

INVITED REVIEW PAPER

Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects

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Abstract

Predicted changes in the climate of European viticultural regions over coming decades may alter significantly both the spectrum and the distribution of grape varieties currently used. Changes observed over recent years confirm those predictions. In particular, shifts in precipitation patterns will affect most European regions, with increased risk of drought, and given this scenario, the consequences would be most dramatic for the Iberian peninsula. Soil practices may have to be adapted to account for changes in soil moisture and decay rates of organic matter. Rising CO₂ concentration alone may increase grape production and water use efficiency, but more comprehensive studies predict decreases in yield when increasing temperature and changes in solar radiation are considered simultaneously. As part of those changes in solar radiation, levels of UV-B radiation will probably continue to rise, and will have a direct impact on grape composition and thus flavour development via alteration of secondary metabolites such as flavonoids, amino acids and carotenoids.

Abbreviations and definitions

UV-B radiation solar radiation in the wavelength range 280–320 nm; **ppm** parts per million by volume; **GCM** global circulation model; **TOMS** total ozone mapping spectrometer

Keywords: grapevines, European viticulture, climate change, UV-B radiation, flavour development, CO₂ effects, temperature, rainfall

Introduction

Global climate change has been a public discussion topic for several years. It is difficult to predict changes in climate and sea level due to the enhancement of the so-called greenhouse effect (including temperature rise, CO₂ increase, and nitrogen deposition) but atmospheric CO₂ concentration is measurably increasing and is expected to be double current levels during the next century, with marked effects on current agroclimatic conditions. Post-industrial mankind has effectively accelerated global respiration by a factor of about 10 million times via combustion of several billion years worth of accumulated photosynthate and other organic carbon.

Global warming aside, shifts in amount, seasonality and distribution of precipitation will occur, together with increases in surface level ultraviolet UV-B radiation due to a depletion of stratospheric ozone. Actions and interactions of climatic factors and mankind-induced changes in vegetation structure are very complex. Moreover, oceans can act as large buffers on more radical short-term (years) changes. Consequently, there is great uncertainty about what to expect over the next century. In contrast to research on natural terrestrial ecosystems and

some agricultural crops, possible effects of a change in climate on grapevines have largely been ignored. This paper addresses certain key issues.

Increased temperature and altered precipitation patterns

Drawing upon output from several simulation models, global mean surface temperature will probably rise between 1°C and 4.5°C, depending on future industrial emissions. Our best estimate points to a 1.8–2.5°C warming by the middle of the next century (Carter et al. 1991; Intergovernmental panels on climate change (IPCC) 1992, 1994, 1998). Within a European context, an increase in temperature of this magnitude would have profound implications for viticulture. Indeed, current temperature development in the northern hemisphere clearly shows a gradual warming trend in all seasons (Figure 1), and especially over the last twenty years (Jones et al. 1999).

This warming has been less pronounced than that in the southern hemisphere over the same time period. However, global circulation models (GCM) currently predict a more rapid warming in the northern hemisphere

