USING HEDONIC MODELS OF SOLAR RADIATION AND WEATHER TO ASSESS THE ECONOMIC EFFECT OF CLIMATE CHANGE: THE CASE OF MOSEL VALLEY VINEYARDS

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Abstract—In this paper we use two alternative methods to assess the effects of climate change on the quality of wines from the vineyards of the Mosel Valley in Germany. In the first, structural approach we use a physical model of solar radiation to measure the amount of energy collected by a vineyard and then to establish the econometric relation between energy and vineyard quality. Coupling this hedonic function with the physics of heat and energy permits a calculation of the impact of any temperature change on vineyard quality (and prices). In a second approach, we measure the effect of year-to-year changes in the weather on land or crop values in the same region and use the estimated hedonic equation to measure the effect of temperature change on prices. The empirical results of both analyses indicate that the vineyards of the Mosel Valley will increase in value under a scenario of global warming, and perhaps by a considerable amount.

I. Introduction

IN this paper we provide and compare the results of two methods for assessing the effects of climate change on the quality of agricultural land using a rich set of data on the vineyards of the Mosel Valley in Germany. The first method uses a structural model of solar radiation to measure the amount of energy collected by a vineyard and then to establish the econometric relation between energy and vineyard quality. Coupling this hedonic function with the elementary physics of heat and energy permits a calculation of the impact of any temperature change on vineyard quality (and prices). Although we show that this approach can, in principle, be applied to any crop grown on any land, the vineyards of the Mosel are a particularly attractive place to assess this method for measuring the effect that expected climate changes may have on quality and relative prices. Since the vineyards of this valley are situated near the far northern boundary feasible for grape production, they differ enormously in their suitability for grape growing. We show that this variability is due primarily to the extent to which each vineyard is able to capture radiant solar energy, so that these data provide a particularly credible experiment for identifying and measuring the appropriate hedonic equation.

The second method uses the so-called Ricardian approach applied by Mendelsohn, Nordhaus, and Shaw (1994) to the study of effects of climate change on agriculture. Their empirical research, based as it is on hedonic models from highly aggregated data, has been critiqued and extended to consider difficult issues of functional form and specification by Schlenker, Hanemann, and Fisher (2005, 2006) and Deschênes and Greenstone (2006). These more recent studies generally find considerable heterogeneity in the expected effects of climate change. Depending on the region considered, climate change may lead to either positive or negative effects on land values, with considerable uncertainty about the aggregate effect. Our approach follows this more recent work by studying a very specific area and type of crop and by establishing the economic relation using time-series variation in the weather.

As is well known, there are likely to be winners and losers from any potential climate change. The empirical results of both analyses are broadly similar and indicate that the vineyards of the Mosel Valley will increase in value under a scenario of global warming, and perhaps by a considerable amount. Vineyard and grape prices increase more than proportionally with greater ripeness, so that we estimate a 3°C increase in temperature would more than double the value of this vineyard area, while a 1°C increase would increase prices by more than 20%.

The paper is structured as follows. In section II, we explain how solar radiation is captured by a vineyard and how an energy value can be calculated for each vineyard site using the basic physics of solar panel construction. Section III discusses the data we use for the analysis, including the data on vineyard quality that we have constructed and the hedonic characteristics of the vineyards we study. In section IV, we present the estimates of our hedonic model of vineyard site quality, while section V contains our calculations of the impact of possible climate change on the quality distribution of vineyard sites. In section VI, we report estimates of the effect of time-series variation in the weather on wine prices and accounting profits and compare the implied estimated effects of climate change on land prices with those we obtain from the cross-section model of vineyard quality determination. We summarize our findings in section VII.

II. Radiation Use Efficiency, Solar Panels, and Vineyards

Commercial viticulture is found only between 35° and 50° latitude. Located between 49.61° and 50.34° latitude, the vineyards of Germany's Mosel region are thus at the cold limit for grape growing. As a result, all Mosel vineyards depend on special site characteristics to ensure winter survival and ripening (Gladstones, 1992). As we will show, with these growing conditions, a good vineyard site must be, among other things, a natural solar panel, maximizing

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Table 1.—Solar Radiation Efficiency of Selected Crops

	Crop	RUE_{max}[a]
C_4 species	Sugarcane	2.0
	Maize	1.8
	Grain sorghum	1.7
C_3 species	Potato	1.7
	Wheat	1.6
	Sunflower	1.6
	Rice	1.4
	Soybean	1.3
Other	Tomato	1.5
	Cauliflower	1.1
	Apple	0.8
	Grapevine (merlot)	0.7

Sources: Sinclair and Muchow (1999), Environmental Protection Agency (2002), and Castelan-Estrada (2001).

[a] Maximum RUE in gram dry matter $MJ^{-1}m^{-2}$ of intercepted solar radiation.

the incoming solar radiation with its angle of incidence and orientation.

A. *Radiation Use Efficiency*

Surprisingly, formal research on the influence of light on crop growth dates primarily from the late 1950s (De Wit, 1959). Some twenty years later, Monteith (1977) provided the basis for calculating the quantitative relationship between intercepted solar radiation (energy) and the amount of dry biomass produced. This relationship is expressed by the term *radiation use efficiency* (RUE), and it measures the mass accumulation in gram dry matter per $MJ^{-1}m^{-2}$ of intercepted solar radiation. It is this biomass that represents the economically valuable output of a plant.

Subsequent studies have estimated RUE for different crops (Sinclair & Muchow, 1999), and this research continues today. It is likely that the RUE is fairly similar for the members of a specific crop but varies significantly among crop species. As shown in table 1, C_4 species such as maize, sorghum, and sugarcane have significantly higher RUE than do the C_3 species, such as potatoes, wheat, barley, rice, soybeans, and sunflowers.[1] The only study of the RUE of grapevines (*Vitis vinifera*) of which we are aware is for the Merlot variety (Castelan-Estrada, 2001). With a radiation use efficiency between 0.57 and 0.70 g $MJ^{-1}m^{-2}$, this study indicates that in terms of RUE, *Vitis vinifera* belong to the least efficient plants. It follows that the energy intensity of a particular site is far more important for grapevines than it is for wheat or cauliflower.

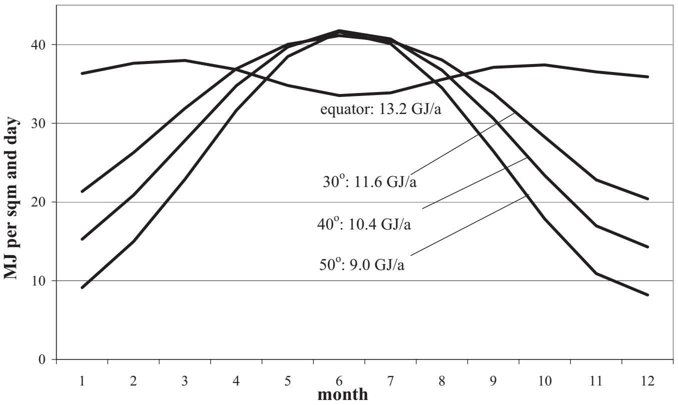
B. *Vineyards as Solar Panels*

Only a part of solar radiation reaches the surface of the earth directly (*beam radiation*). Another part is scattered by the atmosphere and reaches the surface as so-called *diffuse radiation.* The sum of both is referred to as *total solar radiation.* However, it is apparent that total solar radiation is highly dependent on the amount, kind, and density of clouds, and it varies with time and place. For simplicity, engineers often calculate the so-called extraterrestrial radiation, that is, the radiation that would be available if there were no atmosphere (Duffie & Beckman, 1991). This is the simplification we will use to construct a measure of the differences in solar radiation input provided by the different vineyards of the Mosel Valley. Since all these vineyards lie in a very small geographical region, we know that differences across vineyards in total radiation are due primarily to differences in site characteristics, not to differences in the weather.

Figure 1 shows the extraterrestrial radiation on a horizontal surface for different geographical latitudes in the Northern Hemisphere. It is apparent that there is a large difference in both the total amount of energy as well as its distribution over the year. While a plane at the equator receives the maximum energy amount of about 13.2 $GJm^{-2}a^{-1}$, the incoming radiation decreases with increasing latitude. With an energy level of 9.1 $GJm^{-2}a^{-1}$ the Mosel-Saar-Ruwer region obtains only two-thirds of the total maximum energy amount. Moreover, whereas the energy flux at the equator is comparatively evenly distributed, the radiation pattern becomes increasingly focused on June 21 the farther north one gets. Daily solar radiation in the North is even greater in the summer than at equatorial latitudes because of the North's long summer days. As figure 1 indicates, the farther north one goes, the less energy there is available during off-peak times in late spring and late summer. For instance, at the end of October, the main harvest time for Riesling grapes in the Mosel valley, there is only a photon flux of 13 $MJm^{-2}day^{-1}$ compared to 37 $MJm^{-2}day^{-1}$ at the equator, that is, only one-third of the maximal achievable amount.

This energy deficit at high latitudes can be remedied by the right slope. Figure 2 shows the solar radiation for the Mosel city of Trier (49.8° north) by inclination (assuming a southern orientation). Although a plane surface receives only 9.1 $GJm^{-2}a^{-1}$ (as already shown in figure 1), increasing inclination enhances the energy level significantly. A tilt

Figure 1.—Solar Radiation by Latitude on a Horizontal Surface in the Northern Hemisphere



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[1] C_4 crops produce less complicated nutrients like sugar and starch, whereas C_3 crops produce more complex and higher-quality nutrients like oil and protein.

