranean Coast South	Valencia / València	Albacete
Mediterranean Coast South	Región de Murcia	Alcantarilla
Northwest Spain	Galicia	Santiago de Compostela
Northwest Spain	Principado de Asturias	Asturias
Northwest Spain	Cantabria	Santander/Cantabria

Table 2: Summary Statistics on Wine Production by Wine Region 1990 - 2007

	Avg. Annual Product - Total (1,000 hl)	Avg. Annual Product – Class 1 (1,000 hl)	Avg. Annual Product – Class 2 (1,000 hl)	Avg. Annual Product – Class 3 (1,000 hl)	Avg. Annual Product – Low Quality (1,000 hl)
Andalucía Malaga, Cadiz, Granada, Sevilla, Huelva, Cordoba	1,859.6 (447.3)	41.4 (37)	1,260.1 (383.0)	189.5 (421.3)	401.4 (161.3)
Central Plateau Comunidad de Madrid, Albacete, Ciudad Real, Toledo, Cuenca, Badajoz, Guadalajara, Cáceres	21,732.3 (5,819.1)	4,620.3 (2,998.0)	2,170.2 (3,915.2)	0.0 (0.0)	15,186.2 (6,309.3)
Duero River Valley Salamanca, Segovia, Zamora, León, Valladolid, Burgos	1,320.9 (425.2)	615.8 (298.5)	85.2 (160.5)	0.0 (0.0)	589.2 (169.1)
Ebro River Valley La Rioja, Comunidad Foral de Navarra, Zaragoza, Huesca, Gipuzkoa, Araba	4,142.6 (990.6)	811.8 (244.5)	2,724.6 (1,017.0)	5.3 (6.3)	561.7 (407.1)
Islands Illes Balears, Canarias (ES)	225.1 (59.7)	92.6 (77.7)	3.4 (7.3)	0.0 (0.0)	129.7 (90.7)
Mediterranean Coast North Barcelona, Girona, Castellón, Tarragona	3,292.2 (377.7)	342.2 (664.0)	2,495.2 (750.1)	0.0 (0.0)	422.7 (171.0)
Mediterranean Coast South Alicante, Murcia, Valencia	3,207.6 (520.4)	1,482.6 (895.6)	849.3 (1,040.5)	0.0 (0.0)	930.9 (672.8)
Northwest Spain Galicia, Cantabria, Principado de Asturias	1,468.1 (378.8)	0.0 (0.0)	377.8 (180.4)	33.7 (134.7)	1038.3 (299.5)
All of Spain	37,248.4 (7,607.7)	8,006.7 (4,097.7)	9,965.8 (6,079.1)	228.5 (427.2)	19,260.1 (7,523.9)

Notes: Class 1 indicates quality wine with an average yield <30 hl/ha; Class 2 indicates quality wine with an average yield 30-<70 hl/ha; Class 3 indicates quality wine with an average yield 70-<110 hl/ha; Low Quality indicates wine production outside of Class 1, 2, or 3 quality levels

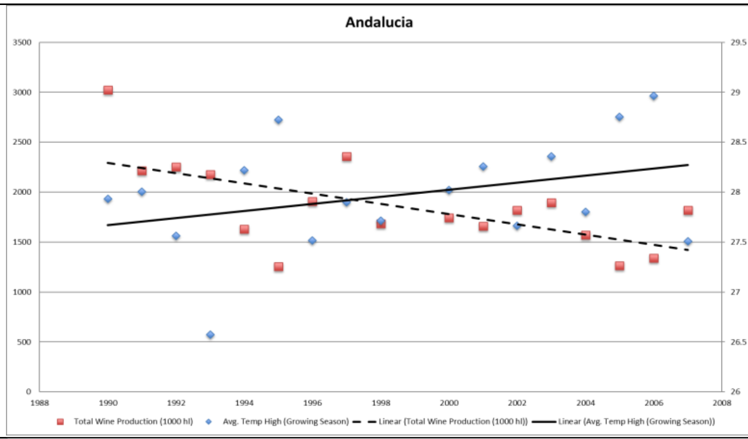
Table 3: Climate Statistics by Wine Region 1990 - 2007