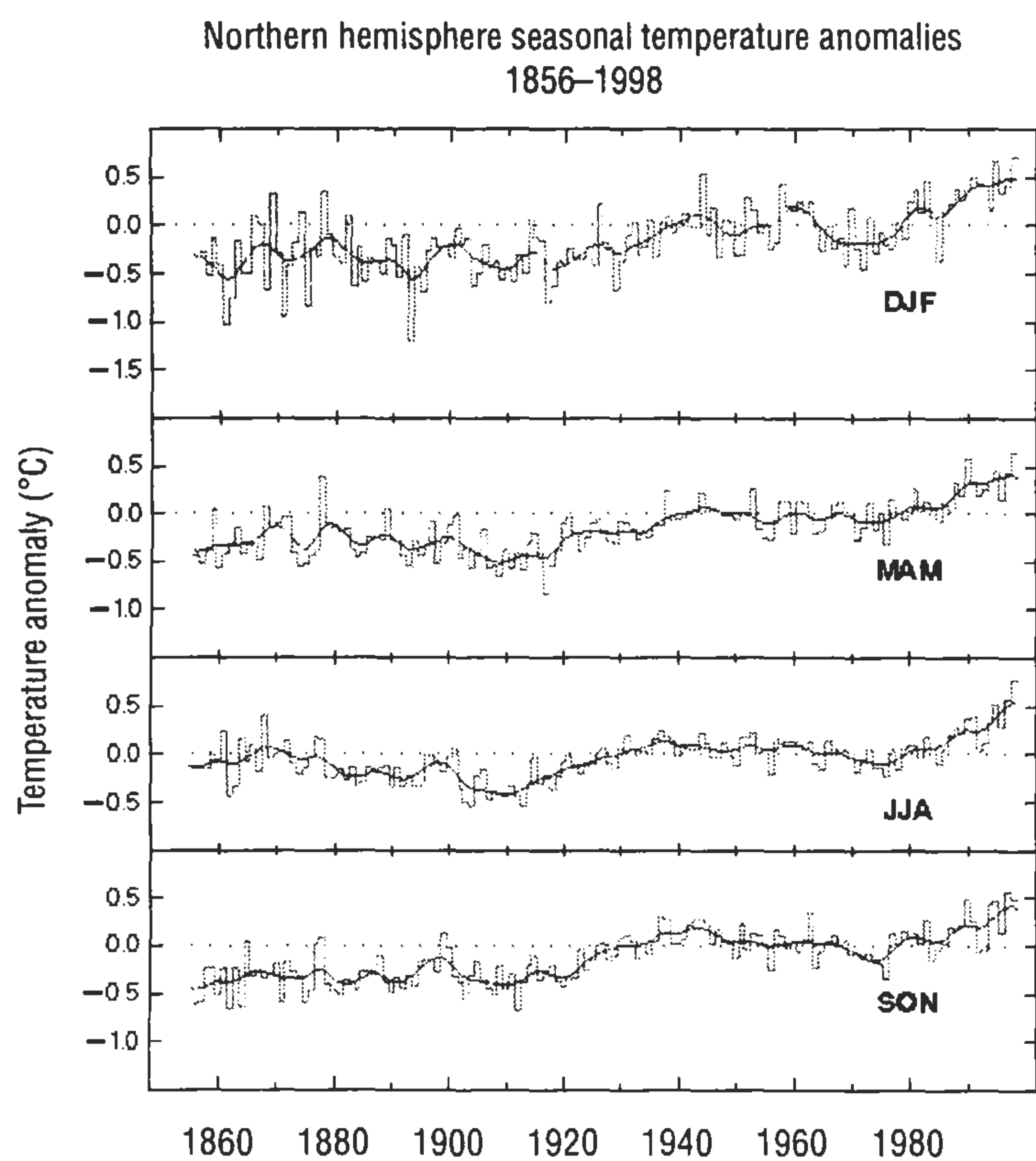


Figure 1. Temperature development compared to the long term mean in different seasons in the northern hemisphere since 1856. Letters are abbreviations for months (DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November) (Jones et al. 1999).