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FIGURE 2.—SOLAR RADIATION BY INCLINATION ON A SOUTHWARD-ORIENTED SURFACE IN TRIER (49.8° NORTH)

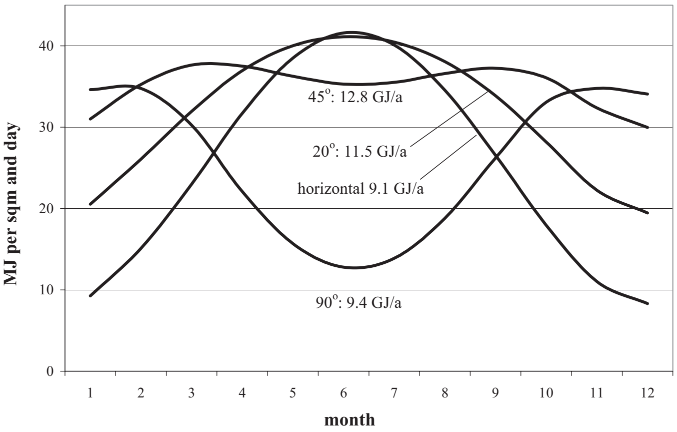
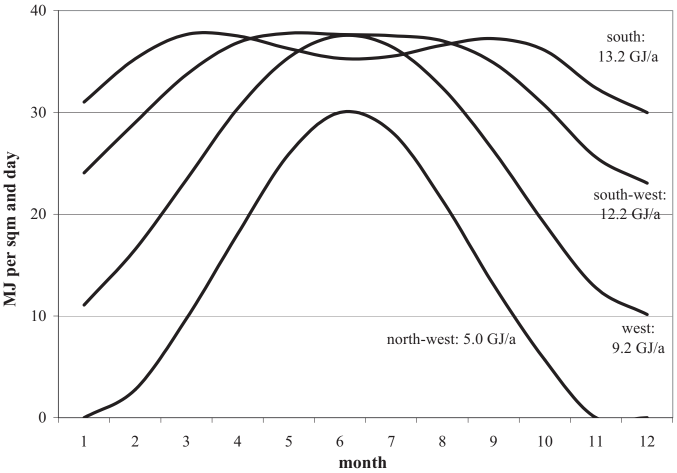


FIGURE 3.—SOLAR RADIATION BY ORIENTATION ON A 45° TILTED SURFACE IN TRIER (49.8° NORTH)



of 45° provides more than 40% more energy (12.8 $\text{GJm}^{-2}\text{a}^{-1}$) and only 3% less than the maximum amount achievable at the equator. Moreover, the distribution over the year strikingly resembles that of the equator; the energy flow from March to October is almost the same. Hence, a vineyard's inclination can almost perfectly offset its unfavorable latitude. However, this does not mean that the steeper vineyards are always better. Vineyards that are tilted more than 45° receive less energy than those with less inclination (at this latitude), and the energy received is also more unequally distributed over the course of the year. For example, an inclination of 90° yields only slightly more solar radiation than a horizontal surface does. The optimal inclination is dependent on the latitude: the farther north, the steeper the optimal site must be. With respect to the Mosel Valley the optimal tilt is about 45°.

The calculations thus far are based on the assumption that the tilted vineyard has a southern orientation. Figure 3 shows the impact of a different orientation for the vineyard on solar energy, holding the latitude constant (at Trier's) and holding the inclination at its optimal level for this latitude: 45°. A southern aspect is the ideal, and with increasing deviation from a southern aspect, the energy yield falls dramatically. If the tilted vineyard is west facing, the yearly solar radiation is less than on a horizontal surface (8.9 compared to 9.1 $\text{GJm}^{-2}\text{a}^{-1}$ given in figure 2). A sloping vineyard with a northwestern aspect receives only 4.7 $\text{GJm}^{-2}\text{a}^{-1}$, less than a horizontal plane in the Arctic Circle.[2]

C. *Calculation of Solar Radiation*

Given data on the latitude (φ), slope (β), and orientation (γ) for any vineyard or agricultural site, we show in the appendix how to calculate a single measure of solar radiation for each month of the year. We aggregated these monthly figures for the vineyards of the Mosel to obtain measures of solar radiation during both the critical ripening period for grapes (September and October) and the full year. These are the data we use in our hedonic analysis.[3] Summary statistics of these measures are contained in the bottom two rows of table 4. The data indicate remarkable variability among the vineyards. For example, the annual energy yield ranges from a high of 12.802 GJm^{-2} to a low of 5.568 GJm^{-2}, or nearly a 130% difference. The total variability in our measure of solar radiation in the crucial ripening period for grapes is even greater and spans the range from 2.237 GJm^{-2} to 0.695 GJm^{-2}, or nearly a 220% difference.

D. *Other Factors That Affect Vineyard Sites*

Gladstones (1992) provides a detailed analysis of several other factors that make specific geographic sites more or less suitable for the production of high-quality grapes. Important factors include those that reduce diurnal (night-day) temperature differences. Nearness to a body of water and, especially, soil type are important determinants of diurnal fluctuations. Thus, the heat storage capacity and solar reflectivity (measured by its albedo number, α) of some soils is of considerable potential importance in determining the quality of a vineyard site, and we also measure these factors in the empirical analysis below.

III. Data

Our analysis makes use of data from two different sources on very specific vineyard sites.[4] Unfortunately the

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[2] This raises the question of why there are steep vineyards with unfavorable orientations at all. The energy yield is lower than on a plane surface, while the labor costs are considerably higher. It seems likely that these vineyard sites were selected for noneconomic reasons, such as their nearness to a cloister.

[3] Detailed calculations for individual vineyards are available from the authors on request.

[4] German vineyard sites have precise names to avoid duplication. A vineyard in the town of Berncastel is a "Berncasteler." The "Doctor" vineyard in the town of Berncastel is thus known as the "Berncasteler Doctor" to distinguish it from any other vineyard named "Doctor."

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TABLE 2.—FRENCH RANKING OF MOSEL VINEYARDS IN 1804 GRADES BY VILLAGE AND REPURCHASE PRICE

Grade	Village	Repurchase Price in Francs/1,000 Liter
1	Dusemond (Brauneberg)	172
2	Piesport, Wehlen, Machern, Graach, Zeltingen, Erden, Lösenich	150
3	Niederremmel, Müstert, Reinsport, Berncastel, Grünhaus, Kesten, Oberremmel, Minheim	140
4	Kous (Cues), Lieser, Winterich, Ürzig, Kröf, Köwerich, Mülheim, Thron, Kinheim, Kindel, Wolf, Kasel, St. Matthias, Okfen, Kastel, Staadt, Neumagen	129
5	Trittenheim, Mehring, Monzel, Waltrach, Isselbach, Konz	118
6	Rachtig, Awelsbach, Mertesdorf, Veldenz, Thörnich, Reul, Maring, Burgen, Olewig, Krutweiler, Ayl, Bibelhausen, Irsch/Saar	107
7	Pfalzel, Pichter, Merzlich, Niederleuken, Klüsserath, Wawern, Pölich, Köwerich, Platten, Filzen/Mosel, Neudorf, Trier, Hamm, Komlingen, Nennig, Mies, Helfand, Detzem, Schweich, Longen, Lörsch, Ensch, Longuich, Osan	96
8	Niedermennig, Leiwen, Schleich, Fell, Löwenbrück, Kreutz, Kürenz, Feyen, Palzem, Rölingen, Fasterau, Beurig, Perl, Sendorf	86
9	Wittlich, Andel, Pallien, Erang, Metzdorf, Euren, Zewen, Oberkirch, Monaise, Niederkirch, Ruwer, Pellingen, Irsch-Olewig, Kenn, Feilz, Plein, Luxem, Kernscheid, Issel, Bekond, Hetzrath, Rivenich, Riol	75
10	Bengel, Springirsbach, Korlingen, Drees, Bergweiler, Hupperat, Flusbach, Bausendorf, Olkenbach	64

Source: According to Le Ministre des Finances de la France (1811) and Heger (1905).

definition of these distinct vineyard sites has changed at times so that our two key sources are not based on precisely the same vineyard definitions. Stöhr, Cüppers, and Fass (1981) provide a comprehensive description of all the geographic characteristics of the Mosel-Saar-Ruwer vineyard sites as they were defined in 1971.[5] These data were taken as the baseline for our calculations. We supplemented these data on the geographic characteristics of the vineyards with measures of the historical prices of the vineyards based on taxation records, primarily from the nineteenth century. Since the latter data were based on finer divisions of vineyards, that is, smaller vineyard sites, we lose some information by aggregating to the 1971 benchmark.[6]

A. *Vineyard Price and Quality*

The most difficult aspect of our data construction is the ranking by price of the respective vineyards. Prices of vineyard sites have been assessed for taxation purposes in the Mosel since the seventeenth century. An early example of such a ranking that was made by the French, who controlled the Mosel area in the early part of the nineteenth century, is contained in table 2. A "repurchase price" was set for the wines of each vineyard, and this formed the basis for its taxation.[7] However, we rely primarily on the work of the Prussian tax administration during the mid-nineteenth century for our ranking of vineyards by price. Using the work started by the French, the Prussians completed a meticulously detailed land register in the 1830s in order to tax the land according to the value of its production. Using the method very similar to that used for the classification of Bordeaux wines in 1855 (Penning-Roswell, 1986; Markham, 1998), the value of vineyard sites was taken as proportional to the average prices for the wines of each vineyard over a 24-year period from 1837 to 1860 (Beck, 1869).[8] The Prussian tax administration distinguished eight different net yield grades, and in 1869, this ranking was published by the Government of the King of Prussia (Beck, 1869). This list distinguishes the different vineyards within the various villages. To provide the detailed location of the vineyard sites, the government also published a map of these sites for the administrative district of Trier (the upper Mosel) in 1868 (Clotten, 1868) and a similar map for the lower Mosel (for the district of Koblenz) in 1897 (Lintz, 1897).