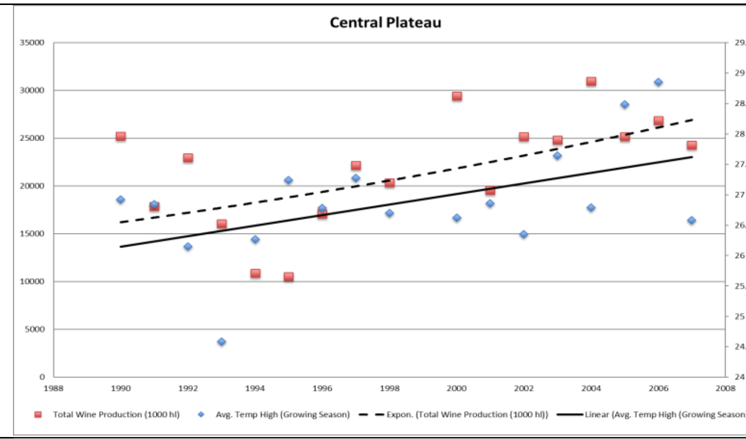
Wine Region	Avg. Growing Season High Temperature	Avg. Growing Season Low Temperature	Avg. Off Season High Temperature	Avg. Off Season Low Temperature	Avg. Growing Season Precip. Count	Avg. Off Season Precip. Count
Andalucía Málaga, Cádiz, Granada, Sevilla, Huelva, Córdoba	27.9 (0.6)	15.7 (0.6)	17.4 (0.7)	7.1 (1.0)	0.6 (0.2)	1.2 (0.4)
Central Plateau Comunidad de Madrid, Albacete, Ciudad Real, Toledo, Cuenca, Badajoz, Guadalajara, Cáceres	26.9 (0.9)	13.2 (0.6)	13.9 (0.8)	3.5 (1.2)	0.8 (0.2)	1.3 (0.4)
Duero River Valley Salamanca, Segovia, Zamora, León, Valladolid, Burgos	22.3 (1.0)	9.7 (0.6)	10.2 (0.8)	1.6 (1.0)	0.7 (0.2)	1.2 (0.4)
Ebro River Valley La Rioja, Comunidad Foral de Navarra, Zaragoza, Huesca, Gipuzkoa, Araba	24.1 (1.0)	12.6 (0.6)	12.8 (0.8)	4.4 (0.7)	1.4 (0.3)	2.0 (0.6)
Islands Illes Balears, Canarias (ES)	25.5 (0.5)	17.5 (0.6)	19.1 (1.3)	11.2 (2.4)	0.6 (0.2)	1.2 (0.4)
Mediterranean Coast North Barcelona, Girona, Castellón, Tarragona	25.0 (0.8)	14.7 (0.6)	14.8 (0.7)	4.9 (0.9)	0.9 (0.3)	1.0 (0.3)
Mediterranean Coast South Alicante, Murcia, Valencia	26.9 (0.9)	14.1 (0.6)	14.9 (1.0)	4.1 (1.2)	0.5 (0.2)	0.8 (0.4)
Northwest Spain Galicia, Cantabria, Principado de Asturias	20.0 (0.7)	12.7 (0.5)	13.6 (0.6)	7.0 (0.8)	2.1 (0.4)	3.2 (0.6)
All of Spain	25.1 (0.8)	13.4 (0.5)	14.1 (0.6)	4.8 (0.9)	1.0 (0.2)	1.5 (0.3)

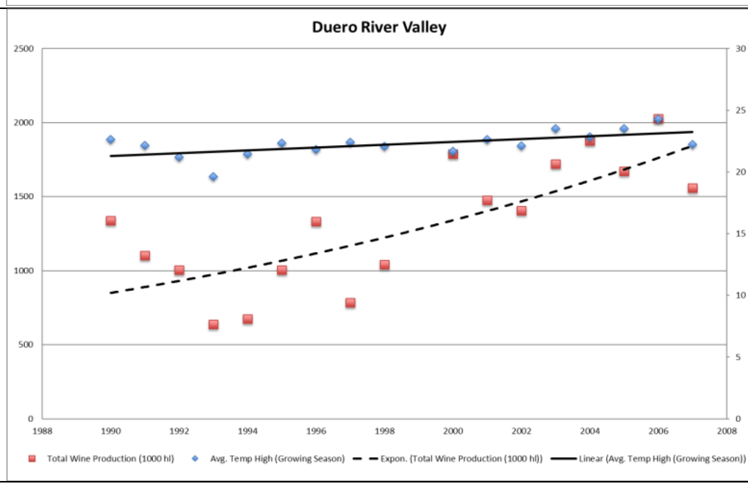
Notes: The growing season is from April-October and the off season (winter) is November-March. All temperatures are reported in degrees Celsius. Precipitation counts measure the mean number of hourly reports each day that include at least some precipitation or thunderstorm report