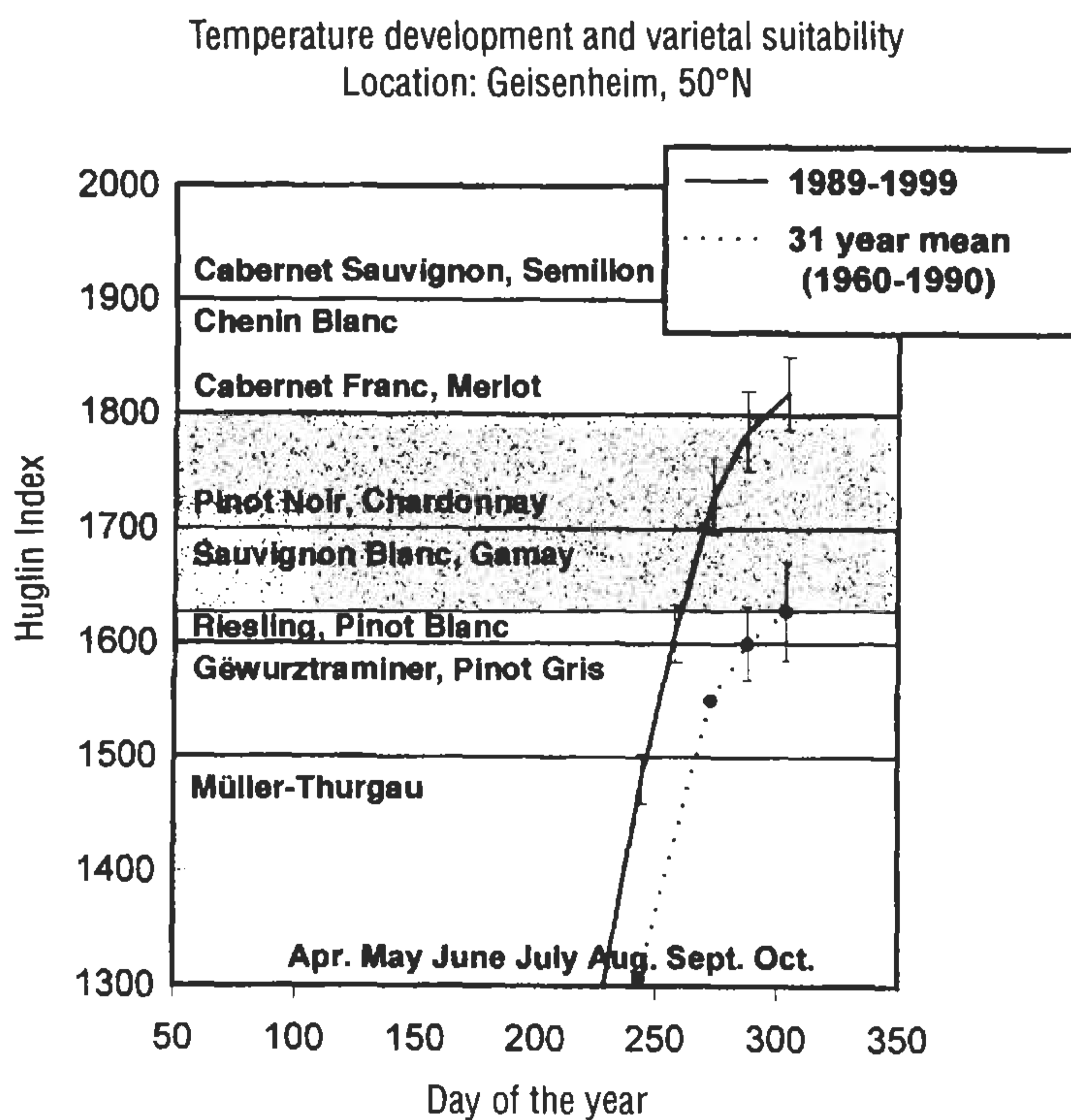


Figure 2. Varietal suitability calculated based on the Huglin Index for Geisenheim, Germany. The continuous line is an average over the past 11 years. The dashed line shows average values for 1960–1990. Based on temperature data from Deutscher Wetterdienst, Geschäftsstelle Geisenheim.

over the next 50 years (Evans 1996). This would considerably change the margins of suitability for grapegrowing, shifting the northern boundary for viticulture under this scenario on the order of 10–30 km per decade up to 2020 with a predicted doubling of this rate between 2020 and 2050 (Kenny and Harrison 1993). This would also pro-

foundly change the distribution of suitable varieties within Europe. Calculations using the Huglin (1986) climate index classification for varietal suitability in Geisenheim shows that Riesling, Pinot Gris and Pinot Noir are suitable cultivars for this location (Germany, latitude 50° N; and based on the average temperature distribution over 30 years (1960–1989) Figure 2). If instead, estimates of suitability are based on the average temperature development during the last 11 years (1989–1999), cultivars such as Merlot or Cabernet Franc become possible choices (Figure 2).

This warming trend can also be demonstrated via a large decrease in the frequency of autumn (October) frost events over the past 100 years (Hoppmann and Hüster 1988). Similarly, a modelling analysis on the probability of spring frost damage to tree species in Northern Europe diagnosed a reduction in risk under climatic warming (Kramer 1994). Indirect estimates of the growth of terrestrial vegetation by use of satellite data from measurements of the normalised difference vegetation index (NDVI) have recently confirmed that plant growth and growing season length is significantly increasing, especially in the northern high latitudes (> 45°N) (Myneni et al. 1997).

Concurrent with global warming are predictions of altered precipitation patterns (both annual total and seasonality). For central Europe, these include a higher incidence of strong precipitation events in winter, higher frequency of extreme temperatures and less precipitation in summer. Hulme et al. (1992) have analysed annual and seasonal changes in the distribution of precipitation on a global scale for the periods 1931–1960 and 1960 to 1990. The two most prominent features are (i) Northern Russia, with increased precipitation of up to 20% and (ii) the African Sahel, between latitudes 10°N and 30°N, where precipitation will decrease by between 20 and 50%. Significant changes have already occurred over all continents and are predicted to continue based on GCMs following a doubling in atmospheric CO₂ concentration (Hulme et al. 1992).

Even if annual total precipitation and/or seasonality plus regional distribution are unaffected, water evaporation rates will still increase due to higher surface temperatures of oceans and land masses. The evaporation rate from the sea surface is about 44000 km³/year. If the present average sea temperature of roughly 11.5 °C increases by 1°C, evaporation will increase by 20% leading to higher humidity and probably more precipitation in a more uneven spatial and temporal distribution (Varallyay 1994). For land masses, changes in evaporation rates may reduce soil moisture over the long term. Some predictions estimate that temperature changes induced by a doubling in CO₂ concentration would cause a 20 to 30% reduction in soil moisture in northern Europe, 30 to 50% in western Europe, 20 to 40% in central Europe, 20 to 30% for most of the Mediterranean region, and as much as 70% for the Iberian peninsula (Stigliani and Salomons 1992) (Figure 3). Implications for viticulture, and resulting socio-economic consequences are dramatic, and especially in southern Europe where