We use these maps to construct a price-based ranking of the vineyards. Unfortunately the vineyard sites ranked by price in Beck (1869) are not necessarily identical to those used by Stöhr et al. (1981) to provide vineyard site characteristics. Accordingly, the maps of 1868 and 1897, respectively, as well as the maps provided by Stöhr et al., were used to apply the Prussian ranking to contemporary vineyard sites.

The estimates we obtained were compared to the vineyard-size figures published by the Prussian government (Beck, 1869). The comparison of these figures as well as the maps ensures a certain degree of consistency. In addition, any "new vineyards" that did not exist during the period of the 1869 ranking were excluded from the analysis. As a result,

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[5] The Mosel River is the largest tributary of the Rhine. The grape-growing region known as the Mosel, which runs with the river roughly 206 kilometers northeast from Trier to Koblenz, actually consists of a system of river valleys that includes the tributaries the Saar and the Ruwer. Thus, the official term for this wine area is "Mosel-Saar-Ruwer."

[6] For instance, in 1910 there were about 4,550 defined vineyard sites within a demarcated area of 6,800 hectares (Goldschmidt, 1925). The German wine law of 1971 defines only 523 vineyard sites within an area of 11,985 hectares (Stöhr et al., 1981; Statistisches Bundesamt, 1998).

[7] The Napoleonic administration promoted the self-reliability and independence of vintners from church and nobility and allowed vintners to pay their rent in money. The "repurchase price" was the price a vintner had to pay if he wanted to repurchase his in-kind rent (i.e., grapes) to market himself.

[8] In order to avoid distortions caused by differences in prices across different vintages, the optimal estimation period and the appropriate computational method were discussed in great detail at the time (e.g., Daezel, 1815; Flotow, 1820; Gebhard, 1824; Schimmelfennig, 1831).

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Table 3.—Distribution of Vineyard Site Ranking

Rank	Number	Percent
1	1	0.29
2	11	3.20
3	23	6.69
4	59	17.15
5	63	18.31
6	85	24.71
7	69	20.06
8	33	9.59
Total	344	100.00

Source: Own calculations.

Table 4.—Descriptive Statistics of Variables

Variable	Mean	S.D.	Minimum	Maximum
Rank	5.52	1.56	1	8
Slope (degree)	38.28	7.97	0	45
Orientation[a]	46.71	28.68	0	135
Latitude (degree)	49.95	0.20	49.61	50.34
Altitude (in meters)	120.02	43.83	22	226
Hectare	26.31	37.99	0.2	420
Energy (GJm^{-2} per year)	11.27	1.47	5.57	12.8
Energy (MJm^{-2} in Sept/Oct)	1,872.3	318.0	694.6	2,237.4

[a] Deviation from southern orientation in degrees.

of the 523 currently recognized vineyards, only 344 vineyard sites are included in our analysis. Finally, the results of our analysis were cross-checked with the "new" vineyard classification constructed by Stuart Pigott (1995), which is also based on the older Prussian ranking. Our ranking, like those before, distinguishes eight ordinal grades of vineyard quality, where rank 1 denotes the highest quality and rank 8 denotes the lowest quality.

Table 3 provides the frequency distribution of our rankings. It is obvious that the larger average vineyard site size in the current definitions leads to a leveling out of the quality distribution compared to older definitions. While the Prussian ranking had 60 vineyards comprising 44 hectares ranked in the top-quality group, the application of the Prussian ranking to current vineyard sites shows that only one, the Berncasteler Doctor, is ranked wholly in the top-quality category.[9] With today's list of vineyard sites, only 10% of all vineyard sites belong to even the first three ranks, while most fall into ranks 6 and 7.

B. *Physical Vineyard Site Characteristics*

Data on physical vineyard attributes were taken from Stöhr et al. (1981). For each site, they report the latitude, slope, altitude, orientation, depth of soil, type of soil, and size of the vineyard. The slope is given as a fraction of the vineyard that is steep, middle, or flat. We constructed the variable "slope" as a weighted average of these slope measures, where 45° is take as steep, 22.5° is middle, and 0° is flat. Table 4 shows the basic results of our calculations. The average slope of a Mosel vineyard is very steep, at 38°, which is not far from the optimum of 45°, although at least one vineyard is entirely flat.

Stöhr et al. (1981) provide the "prevailing orientation" of the vineyards in twelve categories according to the entries on a compass. These are, for example, south or southwest. We assigned a value to the variable "orientation" by the degrees of deviation of the vineyard from south: 0° for southern orientation, 90° for west or east, and 180° for north. For instance, an aspect given as south-southwest (SSW) would be measured as 30°, which we assume is the average orientation of the vineyard. When a vineyard had a compound orientation measure, such as "south and west," we simply assumed a 50/50 relation and defined the deviation from south as 45°. Overall, the data in table 4 show that while a south-southwest orientation is the average, there is considerable variation, with at least one vineyard facing northwest (135°).

The altitude of a vineyard is given in meters at its lowest and its highest point. The altitude of these Mosel vineyards ranges between 320 m in the Saar valley and 65 m near the Rhine River. Altitude alone seems unlikely to affect a Mosel vineyard's quality given that all these vineyards are well below 500 meters (Gladstones, 1992). However, since the impact of large water bodies on diurnal air circulation is considered important for quality (Gladstones, 1992), we used data on the altitude of the Mosel River to calculate the altitude difference between the vineyard and the water body. We expect a large difference to have a negative effect on wine quality and a vineyard's ranking.

Stöhr et al. provide measures of the soil's depth as deep, moderate, and flat. We calculated the depth of the soil as a single variable ranging from 0 to 1, where 1 is deep and 0 is flat. For instance, a vineyard like the Erdener Praelat, which is described as deep to moderately deep, was assigned the value 0.75. The impact of soil depth on wine quality is not well understood. On the one hand, shallow and rocky soils limit potential vine rooting depth and provide only restricted water storage capacity. On the other hand, shallow and rocky soils provide fine drainage and resistance to soil erosion, which is particularly important on slopes. Since the Mosel region is not characterized as a particularly dry climate, the latter may be the more important effect (Gladstones, 1992).

Besides the depth of the soil, we also have measures of the kind of soil. This is particularly important because of the heat storage capacity of certain soils. Heat is absorbed during the day, which is followed by marked and prolonged re-radiation of warmth at night. Slate is one of the most heat-absorbent soils.[10] In fact, the entire Mosel-Saar-Ruwer region is characterized primarily by different forms of slate, although other soils prevail in the valley around Trier

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[9] The size of this vineyard is only 1.0 hectare, which is much smaller than the average vineyard size of 21.2 hectares.

[10] Because of its low reflectivity of solar radiation (measured by its albedo value), slate is also considered an important building material for the passive usage of solar energy. Common albedo values are: slate 0.10, wet sand 0.15, dry sand 0.25, concrete 0.30, and limestone 0.40 (SolVent, 2001).

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(sandstone) and between Trier and the border with Luxembourg (limestone). However, single vineyards often contain many alternative soil types. We distinguish twelve kinds of soil: weathered slate, slate quartzite, clay slate, greywacke, quartzite, sandstone, limestone, gravel, finesoil, alluvial soil, sand, and clay/loam. We constructed a set of dummy variables for these soil types, where the variable takes a 1 if this soil type exists in the vineyard and 0 otherwise.

All of these variables are assumed to reflect the average characteristics of the vineyard. However, within a single vineyard, conditions can deviate substantially from this average, and the deviation is likely to be larger the larger the size of the vineyard. We therefore also included in our hedonic analyses a measure of the total size of the vineyard. If the uncertainty associated with vineyard quality leads to lower quality and prices, then we expect larger vineyards to, other things the same, be of lower quality.

Though most of the vineyards of the Mosel-Saar-Ruwer region are near one of the rivers for which they are named, a small number of remote vineyards are located near castles or cloisters. Since these vineyards do not benefit from the smaller diurnal temperature fluctuations due to proximity to a large water body, we also introduced a dummy variable that takes on the value unity when a vineyard is remote and 0 otherwise. We expect it to have a negative effect on vineyard quality.