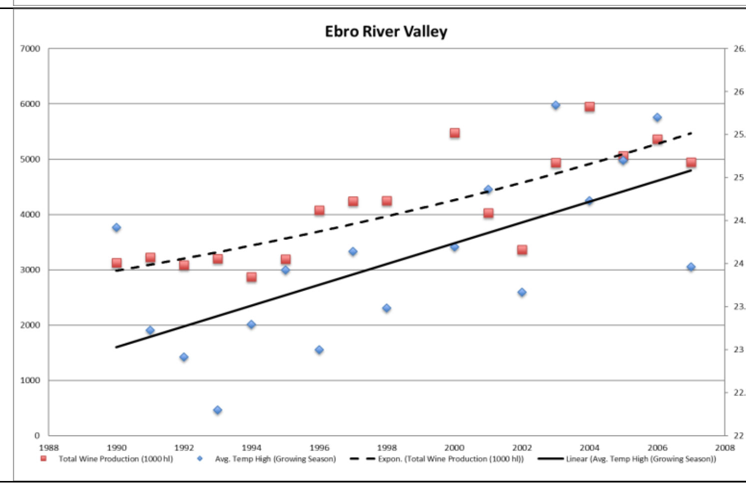
4.2 The relationship between climate and wine production

To begin investigating the relationship between yields and climate change, we start with presenting simple graphs illustrating overall trends in average high temperatures and overall wine production levels by the eight wine regions. The scatterplots include yields (1,000 hectoliters) and average high temperatures by year along with fitted trend lines.


Andalucia
Total Wine Production (1000 hl)
Avg. Temp High (Growing Season)
Linear (Total Wine Production (1000 hl))
Linear (Avg. Temp High (Growing Season))


Central Plateau
Total Wine Production (1000 hl)
Avg. Temp High (Growing Season)
Expon. (Total Wine Production (1000 hl))
Linear (Avg. Temp High (Growing Season))


Duero River Valley
Total Wine Production (1000 hl)
Avg. Temp High (Growing Season)
Expon. (Total Wine Production (1000 hl))
Linear (Avg. Temp High (Growing Season))


Ebro River Valley
Total Wine Production (1000 hl)
Avg. Temp High (Growing Season)
Expon. (Total Wine Production (1000 hl))
Linear (Avg. Temp High (Growing Season))