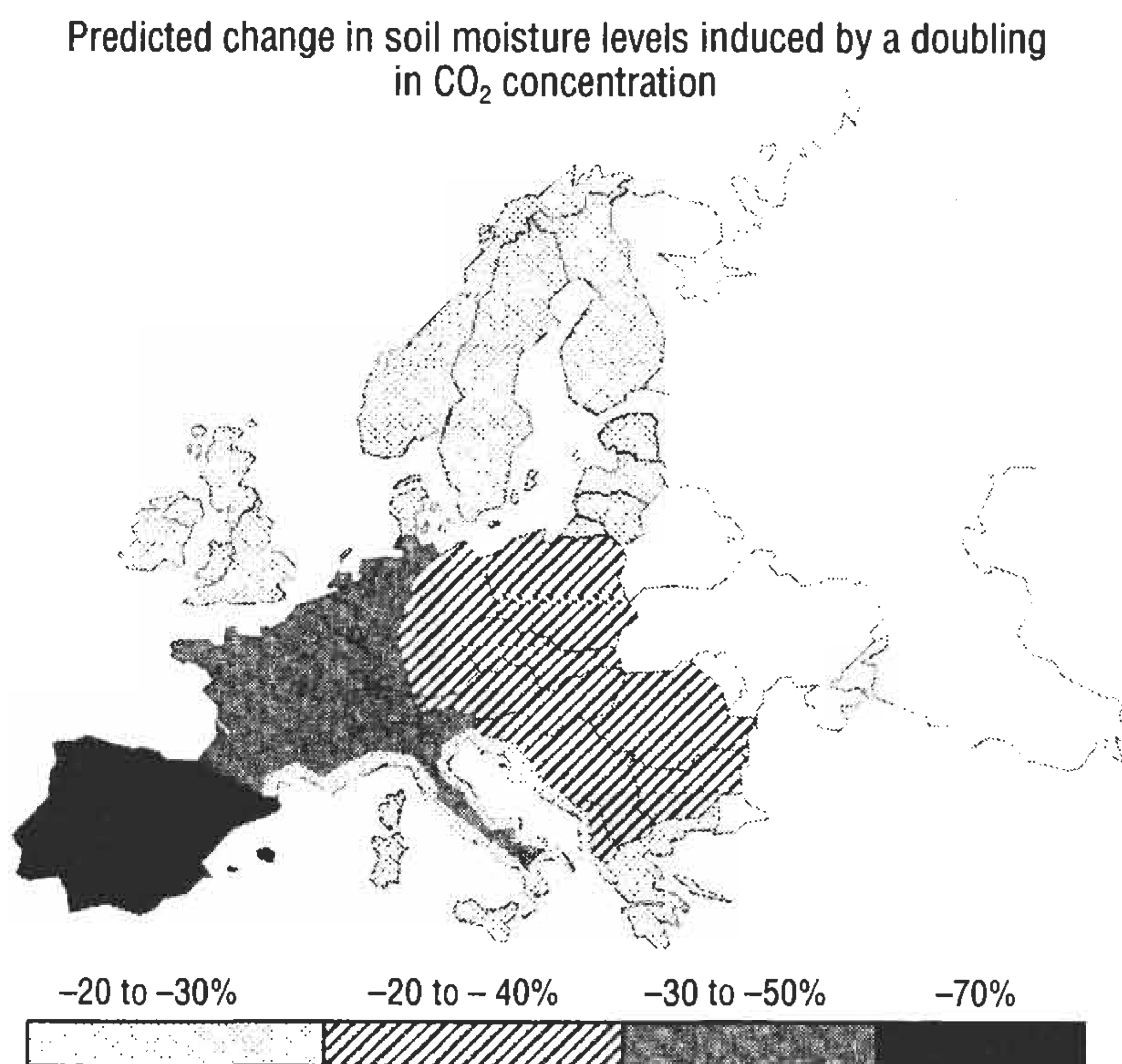


Figure 3. Predicted distribution of soil moisture content across Europe induced by a doubling in ambient CO₂ concentration. Based on data from Stigliani and Salomons (1992).

water is a scarce resource and irrigation is often not possible.

Shifts in precipitation patterns may necessitate introduction of cover crops over winter in order to minimise soil erosion and to maximise water and nutrient storage. Favis-Mortlock (1994) has shown that an increase of 8 to 15% rainfall in winter will increase erosion by 27 to 35%. On the other hand, higher frequency of extreme temperatures in summer will automatically lead to increased evapo-transpiration. That increase, coupled with reduced precipitation in summer rainfall areas, may render full or partial use of cover crops impossible in countries where this is currently common practice (viz. Germany, Switzerland and northern Italy).