IV. Hedonic Model of Vineyard Quality

Given the discrete natural order of the dependent variable and the fact that the differences between the ranks are not necessarily equivalent, we fit our hedonic model using an ordered probit function.[11] In this setup, the observed response is taken to depend on a latent variable y_i^*, which depends linearly on the explanatory variables $\mathbf{X_i}$:

$$y_i^* = \mathbf{X_i}\boldsymbol{\beta} + \varepsilon_i, \quad \text{with } \varepsilon_i \sim N(0, 1). \tag{1}$$

The observed category of y_i is based on y_i^* and can take on eight values:

$$y_i = \left\{ \begin{array}{c} 1 \text{ } if \text{ } y_i^* \le \gamma_1 \\ j \text{ } if \text{ } \gamma_{j-1} \le y_i^* < \gamma_j \\ \cdot \\ 8 \text{ } if \text{ } \gamma_7 \le y_i^* \end{array} \right\}. \tag{2}$$

The probability of y_i being in a particular rank is

$$\begin{aligned} \Pr(y_i = 1) &= \Pr(y_i^* < \gamma_1) = \Pr(\mathbf{X_i}\boldsymbol{\beta} + \varepsilon_i < \gamma_1) \\ &= \Pr(\varepsilon_i < \gamma_1 - \mathbf{X_i}\boldsymbol{\beta}) = \Phi(\gamma_1 - \mathbf{X_i}\boldsymbol{\beta}) \end{aligned} \tag{3}$$

$$\begin{aligned} \Pr(y_i = 2) &= \Pr(\gamma_1 \le y_i^* < \gamma_2) \\ &= \Pr(\gamma_1 \le \mathbf{X_i}\boldsymbol{\beta} + \varepsilon_i < \gamma_2) \\ &= \Pr(\varepsilon_i < \gamma_2 - \mathbf{X_i}\boldsymbol{\beta}) - (\varepsilon_i \le \gamma_1 - \mathbf{X_i}\boldsymbol{\beta}) \\ &= \Phi(\gamma_2 - \mathbf{X_i}\boldsymbol{\beta}) - \Phi(\gamma_1 - \mathbf{X_i}\boldsymbol{\beta}) \end{aligned}$$

. . .

$$\begin{aligned} \Pr(y_i = 8) &= \Pr(y_i^* \ge \gamma_7) = \Pr(\mathbf{X_i}\boldsymbol{\beta} + \varepsilon_i \ge \gamma_7) \\ &= \Pr(\varepsilon_i \ge \gamma_7 - \mathbf{X_i}\boldsymbol{\beta}) = \Phi(\mathbf{X_i}\boldsymbol{\beta} - \gamma_7), \end{aligned}$$

where $\Phi(\cdot)$ denotes the cumulative normal distribution function.

The results of the estimation are contained in table 5 for several specifications of the basic set of independent variables (**X**) that determine quality. These vineyard quality variables, discussed earlier, are listed as the row labels in table 5. In a first specification (column 1), we include variables related to soil characteristics and include as separate variables the three determinants (slope, orientation, and latitude) of our measure of the solar energy captured by the vineyard. This is a reduced-form regression that we use to test the basic predictions of our model of energy retention. In order to extrapolate the impact of a change in climate on vineyard quality, it is essential that this model of energy retention provides a reasonable approximation of how radiant energy affects vineyard site quality.

The results in columns 2 and 3 reflect the imposition of the constraint that the three energy variables are captured by the specific formula contained in the appendix. Comparing the unconstrained results in column 1 to the results in columns 2 and 3 provides a basic empirical test of the accuracy of this formula for predicting how solar energy affects vineyard prices.

In fitting the constrained model, we aggregated the variables slope, orientation, and latitude in two ways to determine a measure of potential energy. In column 2 we use a formula that assumes that the energy the plant receives throughout the entire year is the appropriate measure, while in column 3, we assume that the energy the plant receives in the fall is the appropriate measure. Neither of these measures is likely to be ideal, but they are very highly correlated in any event. Moreover, these two extreme cases span all the reasonable alternatives.

A comparison of the results indicates that the constrained measure of "fall energy" in column 3 provides a slightly better fit to the data (judging from the maximized likelihood ratio) than the measure of "annual energy," and so we rely on it for further analyses. A straightforward way to assess the goodness-of-fit qualities of an ordered probit model is a comparison of predicted and actual results. In table 6 we use the results of column 3 of table 5 to assess the model's predictive quality. Predicted quality ranks are listed in the first column, and the distribution of the deviations of the actual from the predicted ranks is listed in the remaining columns for each predicted rank. For example, 85 vineyards are predicted to be in the largest category, rank 6, of which 54 predictions are correct, 28 are off by one rank, and 3 are off by two ranks. Overall, the ranks of 50.9% of all vineyards are predicted correctly, while 42.2% of the predictions

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[11] See Davidson and MacKinnon (1993) or Greene (2003), for example.

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Table 5.—Determinants of the Vineyard Site Ranking Results of the Ordered Probit Model

Variable	(1)	(2) (Annual Energy)	(3) (Fall Energy)
Slope	−3.13***		
	(−6.44)		
Orientation	0.04***		
	(12.71)		
Latitude	0.29		
	(0.57)		
Energy (KJm^{-2})		−0.86***	−4.10***
		(−11.50)	(−11.53)
Clay slate	−2.35***	−2.09***	−2.13***
	(−7.21)	(−6.79)	(−6.89)
Weathered slate	−1.59***	−1.32***	−1.35***
	(−5.92)	(−5.10)	(−5.20)
Slate quartzite	−0.72*	−0.53^{+}	−0.57^{+}
	(−2.23)	(−1.71)	(−1.86)
Sandstone	−0.38	−0.17	−0.20
	(−0.97)	(−0.32)	(−0.41)
Finesoil	−0.11	−0.27	−0.26
	(−0.41)	(−1.19)	(−1.15)
Sand	1.05***	1.12***	1.08***
	(3.48)	(4.38)	(4.21)
Clay, loam	0.86***	0.91***	0.89***
	(3.88)	(4.10)	(4.04)
Quartzite	0.65^{+}	0.81*	0.80*
	(1.70)	(2.15)	(2.14)
Gravel	−0.04	0.17	0.12
	(−0.08)	(0.37)	(0.25)
Graywacke	−0.03	0.13	0.10
	(−0.12)	(0.88)	(0.68)
Limestone	−0.20	0.17	0.06
	(−0.31)	(0.25)	(0.09)
Alluvial soil	−0.08	0.02	−0.04
	(−0.20)	(0.07)	(−0.13)
Depth of soil	1.70***	1.94***	1.91***
	(6.06)	(6.97)	(6.87)
Altitude difference[a]	0.01***	0.01***	0.01***
	(3.57)	(2.83)	(2.88)
Vineyard size	0.01***	0.01***	0.01***
	(5.39)	(6.71)	(6.61)
Remote vineyard	1.36***	1.41***	1.29***
	(3.98)	(4.31)	(3.80)
γ_1	8.48	−13.63***	−11.84***
	(0.35)	(−11.65)	(−11.60)
γ_2	9.98	−12.19***	−10.38***
	(0.41)	(−11.06)	(−11.00)
γ_3	10.80	−11.38***	−9.56***
	(0.45)	(−10.81)	(11.00)
γ_4	11.97	−10.31***	−8.46***
	(0.50)	(−10.06)	(9.83)
γ_5	13.05	−9.34***	−7.47***
	(0.54)	(−9.34)	(8.96)
γ_6	14.65	−7.846***	−5.926***
	(0.61)	(−8.28)	(−7.59)
γ_7	16.81	−5.782***	−3.826***
	(0.70)	(−6.56)	(−5.31)
Log likelihood	−376.0	−397.3	−393.5
Pseudo-R^2 (in %)	39.7	36.3	36.9

Note: Huber-White robust z-statistics in parentheses.
Significance level of 1% (***), 2% (**), 5% (*), 10% (+).

are off by a deviation of one rank. Taken together, the average deviation is only 0.57 quality ranks.

A test of the constraint that energy determines vineyard quality in the precise form we have assumed may be based on a comparison of twice the difference in the log likelihood between columns 1 and 3 of table 5. This test rejects the precise constraint at any reasonable level of statistical significance, but it is apparent from table 6 that the constrained measure captures the major variability in the data. As a result, we use the basic results in column 3 of table 5 in simulating the effects of climate change in the analysis below.

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TABLE 6.—PREDICTION AND DEVIATION BY RANK

	Deviation by Number of Ranks								
Rank	0	1	2	3	4	5	6	7	Sum
1	0	0	1	0	0	0	0	0	1
2	5	0	4	1	1	0	0	—	11
3	0	19	3	1	0	0	—	—	23
4	33	20	6	0	0	—	—	—	59
5	24	35	4	0	0	—	—	—	63
6	54	28	3	0	0	0	—	—	85
7	41	28	0	0	0	0	0	—	69
8	18	15	0	0	0	0	0	0	33
Sum	175	145	21	2	1	0	0	0	344
in %	50.9	42.2	6.1	0.6	0.3	0.0	0.0	0.0	100.0

Source: Own calculations.

Since the vineyard ranking is defined as 1 being best and 8 being worst, a positive influence of an independent variable on the quality of the vineyard is indicated by a negative sign. It is apparent that the potential solar radiation variable has a significant effect on the rating of a vineyard site. In addition, slate of any type increases the quality of the vineyard, especially weathered slate and clay slate. As expected, sand, gravel, and loam have a far lower ability to store heat and are, by comparison with slate, less advantageous for the vineyard's quality.

The results in table 5 also provide evidence for the importance of a water body close to the vineyard. Vineyards that are remote from the Mosel River and those that are far above the river suffer from these features. Both of these factors lead to larger diurnal temperature fluctuations and thus to lower-quality vineyard sites.

Finally, the estimates confirm the hypothesis that larger-sized vineyards, given our measurements of the other measures of a vineyard's qualities, do suffer a disadvantage in quality.

The estimated coefficients of an ordered probit model must be interpreted with some care. The sign of $\hat{\boldsymbol{\beta}}$ shows the direction of the change in the probability of falling in the end point rankings ($y_i = 1$) and ($y_i = 8$) when $\mathbf{X}$ changes. $\Pr(y_i = 1)$ changes in the opposite direction of the sign of $\hat{\boldsymbol{\beta}}$, and $\Pr(y_i = 8)$ changes in the same direction as the sign of $\hat{\boldsymbol{\beta}}$. The effects on the probability of falling in any of the middle rankings are unclear, a priori.