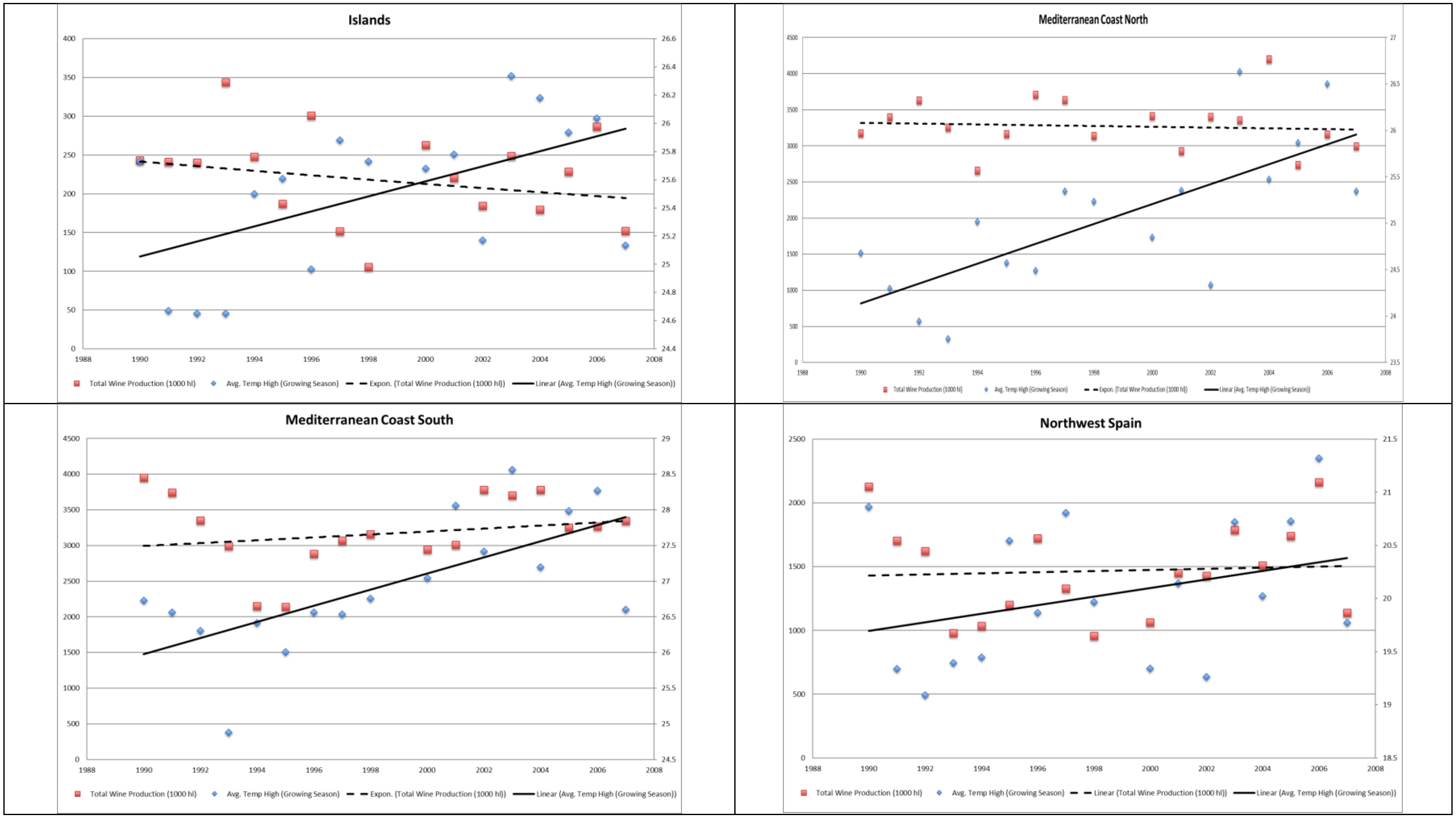


Figure 4: Trends in Total Wine Production and Average High Temperatures by Wine Region

The above set of charts depicts trend lines in total production of wine (1000 hl) and average high temperature (Celsius) during the growing season for each of the eight overarching regions. The coastal regions as well as northwest Spain appear to remain relatively constant in production as average high temperatures rise. Andalucía and the Islands appear to decrease in production with rising temperatures while the Central Plateau and River Valleys experience positive production growth.

While the trend lines provide some initial insight into the relationship between climate variables and wine production, we turn to regression analysis for a more in depth analysis. In order to determine the significance and impact of the given climate variables on Spanish wine yields, we follow Ashenfelter and Strochmann (2010) and Adams et al. (2003) and regress the production levels (per hectare) by wine quality in each region on the climate variables of average high temperature in the growing season and precipitation counts in growing and off seasons (winter). Later in this section, we estimate another set of models to allow for nonlinear effects of climate by including squared terms for the weather variables into the model. The regression reveals the extent that changes in climate correlate with changes in wine yields in each region by wine quality. The following represents the initial regression equation for each region and quality (we consider high quality and total wine production).

$$\ln(WineProd / Hectare)_{it} = b_0 + b_1 TempGrowing_{it} + b_2 Precip_{it} + b_5 \Pr ecipWinter_{it} + f\,Year + e_{it}$$

The variable *TempGrowing* is the average of the monthly high temperatures in the growing season for each sub region (indexed by *i*) in a given year (indexed by *t*). *Precip* measures the average number of hourly reports each day that include at least some precipitation or thunderstorm reporting. *PrecipWinter* is the same variable but for the off season preceding the growing season. Year is a vector of dummy variables to capture any year-specific fixed effects.