In recent years, off-flavour problems in white wine have been linked to competition problems for water and nitrogen between cover crop and grapevines in dry years (Rapp et al. 1993). However, soil erosion and nitrogen leaching coupled to reduced water quality for human consumption may preclude going back to clean cultivation. In other viticultural areas with no summer rain, like the 'La Mancha' area south of Madrid in Spain, soil tillage systems also may have to be changed completely. Common practice in these and other comparable regions in Europe is to impose very frequent shallow tillage to avoid capillary rise of water from deeper soil layers with subsequent unproductive evaporation. Contrary to intuition, at low soil water content a no-tillage system may actually conserve much more water.

Soil water is not the only edaphic factor affected through changes in temperature and precipitation. Soil respiration is positively correlated with an increase in these same variables. As a consequence of faster respiration, soil organic matter content will be reduced in the long term and may require different ways of soil management practices. Using models for different terrestrial

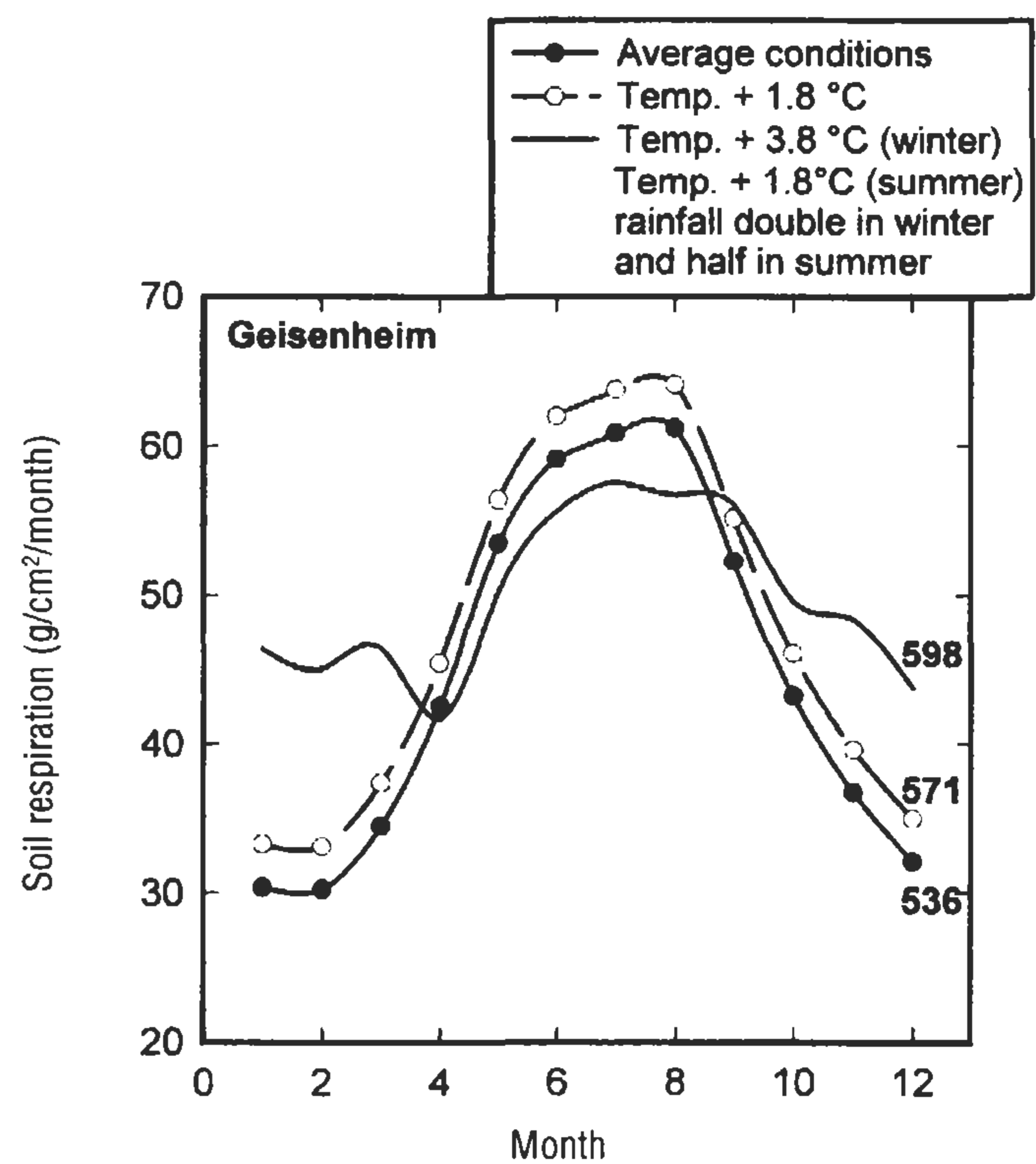


Figure 4. Simulation of soil respiration under various climate scenarios for Geisenheim, Germany. Numbers next to the curves give cumulative annual rates of soil respiration.