Table 7 reports the marginal effects of the significant variables of the model listed in column 3 of table 5 that uses the fall radiation variable. Marginal effects are measured relative to the baseline probabilities given in the first line. As the table shows, the percentage of vineyard sites expected to be ranked 1 is 0.27%, while the percentage for rank 2 is 3.32%. The following set of rows reports the effect of a change of 10% in the value of an independent variable on these percentages. Thus, an increase in potential solar radiation by 10% will increase the vineyard's probability of being ranked 1 by 1.19% to 1.46%. Similarly, the probability of being ranked 2 will increase from 3.34% to 9.33%. Since the changes sum up to 0, energy increases entail a drop in the likelihood of being in rank 6, 7, or 8. Similarly, deeper soil, a greater altitude difference between the vineyard and the Mosel River, and a larger vineyard size decrease the probabilities of being in the high-quality ranks. However, it is apparent that the marginal effect of the solar radiation variable is substantial compared to the effects of each of these other variables.

The marginal effects of the dummy variables were calculated as the effect of the difference between the values 0 and 1 while holding the other variables at their mean values. The marginal effects of these variables show the great importance of soil type on vineyard quality and also the great importance of having a vineyard site that is influenced by proximity to the Mosel River.

TABLE 7.—MARGINAL EFFECTS OF MODEL USING FALL SOLAR RADIATION

	Probability (in %)							
	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8
Baseline	0.27	3.32	6.52	16.79	18.95	24.61	19.65	9.74
	Change in Probability (in %)							
Continuous variables[a]								
Fall energy	1.19	5.96	5.17	3.35	−2.07	−5.06	−5.45	−3.09
Depth of soil	−0.02	−0.25	−0.44	−0.71	−0.21	0.24	0.60	0.78
Altitude[b]	−0.02	−0.24	−0.34	−0.44	−0.04	0.32	0.42	0.36
Vineyard size	−0.01	−0.08	−0.12	−0.19	−0.04	0.23	0.05	0.15
Dummy variables[c]								
Clay slate	4.46	14.90	9.68	7.42	−0.38	−9.69	−15.92	−10.48
Weathered slate	1.85	6.02	5.98	8.31	2.46	−5.36	−10.60	−8.66
Slate quartzite	0.56	3.41	3.59	3.30	−0.65	−3.27	−3.91	−3.04
Sand	−0.26	−2.87	−4.83	−9.13	−4.14	4.38	8.60	8.26
Clay, loam	−0.24	−2.67	−4.44	−7.78	−2.82	4.17	8.13	5.65
Quartzite	−0.23	−2.44	−3.99	−7.01	−2.35	3.99	6.29	5.74
Remote	−0.26	−3.13	−5.64	−11.66	−6.44	5.29	10.99	10.86

[a] Effect of a 10% increase.

[b] Difference in altitude between vineyard and Mosel River.

[c] Difference between the values 0 and 1.

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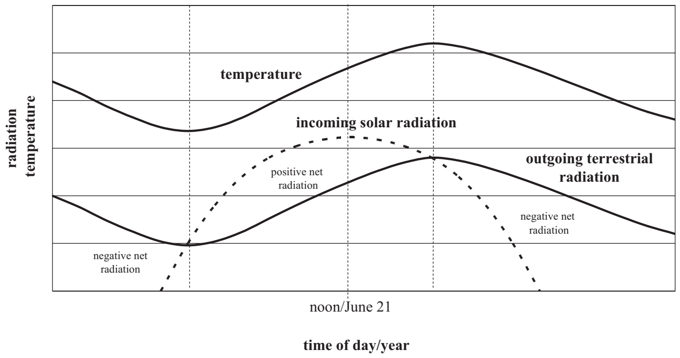
FIGURE 4.—SOLAR RADIATION AND TEMPERATURE



V. Solar Radiation and Global Warming

Since vineyard quality is dependent on solar energy absorption, it follows that in a place like the Mosel Valley, climate change that leads to warmer temperatures will lead to higher-quality wines and prices. Land prices, which represent the capitalized value of these wine prices, less other costs of production, should therefore also increase. It follows that the many recent studies that predict that climate change is leading to warmer temperatures also predict increased land values in areas like the Mosel Valley. In what follows, we set out a simple model that permits us to estimate the effect of climate change on the overall quality of the Mosel's vineyards and thus on their prices.

Most scenarios about global temperature change[12] provide a summary measure of expected temperature changes, whereas we have established the connection between solar energy reception and vineyard quality. Although there is, of course, a relationship between solar energy and the earth's temperature, the relationship involves a comparison of energy inflow and outflow. Absorbed energy from the sun is converted to heat, which causes the earth to warm up. However, the temperature maximum occurs not at the time of maximum solar energy input but later. This lag is the result of the energy storage system and the resistance to energy flows. Figure 4 shows that in a simple model, temperature is the result of the influx of solar energy and the energy radiated by the earth. Thus, as long as the net influx is positive, temperatures will rise and vice versa. The result is that the temperature maximum is attained after the influx maximum.

We use the following simplified model to establish the interrelations between solar radiation and temperature (see Hartmann, 1994, and Andrews, 2000) for the purpose of simulating the effect of various global warming scenarios on vineyard quality and prices.

With radius R and the earth's receptive surface πR^2, the energy absorbed by the planet is equal to

$$(1-\alpha)\pi R^2 S = \text{(energy absorbed by the earth)}, \tag{4}$$

where α is the albedo number of the earth's atmosphere and S is the solar constant. We assume that $\alpha = 0.3$, which implies that the earth reflects 30% of the incoming solar energy back to space.

If the earth is assumed to emit like a blackbody,[13] the energy radiated from our planet is, according to the Stefan-Boltzmann law, equal to

$$(4\pi R^2)\sigma T_s^4 = \text{(energy radiated from the earth)}, \tag{5}$$

where T_s is the planet's surface temperature and σ is the Stefan-Boltzmann constant.[14]

Setting equations (4) and (5) equal and solving for the equilibrium temperature yields

$$T_s = \sqrt[4]{(1-\alpha)S/4\sigma}. \tag{6}$$

According to equation (6), the earth's surface temperature is equal to 255K (or −18°C) which is well below the measured average temperature of approximately 288K (or 15°C).

To make this model more realistic, it is necessary to incorporate the atmospheric effects that are associated with the earth and act like a greenhouse. If we assume an atmosphere that absorbs all long-wave terrestrial radiation but is transparent to short-wave solar radiation, at the top of this atmospheric layer the energy balance remains the same with

$$\sigma T_a^4 = (1-\alpha)S/4, \tag{7}$$

where T_a is the atmospheric temperature. Assuming further that $\sigma T_s^4 = 2\sigma T_a^4$, that is, half of the energy absorbed by the atmosphere is reflected back to the earth, we get

$$T_s = \sqrt[4]{(1-\alpha)S/2\sigma}. \tag{8}$$

Equation (8) predicts an average temperature of 303K (or 30°C) for the earth, which is much closer to the observed value.

Equation (8) allows us to compute changes in radiant energy associated with any given temperature variation. Accordingly, a temperature increase of 1°C is associated with additional radiation energy of 47.43 MJ/month. Similarly, a temperature increase of 2°C or 3°C translates into radiation energy increases of 94.87 and 142.82 MJ/month, respectively.

Table 8 reports the changes in a vineyard's probability of being in a certain rank using the results in table 7 and

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[12] See Johns et al. (1997).

[13] A *blackbody* absorbs all the radiant energy it receives, regardless of the wavelength.

[14] The Stefan-Boltzmann constant is equal to $5.67 * 10^{-8}$ JK^{-1}.

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Table 8.—Global Warming and Vineyard Ranking

		Probability (in %)							
		Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8
Baseline		0.27	3.32	6.52	16.79	18.95	24.61	19.65	9.74
		Change in Probability (in %)							
Temperature increase	Energy increase (MJ/month)								
1°C	47.43	0.32	2.19	2.46	2.45	−0.29	−2.21	−2.79	−2.13
2°C	94.87	0.95	5.21	4.95	3.88	−1.23	−4.50	−5.44	−3.82
3°C	142.82	2.06	9.02	7.10	4.22	−2.54	−6.80	−7.93	−5.24
		Number of Vineyards							
Baseline		0	6	4	79	64	94	69	28
1°C increase		0	13	5	111	43	91	62	19
2°C increase		0	30	11	121	37	83	47	15
3°C increase		2	56	10	115	39	73	36	13

Table 9.—Global Warming and Land Values, in 2003 Prices

	Baseline	Simulation 1°C	Simulation 2°C	Simulation 3°C
Hectares				
Rank 1	0.0	0.0	0.0	7.8
Rank 2	19.3	71.1	375.5	851.6
Rank 3	10.8	32.1	212.8	134.6
Rank 4	1,283.4	1,958.2	2,317.2	2,338.0
Rank 5	1,365.5	995.8	965.2	1,086.4
Rank 6	2,384.9	2,640.6	2,582.7	2,366.2
Rank 7	2,851.1	2,431.9	1,843.7	1,550.5
Rank 8	1,134.6	919.9	752.5	714.5
Total	9,049.6	9,049.6	9,049.6	9,049.6
Value in million €	231.3	276.1	371.0	467.4

various assumptions about the likely magnitude of climate change. For example, a temperature increase of 1°C corresponds to an increase in potential solar radiation of 47.43 MJ/month, which changes the likelihood of an average vineyard being rated number 1 by 0.32%, that is, from 0.27% to 0.59%. Similarly, the likelihood of being rated number 8 will decrease by 2.13%, that is, from 9.74% to 7.61%. Predicted temperature increases in the Mosel area for the near term are around 2°C for moderate warming scenarios, with higher predicted temperature increases in the longer term. These three scenarios should provide a general indication of magnitudes to be expected.[15]

As also reported in table 8, the number of vineyards in each category will change with increased warming. While in the base scenario only 10 vineyards were rated quality 1, 2, or 3, a temperature increase of 1°C will lift this number to 18. In comparison, if temperatures increased by 3°C, 68 vineyards would be rated within the best three categories.