Overall, the climate variables seem to be more significant when regressing the total production/hectares for a given region compared to only the high-quality production/hectares. It is important to note that the r-squared measures for all of these regressions are fairly low. This means that most of the variation in production levels is not captured by the three weather variables and year variables we include. All of the F-tests were significant at some level, except for Andalucía in total production, indicating that the models as a whole are effective but many of the individual variables by themselves are not. For high quality production, increases in the average high temperature seem to be mostly significant in causing decreases in yield. For example, in Andalucía, as the average high temperature increases by 1 degree Celsius we predict about a 43.4% decrease in high quality production. These changes appear to be very drastic. When considering Spain as a whole, increases in average high temperature result in a slight decrease in yield. Precipitation counts during the growing season are almost entirely insignificant, except for the Islands and Northwest Spain regions with only 21 and 15 observations respectively. Precipitation counts during the off season are only significant in the Ebro, Med. Coast North, and Central Plateau regions as well as Spain as a whole. Each indicates a positive relationship of off season counts with yield.

Table 4: High quality wine production/ha as a function of climate variables

	SPAIN	Anda-lucía	Central Plateau	Duero River Valley	Ebro River Valley	Islands	Med. Coast North	Med. Coast South	NW Spain
Temp Growing	-0.078*** (0.026)	-0.434*** (0.145)	0.004 (0.059)	-0.415*** (0.120)	-0.143*** (0.025)	0.248 (0.159)	-0.129*** (0.047)	-0.054 (0.043)	0.167* (0.085)
Precip Growing	0.020 (0.123)	-1.747 (1.355)	-0.376 (0.238)	-0.174 (0.610)	-0.031 (0.091)	0.896** (0.315)	-0.030 (0.093)	0.439 (0.278)	0.247* (0.122)
Precip Winter	0.160* (0.090)	0.175 (0.499)	0.319** (0.124)	0.088 (0.291)	0.134* (0.068)	-0.138 (0.128)	0.109** (0.053)	0.110 (0.130)	0.101 (0.069)
Year	0.006 (0.012)	0.038 (0.053)	-0.075*** (0.016)	0.075** (0.033)	0.043*** (0.010)	-0.031 (0.022)	0.018** (0.008)	-0.019 (0.014)	0.023* (0.012)
Constant	-14.10 (23.94)	-67.30 (105.3)	145.2*** (30.59)	-145.1** (65.35)	-85.09*** (20.00)	52.14 (43.87)	-34.99** (16.24)	35.17 (27.15)	-54.35** (24.27)
Num of obs.	419	68	83	67	84	21	41	40	15
R-squared	0.047	0.135	0.273	0.211	0.497	0.615	0.283	0.222	0.567
F	5.11***	2.46*	7.32***	4.13***	19.50***	6.39***	3.54**	2.50*	3.27*

Notes: The dependent variable is ln (production of quality wine / hectares devoted to quality wine). *,**,*** indicate significance at the 0.10, 0.05 and 0.01 levels, respectively.

In looking at total production regressions, climate variables seem to be more significant in given regions rather than a specific variable across all regions. The Duero and Andalucía regions were the only two regions without a least one significant climate variable. As in the high-quality regressions, the regions with significant average high growing season temperature variables demonstrate a negative relationship between production and temperature. Surprisingly, growing season precipitation counts have significant positive relationships with yield in 4 of the 8 regions, although 3 of the 4 are southern regions that tend to be drier. Off season precipitation counts have significant positive relationships with yield in only the Ebro and Northwest regions. When considering all of Spain, all three climate variables regressed were highly significant and positive. It appears as though the country as a whole has slightly more to gain than lose, in total production per hectare, from temperature increase, growing season precipitation increases in drier regions, and off season precipitation increases.