ecosystems, Robinet (1994) estimated a global increase in soil carbon loss of around 20% with a tendency for stronger responses at high latitudes. Applying one of the proposed models to a viticultural situation, soil respiration rates were estimated for Geisenheim under various scenarios of changes in temperature and rainfall distribution (Schultz 1996). Higher winter temperatures coupled with higher relative precipitation in winter as compared to summer yielded large increases in organic matter decay rates (Figure 4).

Accompanying these anticipated increases in ambient temperature and atmospheric CO₂, a large additional deposition of nitrogen is expected, and especially in the northern hemisphere (Holland et al. 1997). This nitrogen comes from two sources (i) from vehicles and other machines that use fossil fuel and (ii) from fertilizer application in agriculture. Total nitrogen deposition from these combined sources could be as high as 150 kg per ha per year in Central Europe, down to small quantities of 10 to 15 kg/ha/year in parts of the eastern United States (Holland et al. 1997). Given the relatively small requirement of nitrogen for growth and production of grapevines, excess nitrogen may cause changes in soil microbial activity and lead to nitrate leaching into ground water. Soil management systems must be developed to forestall such adverse environmental outcomes.

Elevated atmospheric carbon dioxide

Plants transform inorganic atmospheric carbon (CO₂) into chemically reduced forms of terrestrial carbon (carbohydrates) via photosynthesis. As the primary biological process within the global carbon cycle, photosynthesis also directly links changes in the earth's atmosphere caused by humans to the biological functioning of both natural and agricultural ecosystems (Griffin and Seemann