In order to convert these changes in vineyard quality ranking into changes in vineyard prices, we weight land values in each quality category by the size of the respective vineyards. While the size of each vineyard is given in Stöhr et al. (1981), the land value of each quality class was taken from land sales surveys provided by the governments of the four counties that cover the Mosel area (Landkreis Bernkastel-Wittlich, 2004; Landkreis Cochem-Zell, 2004; Landkreis Mayen-Koblenz, 2004; Landkreis Trier, 2004). The surveys provide average sales prices of vineyard land in 2003, differentiated by municipality and vineyard quality level. This permits us to estimate vineyard-specific market prices.[16] From these data, we calculated average land values for each quality category. The land values range from 0.50 euros per m^2 for vineyards in quality category 8 to 130 euros per m^2 for vineyards in quality category 1.[17]

Table 9 reports the hectares of vineyards in each quality category and in each scenario. While in the baseline scenario only 30 hectares of vineyards are within the top three quality ranks, a temperature increase of 1°C would put more than 100 hectares in these categories. These temperature increases also lead to higher predicted land values. In fact, because of the steeply increasing land prices as we move from lower- to higher-quality vineyards, the change in land values is proportionally greater than the mere increase in temperatures. While a 1°C increase results in an increase in the total vineyard land value of 20% (from 231 million euros to 276 million euros), a 3°C increase in temperature will double the overall land value.

VI. Effects of Annual Weather Changes on Prices, Profits, and Quantities

Our analysis of the effect of the role of solar radiation in determining wine and vineyard quality can be compared to a direct analysis of the effect of year-to-year fluctuations in the weather on agricultural prices and profits. Each ap-

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[15] See, for example, the Hadley Center's work in Johns et al. (1997).

[16] The reported sales prices reflect only the land value and do not include the value of vines that might be planted on it.

[17] Our calculations are based on the following land values per m^2: 130 euros (rank 1), 20 euros (rank 2), 10 euros (rank 3), 7 euros (rank 4), 4 euros (rank 5), 2 euros (rank 6), 1 euro (rank 7), and 0.50 euro (rank 8). It is apparent that the prices drop dramatically with quality.

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Table 10.—Weather and Real per Hectare Profits, Subsidies, and Costs of German Wineries

	(1) ln (Profits − Subsidies)	(2) ln (Profits Including Subsidies)	(3) ln (Costs)
Temperature growing season[a]	0.309***	0.305***	0.026
	(5.17)[5.25]	(4.71)[5.11]	(0.18)[0.19]
Rainfall winter[b]	−0.0034***	−0.0031***	−0.0003
	(−9.77)[−9.90]	(−3.23)[−8.51]	(−0.29)[−0.29]
Rainfall growing season[c]	−0.0009***	−0.0009***	−0.0001
	(−4.62)[−4.68]	(−1.75)[−5.67]	(−0.51)[−0.52]
Trend	−0.074***	−0.072***	−0.029
	(−8.79)[−8.91]	(−8.37)[−7.98]	(−1.40)[−1.42]
Fixed effects			
Mosel	8.09	8.14	10.33
Rheinhessen	7.55	7.52	10.14
Rheingau	8.28	8.14	10.35
Pfalz	7.79	7.75	9.86
Baden-Württemberg	8.48	8.43	10.18
Franken	8.11	8.10	10.41
R^2	0.663	0.644	0.538
F statistic	9.17	11.25	8.26
N	52	52	57

[a] February to October, in degrees Celsius.
[b] December to February prior to growing season in ml.
[c] April to October in ml.
Significance level of 1% (***), 2% (**), 5% (*), 6.6% (+); Newey-West robust t-values in parentheses; t-values based on year clustered standard errors in brackets.

proach has its advantages, but in principle, if accurately measured, they should provide similar evidence.

We have two sources of data with which to provide time-series estimates: (a) data from accounting records of vineyard profits and (b) data on retail and auction prices of wine. Each of these data sources has advantages and disadvantages.

A. *Weather and Accounting Profits*

Our data on accounting profits come from a set of test wineries in six German viticultural areas that include the Mosel and some nearby regions. Beginning with the agricultural year 1971–72, the German Department of Agriculture annually has reported aggregate balance sheet and accounting results for a number of sample wineries in the regions known as Mosel-Saar-Ruwer, Rheinhessen, Rheinpfalz, and Baden-Wuerttemberg. For a shorter period starting in 1982, data are also available for the additional regions of Rheingau (1982–2000) and Franken (1986–present). These viticultural regions all lie in the valley of the Rhine River and its tributaries, the Mosel and the Main. They stretch from Freiburg in the south (47.6° N) to Koblenz in the north (50.2° N), a distance of approximately 180 miles, similar to the length of California's major wine-growing region, the San Joaquin valley. These vineyard areas are not identical, and we use separate fixed effects in the empirical analysis for each of them. However, the wines from these regions have many common features, and we expect the effect of growing season temperature changes on profits to be similar across the regions.

The number of test wineries varies by wine region and changes slightly from year to year. There are currently data for about 165 reporting test wineries in the Mosel regions, covering approximately 20% of the bearing acreage. Data for the individual firms are proprietary, and only regionally aggregated figures are published in the annual agricultural reports of the German Department of Agriculture (Federal Ministry of Food, Agriculture and Consumer Protection, 1973–2007).

A potential complication for the analysis is that in all six wine regions, vintners receive considerable subsidies. In 2006, the European Union spent approximately 1.5 billion euros on measures such as wine distillation, storage of wine, and grubbing-up and restructuring schemes (see European Commission, 2006). In addition, there are substantial financial aids provided by the German federal government and the respective state governments for tax-exempt diesel fuels, social insurance, and the maintenance of steep-slope vineyards. It is likely that some of these subsidies are not independent of annual changes in the weather variables. As a result, we report separate analyses of gross profit data (including subsidies) and net profit data (excluding subsidies).

In table 10 we report the results of regressions of profit and costs on some key weather variables. We report the results using the data from a single weather station (Trier) in view of the geographical proximity of the viticultural regions we study. Drawing on data from regional weather stations did not change or improve the precision of the estimates, a result similar to that reported by Lecocq and Visser (2006) for an analysis of the Bordeaux region in France.[18]

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[18] Lecocq and Visser (2006) show for the Bordeaux region that using data on the local weather within a homogenous wine region yields little additional explanatory power over using data from only one weather station. In either case, the weather station data serve only as approximations for the time-series variation in the weather within each vineyard.

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The weather variables we include in the regressions are (a) the average temperature over the growing season (in Centigrade degrees), (b) the total rainfall (in millimeters) in the growing season, and (c) the total rainfall in the winter preceding the growing season. In northern latitudes, warmer and drier growing seasons are expected to lead to higher fruit quality. The precise relation varies with the grape type, but this relation has been quantified in many viticultural areas.[19] Winter rainfall has also been shown to have a positive effect on fruit and wine quality, although this result has not been found for all the viticultural areas where it has been studied. Our primary interest is in the effect of temperature on vineyard profits, but to the extent that rainfall and temperatures are correlated, it is essential to control for these other aspects of the weather in the regressions.

The results in columns 1 and 2 of table 10 indicate a positive and statistically significant effect of growing season temperatures on profits, whereas the effect of both rainfall variables is negative. Both net (market) profits, that is, profits excluding subsidies, and gross profits (including subsidies), exhibit almost identical sensitivities with respect to all the weather variables. The estimates suggest that a temperature increase of 3°C results in profit increases of approximately 150%, which is larger than we found for the structural hedonic model of solar radiation. A more detailed discussion and comparison of the results may be found below.

The results in column 2 indicate that proportional profit changes are not affected by the various subsidies that vintners receive. However, this may be a result of the fact that support measures for German vintners are comparatively small, at least by European standards. Between 1995 and 2005, the Mosel test wineries received direct annual subsidies worth between 800 and 1,200 euros per hectare, which is between 10% and 23% of their respective profits. According to the Farm Accountancy Data Network of the European Union, direct payments for many southern European wineries, especially in Toscana, Umbria, and Midi-Pyrénées, regularly exceed 10,000 euros per hectare (European Commission, 2007).

As reported in column 3, there is no significant relationship between total per hectare cost and the weather variables for these German wineries. In results that are not reported in the table, we found that also to be true for overall costs, as well as for the component costs of personnel, material, depreciation, and other miscellaneous costs.

B. *Weather and Revenues Using Retail and Auction Prices*

In a second time-series analysis, we make use of retail and auction price data. Each data set has advantages and disadvantages. A disadvantage of the retail price data is that they refer to posted prices, which may not be transaction prices. An advantage of these data is that they cover a wide range of Mosel wine producers. The auction prices refer to actual transaction prices, but only a tiny fraction of the very finest Mosel wines are sold at auction. As a result, the auction prices may not be representative of the region more generally.