Table 5: Total wine production/ha as a function of climate variables

	SPAIN	Anda-lucía	Central Plateau	Duero River Valley	Ebro River Valley	Islands	Med. Coast North	Med. Coast South	NW Spain
Temp Growing	0.021* (0.011)	0.046 (0.058)	0.013 (0.030)	-0.048 (0.043)	-0.148*** (0.022)	0.143 (0.125)	-0.346*** (0.059)	-0.094** (0.042)	0.029 (0.074)
Precip Growing	0.290*** (0.055)	-0.523 (0.548)	0.344** (0.134)	-0.262 (0.218)	0.032 (0.078)	0.978*** (0.273)	0.139 (0.139)	0.556** (0.272)	0.210** (0.085)
Precip Winter	0.101** (0.040)	-0.103 (0.202)	0.106 (0.065)	0.014 (0.104)	0.140** (0.060)	-0.169 (0.108)	0.139 (0.086)	0.094 (0.125)	0.201*** (0.070)
Year	0.022*** (0.005)	0.036* (0.021)	0.042*** (0.008)	0.047*** (0.012)	0.042*** (0.009)	-0.036** (0.016)	0.035*** (0.012)	0.013 (0.013)	0.009 (0.010)
Constant	-48.57*** (10.36)	-75.77* (42.58)	-88.52*** (16.15)	-97.04*** (23.31)	-83.28*** (17.55)	63.80** (30.06)	-64.53*** (23.46)	-26.56 (25.89)	-23.15 (20.01)
Num of obs.	490	68	109	67	85	25	54	41	41
R-squared	0.160	0.086	0.310	0.231	0.583	0.613	0.523	0.387	0.537
F	23.12***	1.47	11.66***	4.65***	27.99***	7.91***	13.43***	5.69***	10.43***

Of course, it is possible that climate changes affect production levels in a non-linear fashion. To address this, we regress high quality production per acre by the climate variables and their squared terms based on the following equation:

$$\ln(WineProd\ /\ Hectare)_{it} = b_0 + b_1 AvgHighTemp_{it} + b_2 AvgHighTemp_{it}^2 + b_3 Precip_{it} + b_4 Precip_{it}^2 + b_5 PrecipW_{it} + b_5 PrecipW^2{}_{it} + f\,Year + e_{it}$$

We do this to account for potential nonlinear effects of climate variables. We find little significance in the individual variables of the model. However, the F-tests reveal that Spain and five of the eight regional models as a whole are significant at explaining the relationships between the climate variables and production levels. Temperature shows significance in the Andalucía and Central Plateau regressions with inverse relationships in both, two of the southernmost regions. Precipitation counts in the growing season show no significance but counts in the winter are significant in three models, Andalucía, Ebro River Valley, and Northwest Spain. Based on coefficient values, we can estimate that the majority of the nonlinear temperature and growing season precipitation trends appear to be convex, some increasing and some decreasing, while the majority of winter precipitation trends are concave and decreasing. This implies that winter precipitation counts may have a diminishing marginal effect on high quality production levels.

Table 6: High quality production/ha as a function of squared climate variables

	SPAIN	Andalucía	Central Plateau	Duero River Valley	Ebro River Valley	Islands	Med. Coast North	Med. Coast South	NW Spain
Temp Growing	-0.190 (0.364)	-16.01*** (4.048)	-3.362** (1.478)	-0.719 (2.272)	0.097 (0.486)	-8.397 (14.29)	2.828 (1.763)	-1.111 (1.303)	2.591 (3.432)
Temp Growing^2	0.002 (0.007)	0.281*** (0.073)	0.062** (0.027)	0.008 (0.052)	-0.005 (0.010)	0.168 (0.278)	-0.061 (0.036)	0.020 (0.024)	-0.061 (0.084)
Precip Growing	-0.029 (0.294)	-6.011 (5.209)	0.420 (1.216)	1.333 (3.015)	-0.249 (-0.388)	0.723 (2.088)	-0.170 (0.376)	0.632 (0.928)	-0.065 (0.704)
Precip Growing^2	0.018 (0.092)	4.052 (4.465)	-0.405 (0.613)	-1.166 (2.131)	0.076 (0.129)	0.058 (1.494)	0.054 (0.146)	-0.076 (0.800)	0.091 (0.109)
Precip Winter	0.252 (0.235)	-3.657** (1.768)	0.563 (0.484)	1.363 (1.251)	0.414* (0.222)	-0.002 (0.517)	0.241 (0.207)	0.064 (0.503)	1.424* (0.740)
Precip Winter^2	-0.023 (0.053)	1.188** (0.543)	-0.070 (0.134)	-0.435 (0.407)	-0.074 (0.054)	-0.035 (0.118)	-0.036 (0.056)	0.021 (0.180)	-0.155 (0.086)
Year	0.006 (0.012)	0.049 (0.052)	-0.079*** (0.017)	0.059 (0.036)	0.042*** (0.010)	-0.034 (0.028)	0.023** (0.009)	-0.022 (0.015)	0.031** (0.012)
Constant	-11.90 (24.79)	129.67 (124.60)	198.06*** (38.34)	-111.50 (79.20)	-86.52*** (21.00)	169.12 (190.53)	-82.64** (32.69)	54.81 (37.94)	-96.03* (45.85)
Num of obs.	419	68	83	67	84	21	41	40	15
R-squared	0.048	0.350	0.327	0.228	0.512	0.627	0.344	0.238	0.736
F	2.95***	4.61***	5.20***	2.49**	11.39***	3.13**	2.47**	1.43	2.78