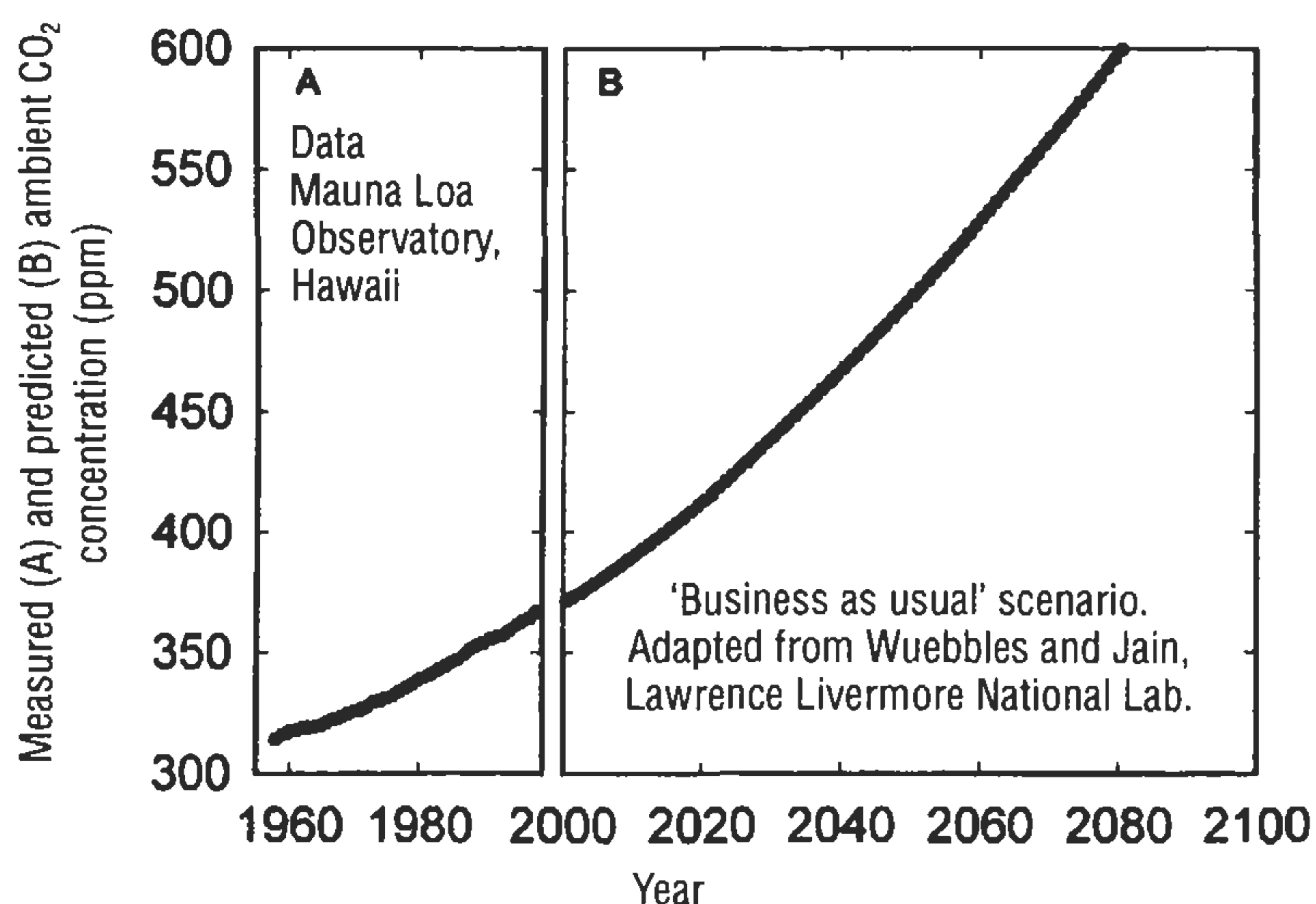


Figure 5. Box A = Ambient CO₂ concentration since 1958 at the Mauna Loa Observatory, Hawaii, Box B = predicted development of CO₂ concentration until the end of this century according to assumptions made for a 'business as usual scenario' by the 1992 Intergovernmental Panel on Climate Change (IPCC). Data for A are from Keeling and Whorf (1999), Scripps Institution of Oceanography, University of California, La Jolla, CA 92093-0244. Data for B are from Wuebbles and Jain (1999) and assume: (1) world population of 11.3 billion by 2100; (2) economic growth at 2.9% for 1990-2025, 2.3% for 1990-2100; (3) energy supplies of 12.000 EJ conventional oil, 13.000 EJ natural gas, solar costs decreasing to \$0.075/kWh, 191 EJ biofuels available at \$70/barrel; (4) internationally agreed controls on SO_x, NO_x, (sulfur and nitrogen oxides) and non-CH₄ (methane) volatile organic compound emissions; (5) partial compliance with Montreal Protocol, with gradual phase out of CFCs (chlorofluorocarbons) in non-signatory countries by 2075.

1996). Over geological time, mineral weathering has driven changes in atmospheric CO₂. By contrast, ocean-atmosphere exchange is an important component of the global carbon cycle over much shorter periods of time (centuries). Compared to rocks, this ocean-atmosphere system has a fast response time to changes in CO₂ partial pressure, but a very low carbon storage capacity.

Atmospheric CO₂ concentration may have been up to 20 times present levels of around 370 ppm at certain times in earth's history, but has remained relatively stable at around 270 ppm over the last 5 centuries (Ehleringer and Cerling 1995). Levels began to rise with industrialisation and related combustion of fossil fuels. The oldest continuous record of direct measurements of CO₂ comes from the top of Mauna Loa, Hawaii, which started in 1957 (Figure 5A). The current level of near 370 ppm is more than 30% higher since the industrial revolution 200 years ago and nearly 20% higher since direct measurements began (Figure 5A).

Fossil fuel consumption will further increase with increase in world population, land clearing, and a higher per capita consumption of energy derived from combustion of fossil fuels. Currently, a person in the United States of America, on average, uses 22 tonnes of carbon per year, whereas a person in India, for example, uses only 0.7 tonnes of carbon per year (Bazzaz 1998). Nevertheless, those same developing nations will contribute dramatically to future CO₂ emissions due to their own industrialisation (for a complete list see the internet

data bank of the Carbon Dioxide Information Analysis Centre at Oak Ridge National Laboratory, Tennessee, USA (<http://cdiac.esd.ornl.gov>)).

On present evidence, this global increase in CO₂ is occurring much faster than the rate at which plants can adapt via changes in photosynthetic attributes. Predictions of how much atmospheric CO₂ concentration will rise during the next century differ between different model analyses but most agree on an approximate doubling by the end of this century (Figure 5B), with some scientists speculating that atmospheric CO₂ concentration could actually exceed 1000 ppm (Bazzaz 1998). The direct response of grapevines to a rise in CO₂ concentration seems to be similar to the results obtained in most of the studies conducted on annual and perennial plants, where an increase in net photosynthesis, biomass, crop yield, light-, nutrient- and water-use efficiency is found (Griffin and Seemann 1996, Bindi et al. 1996a). In the short term, photosynthesis is stimulated by increased CO₂. Results from a field experiment conducted with Riesling in a varietal collection in Montpellier, France, show that instantaneous photosynthetic rate increased by about 35% as a response to a near doubling in CO₂ concentration, whereas transpiration rates remained similar irrespective of temperature (Figure 6). Thus, stomatal conductance was down-regulated with respect to photosynthesis and caused an increase in water-use efficiency (ratio of photosynthesis to transpiration) as has been observed with many other plants (Mott 1990, Griffin and Seemann 1996). Grapes grown in arid regions may therefore be expected to benefit from increased CO₂ and may be able to at least partly overcome some of the adverse conditions created by increases in likelihood and severity of drought events.