We confine our analysis to the Mosel Valley and its five viticultural districts (called Bereich): the Upper Mosel (from Luxemburg to the City of Trier), the Middle Mosel (from Trier to the village of Pünderich), the Lower Mosel (from Zell to the Rhine River), and the two Mosel tributaries, the Saar and the Ruwer Valley.

There is an added complexity in the study of the prices of German wines that results from the way the wines are labeled and marketed. German wines are classified (and labeled) according to the natural sugar content of the must (freshly pressed grapes) measured on the Oechsle scale.[20] In ascending order, the quality levels and Oechsle thresholds for Mosel wines are Quality Wine (no °Oe requirement), Kabinett (70°Oe), Spätlese (76°Oe), Auslese (83°Oe), Beerenauslese and Eiswein (110°Oe), and Trockenbeerenauslese (150°Oe). A primary quality distinction is that with the exception of Quality Wine, it is illegal to add sugar to the must. As a result, wine prices are distinguished by the vineyard where the grapes are grown and by the quality level.

Our retail price data come from the 1994–2006 issues of the Gault Millau Wine Guide for Germany (Diel & Payne, 1994–2006). The wine guide provides detailed information about the wines' characteristics such as age, geographical origin (vineyard and wine district), and quality classification, and the data permit us to calculate wine prices for each wine district and quality level accounting for other characteristics.

Our auction price data come from the period 1992–2006 from the wine associations VDP Grosser Ring and Bernkasteler Ring. These groups of wineries annually present and sell the latest vintage of their wines. The auctions focus on the upper end of the quality scale, and there are rarely any Kabinett quality wines sold. Less than 0.5% of all wine put up for auction is Quality Wine. This quality selection, and the fact that only 0.02% of all Mosel wines (0.08% of the corresponding values) are sold in auctions, implies that these data are not likely to be representative of the regional average response to our weather variables. As we shall see, the response of prices to the average temperature during the growing season is very sensitive to the particular type of wine quality being studied,

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[19] See, for example, Ashenfelter (2008), Haeger and Storchmann (2006), Jones and Storchmann (2001), and Ashenfelter and Byron (1995).

[20] Degrees Oechsle (°Oe) is used in Germany and Switzerland and denotes the specific weight of the must compared to the weight of water at a temperature of 20°C, while much of the English-speaking world uses a measure called brix. One liter of water weighs 1,000 g, which equals 0 degrees Oechsle. Accordingly, grape must with a mass of 1,084 grams per liter has 84°Oe. Since the mass difference between equivalent volumes of must and water is almost entirely due to the dissolved sugar in the must, degrees Oechsle measures the relative sweetness of the grape juice. Approximately, 1 brix is equal to 1 degree Oechsle divided by 4.35 (Peynaud, 1984).

TABLE 11.—WEATHER, WINE PRICES, AND REVENUE

	Dependent Variable		
	(1)	(2)	(3)
	ln (Retail Prices)^{d}	ln (Auction Prices)^{d}	Retail Price Revenue per Hectare^{d}
Constant	1.610***	−4.952***	
	(6.62)	(−10.55)	
Growing season temperature^{a}	−0.019	0.349***	0.354**
	(−0.85)	(3.86)	[2.37]
BA/TBA/Eiswein × growing season temperature^{a}	0.232***	0.217***	
	(36.32)	(5.11)	
Auslese × growing season temperature^{a}	0.108***	0.015	
	(39.43)	(0.37)	
Spätlese × growing season temperature^{a}	0.036***	−0.069***	
	(15.68)	(−1.68)	
Kabinett × growing season temperature^{a}	0.004	−0.112***	
	(1.82)	(−2.71)	
Middle Mosel × growing season temperature^{a}	0.017***	−0.002	
	(5.50)	(−0.05)	
Lower Mosel × growing season temperature^{a}	0.021***	0.034	
	(4.23)	(0.34)	
Saar × growing season temperature^{a}	0.030***	0.008*	
	(8.10)	(0.25)	
Ruwer × growing season temperature^{a}	0.023***	0.004*	
	(5.89)	(0.14)	
Rain winter^{b}	−0.000	−0.002***	−0.0003***
	(−1.89)	(−2.95)	[−3.42]
Rain growing season^{c}	0.000***	0.002***	0.0002
	(2.58)	(7.46)	[3.66]
ln (age)	0.219***	−0.303***	
	(3.39)	(−4.15)	
Trend			−0.028*
			[−2.29]
R^2	0.635	0.721	0.512
F statistic	761.02	517.38	10.09
n	5,263	2,413	50

[a] February to October.

[b] December to February.

[c] April to October.

[d] In real prices.

Significance level of 1% (***), 2% (**), 5% (*); Newey-West robust *t*-values in parentheses; *t*-values based on year clustered standard errors in brackets. Although not reported here, all equations include district-fixed effects.

making it likely that these data may suffer from selection bias. In particular, since the prices of the higher-quality wine types are much more responsive to temperature increases, the auction price data are likely to dramatically overstate the average effect of a temperature change on prices. Although we report the results using these data for completeness, we do not rely on them for our primary analysis.

Although revenue per hectare data are not readily available, they can be computed by multiplying crop yield data by the average prices for each district and each wine quality level. Let R_{idt}, P_{idt}, and Q_{idt} denote per hectare revenue, price, and quantity produced of wine quality level i in district d and at time t; then

$$R_{idt} = \sum_{i=1}^{7} \sum_{d=1}^{5} (P_{idt} \cdot Q_{idt}). \tag{9}$$

Total revenue in wine district d will be determined by prices and quantities produced in each quality category.

FIGURE 5.—WINE QUALITY AND PRICES (PRICE OF SPÄTLESE = 1)

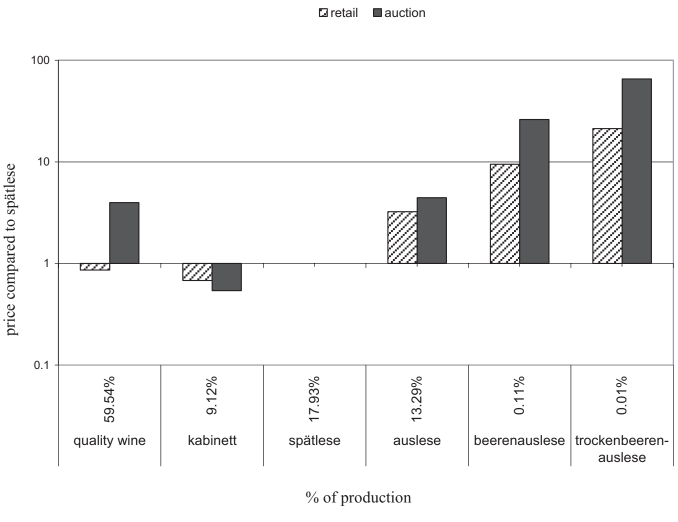

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FIGURE 6.—GROWING SEASON TEMPERATURES AND HIGH-END WINE PRODUCTION Percentage Production of Auslese+ Wines in Selected Mosel Districts

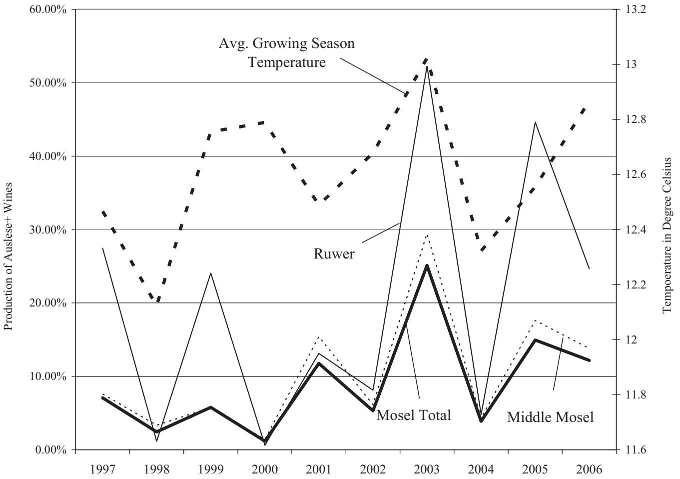
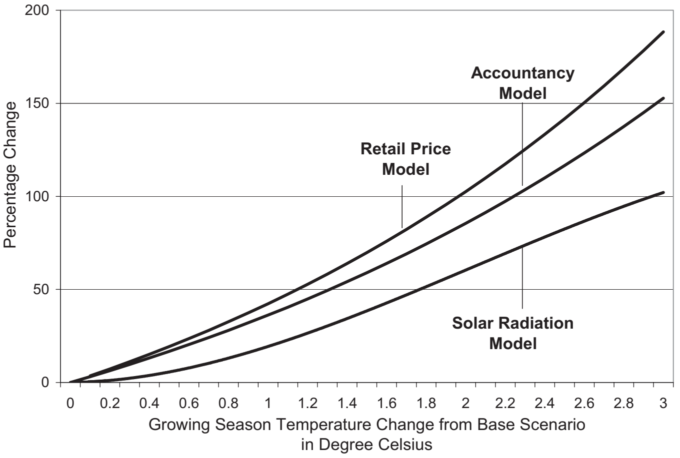


FIGURE 7.—TEMPERATURE CHANGES AND PERCENTAGE CHANGES IN LAND VALUES



Wine production data by district and quality category for the years 1997 to 2006 were prepared and provided by the Statistical Office of the State of Rheinland-Pfalz and its agricultural commission (Landwirtschaftskammer).[21] Detailed production data for the time period before 1997 are not available.