Notes: The models are estimated controlling for year fixed effects but we do not include the coefficient estimates into the table.

5. Conclusions

Spain is one of the most important wine producing nations in the world. While its wine industry does not contribute a great deal to its own GDP, the industry does employ an important portion of its workforce. If those jobs were to be lost, the terrible unemployment environment would worsen. Spain is the largest wine exporter globally and thus, is intertwined in the global wine industry more than any other producer. A significant impact to the Spanish wine industry's production levels would have a broader reaching effect on international trade.

The original thesis we test predicts that as climate change continues, average temperatures will increase and valuable production will shift north with the "wine belts." Spain is in a crucial position in the southernmost portion of the belt. This would indicate that production levels in Spain may shift substantially towards the northern parts of the country, the south left with low quality or without production. With regard to precipitation counts, there is much less certainty in the predictions of how they will change with climate change. We can predict from other research efforts that precipitation during the growing season would generally have a negative effect on wine production because of disease prevalence but during the winter season it would generally have a positive effect by preparing the vines to have a fruitful growing season.

In our linear regressions of high quality production, we find growing season temperature to be significant in 4 of the 8 regional models and in the Spain model carrying inverse relationships with high quality production. These models do not consider vineyard owners potentially switching grape varieties in the future to account for rising temperatures. Growing and winter season precipitation counts are mostly insignificant variables by themselves. Most of the models show production levels negatively affected by growing season precipitation and positively affected by winter season precipitation. We would expect to see these results but the lack of significance as individual variables may indicate that Spain's precipitation counts on average do not change drastically enough to highlight correlations with production level differences. Two regions that show significant positive relationships with growing season precipitation are the Islands and Northwest Spain. The Islands relationship might be explained in that it is one of the driest regions, perhaps in combination with high temperatures, to the point where high quality wine grape production is not particularly hospitable and more precipitation even during the growing season may help production. Northwest Spain's positive relationship with growing season precipitation may be explained in that it is the wettest region and the grape varieties already present in the region are adapted to produce high quality wines in wetter conditions.

This is important to highlight that a region such as Northwest Spain potentially has the most to gain from climate change. With a colder climate, their potential to grow more varieties is greater if temperatures gradually warm. If precipitation decreases coincide with temperature increases, the Northwest region may be able to grow high quality grapes requiring drier conditions. If precipitation holds then the region may still benefit from red varieties that require warmer temperatures but not necessarily drier conditions. Andalucía on the other hand, is a region with the most to lose from temperature increases coupled with precipitation increases. This region is a major high quality producer for Spain and may have to transition to lower quality grape varietals and wine production.

In looking at the linear regressions for total production, we can highlight some differences and similarities between the climate variables effects on high quality vs. low quality production. In total production regressions, temperature has less significance as an individual climate variable and has a significant, slight positive relationship in the Spain model but still has significant negative relationships in regional models. Additionally, the growing and winter season precipitation have numerous significant positive relationships in the models indicating that low quality production on average benefits slightly more than high quality production from any precipitation during the year. Based on the total production regression, it appears that increases in the climate variables will each have a positive effect on overall national production levels despite some regions being negatively affected, whereas high quality production areas overall will suffer from temperature increases.

These regression model predictions of course do not consider changes in grape growing practices and policies undertake by vineyard owners. Vineyard owners may very well adapt the varietals they grow, the irrigation systems they use, or other growing practices to ensure that production levels remain profitable whether that be at the high quality or low quality classes. Adaptations that vineyard owners take may drastically increase the benefits the country could experience from climate change but failure to do so would leave Spanish wine regions unable to fulfill their identities as wine growing regions and unable to produce wine at the same levels prior to climate change.

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