Column 1 of table 11 contains the results of the price equation drawing on retail prices. Since wines are labeled by their (a) quality level (TBA/BA/Eiswein—the highest quality group; and, in decreasing order of quality, Auslese, Spätlese, Kabinett, Quality Wine), and (b) their regions, we have interacted the temperature variable with each of these categories in order to produce quality- and region-specific temperature coefficient estimates. Quality Wine from the Upper Mosel serves as reference. It is apparent that warmer weather has a significantly positive effect on prices. Higher wine qualities, such as Beerenauslese, Trockenbeerenauslese, and Eiswein, benefit from a warmer growing season more than lower qualities do. In addition, the marginal effect of temperature increases is the highest in the districts of the Mosel tributaries Saar and Ruwer.

The results in column 2 indicate that auction prices are even more responsive to temperature changes than retail prices, as we expected.

To obtain an overall estimate of temperatures on gross revenue per hectare, we must combine the information on crop yields by region and quality level with the average prices by region and quality level. Figure 5 shows the relative prices of wines in the various categories. The price differences are enormous, with wines in the highest-quality category, Trockenbeerenauslese, being priced 20 times higher than in the Spätlese category. (At auctions, this ratio is higher, sometimes exceeding 60.) At the same time, the production of high-quality wines is very small.

Figure 6 shows the fraction of wines of Auslese and higher qualities as part of the entire production in selected districts and the Mosel region as a whole over the period 1997–2006. The Ruwer region exhibits the highest variance, with a range from 1% in 1998 to 52% in 2003. Figure 6 also shows the average growing season temperature over the same period, and it is apparent that more high-quality wines are produced in warmer years. The result is that increases in temperatures result in increases in wine prices within each quality segment and that increases in temperatures also shift the quality structure of wines produced upward.

Another interesting feature of figure 6 is the apparent upward trend in temperatures.[22] At the same time, there is also an apparent upward trend in the amount of higher-quality wine being produced. This has led many observers to remark on the increased prosperity of the Mosel wine region in recent years. It is unclear, of course, whether this is a result of permanent climate change or something more transitory.

Column 3 of table 11 indicates that revenue (based on retail prices) and using equation (9) significantly increase with warmer weather, as expected. The rainfall variables are either insignificant or have unexpected signs. Assuming that cost and temperature changes are not correlated (as the accounting data indicated above), these revenue changes will translate directly into changes in profits and land values.

B. *Comparison of the Effects of Climate Change on Land Values*

Figure 7 summarizes the findings of the two different times series analyses and contrasts them with the hedonic cross-sectional model of solar radiation. Since we compute

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[21] These data are available, by request, from the authors.

[22] Using data over the longer period from 1960 to 2006, a regression of average temperature on a trend variable (and a constant term) yields a coefficient of 0.034 at the 0.01% significance level. Thus, since 1960, average growing season temperatures in the Mosel valley have increased by 1.6°C.

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percentage changes in revenue or profits, respectively, the figures translate directly into comparisons of percentage changes in land values.

All three models show a positive relationship between growing season temperatures and profits or land values. They also show that in the range of data we study, prices increase more than proportionately with temperatures. Given the entirely different nature of the models, the results are remarkably consistent. The models predict that a 3°C annual temperature increase will lead to an increase in vineyard values by 102% (solar radiation model), 152% (accounting profits model), or 188% (revenue model). It is apparent that the more structural cross-section model indicates a smaller sensitivity of land prices to temperature changes than the time-series model. It is unclear precisely why this occurs, but the cross-section analysis may be providing estimates that are more appropriate for the analysis of long-term equilibria, while the time-series estimates may be more appropriate for the analysis of short-term effects.

VII. Conclusion

The basic results in this paper show how the link between temperature and solar radiation can be used to construct a structural model to predict changes in agricultural land prices and crop values associated with climate change. The key to building this relationship is to establish the hedonic relation between the determinants of solar radiation received by an area and land values. For vineyard areas, many of the key hedonic characteristics of the vineyard are related to energy absorption, which leads to an important effect of climate change on crop quality. Grapevines have very low radiation use efficiency (RUE), and no doubt the hedonic relationship we estimate is related to this fact. It seems that further research might be usefully guided by measuring the hedonic relationship of solar energy received for crops with different RUEs.

Although our purpose here has been to use this hedonic relationship to evaluate the effect of climate change on land values, it should be clear that to the extent other undeveloped vineyard areas may exist in the world, this relationship could be used to evaluate the economic viability of new plantings. In short, this hedonic relationship could be used for determining vineyard site selection in undeveloped areas.

We have also computed estimates of the effect of annual time-series weather changes on vineyard profitability and wine prices. This provides a check on both methods of analysis. It appears that although the results are far from identical, they do provide estimates of roughly the same orders of magnitude. This suggests that the direct measurement of changes in the weather from year to year may be a useful shorthand method for calculating the order of magnitude of longer-term effects.

As is well known, there are likely to be winners and losers from any potential climate change. Our empirical results indicate that climate change may result in considerable increases in the value of the Mosel vineyard region because of increasing wine quality. A moderate 1°C temperature increase would lead to an aggregate increase in land value of 20% or more, while an increase of 3°C would more than double the land value.

These results have several limitations. First, our empirical analysis does not take account of general equilibrium effects that might result in a restructuring of land prices. The Mosel Valley is suited primarily for grape growing only, so a change in the relative price of vineyards of different quality induced by climate change could have a dramatic effect on our calculations. Second, our results provide only a small part of an overall appraisal of the role of climate change on agricultural values. There are no doubt places where increased temperatures will decrease the quality of wine grapes because of excessive heat. Only additional research will provide the evidence to evaluate these issues more completely.

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APPENDIX

According to Duffie and Beckman (1991) and Iqbal (1983), we calculate the daily extraterrestrial solar radiation $H_{O\beta\gamma}$ as

$$\begin{aligned} H_{O\beta\gamma} = (12/\pi) I_{SC} E_O (&\cos\beta \sin\delta \sin\phi |\omega_{ss} \\ &- \omega_{sr}| \pi/180 - \sin\delta \cos\phi \sin\beta \cos\gamma |\omega_{ss} \\ &- \omega_{sr}| + \cos\phi \cos\delta \cos\beta |\sin\omega_{ss} - \sin\omega_{sr}| \\ &+ \cos\delta \cos\gamma \sin\phi \sin\beta |\sin\omega_{ss} - \omega_{sr}| \\ &+ \cos\delta \sin\beta \sin\gamma |\cos\omega_{ss} - \cos\omega_{sr}|) \end{aligned}$$

with

$$\omega_{sr} = \min\left[w_s, \cos^{-1}\left(\frac{-xy - \sqrt{x^2 - y^2 + 1}}{x^2 + 1}\right)\right]$$

$$\omega_{ss} = -\min\left[w_s, \cos^{-1}\left(\frac{-xy + \sqrt{x^2 - y^2 + 1}}{x^2 + 1}\right)\right]$$

for $\gamma > 0$ (the surface is oriented toward the east) and

$$\omega_{sr} = \min\left[w_s, \cos^{-1}\left(\frac{-xy + \sqrt{x^2 - y^2 + 1}}{x^2 + 1}\right)\right]$$

$$\omega_{ss} = -\min\left[w_s, \cos^{-1}\left(\frac{-xy - \sqrt{x^2 - y^2 + 1}}{x^2 + 1}\right)\right]$$

for $\gamma < 0$ (the surface is oriented toward the west), where

TABLE A1.—CHARACTERISTIC ECCENTRICITY CORRECTION FACTOR AND DECLINATION

Month	Day of the Month	Day of the Year	E_O	δ
January	17	17	1.0340	−20.88
February	16	47	1.0251	−12.53
March	16	75	1.0108	−1.93
April	15	105	0.9932	9.60
May	15	135	0.9780	18.77
June	11	162	0.9692	23.09
July	17	198	0.9673	21.34
August	16	228	0.9746	13.94
September	15	258	0.9885	3.27
October	15	288	1.0058	−8.30
November	14	318	1.0222	−18.11
December	10	344	1.0319	−22.28

Source: According to Klein (1977) and Duffie and Beckman (1991).

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$$x = \frac{\cos\phi}{\sin\gamma\tan\beta} + \frac{\sin\phi}{\tan\gamma}$$

$$y = \tan\delta\left(\frac{\sin\phi}{\sin\gamma\tan\beta} - \frac{\cos\phi}{\tan\gamma}\right)$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta).$$

with

I_{SC} solar constant (4.921 MJ/m^2 hr)
E_O eccentricity correction factor (tables for each day of the year)
β slope, the angle between the plane of the surface and the horizontal, $0° \leq \beta \leq 180°$, ($\beta > 90°$ implies that the surface is downward facing).
δ declination, the angular position of the sun at solar noon (when the sun is on the local meridian) with respect to the plane of the equator, north positive, $-23.34° \leq \delta \leq 23.45°$ (tables for each day of the year)
ϕ latitude, the angular location north or south of the equator, north positive $-90° \leq \phi \leq 90°$
γ surface azimuth angle, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east positive, and west negative; $-180° \leq \gamma \leq 180°$
ω_{ss} sunset hour angle for a tilted surface
ω_{sr} sunrise hour angle for a tilted surface
ω_s sunrise hour angle for a horizontal surface.

The daily extraterrestrial solar radiation was multiplied by the number of days of the respective month in order to obtain the monthly value. Data for the characteristic average day for each month are provided by Klein (1977), and values for the eccentricity correction factor, E_O, and the declination, δ, respectively, are given in table A1.

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