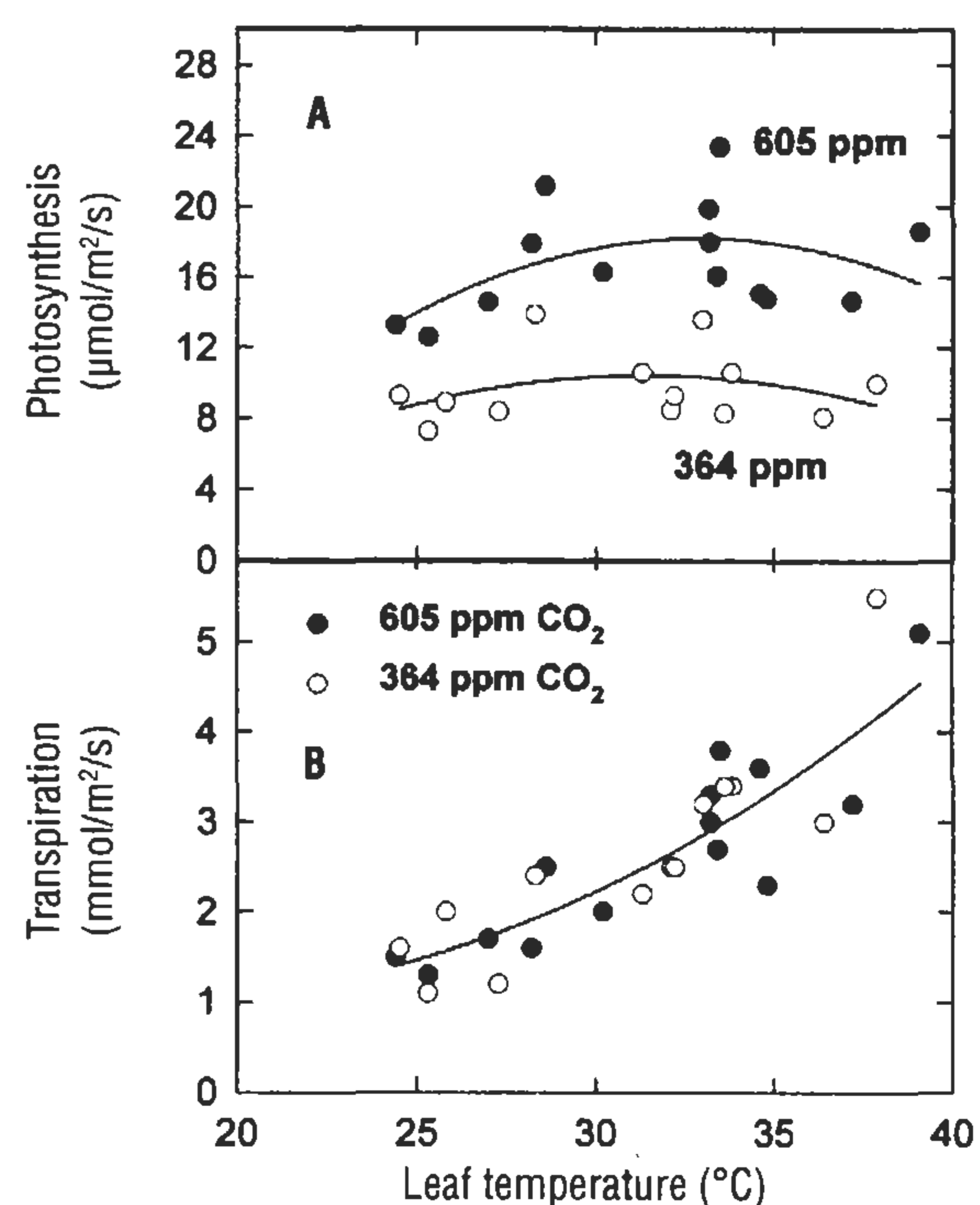


Figure 6. Photosynthesis (A) and transpiration rate (B) by *Vitis vinifera* (L.) variety Riesling as a function of leaf temperature at two levels of ambient CO₂ concentration. The experiment was conducted on Riesling vines in 1995 in an experimental vineyard of the ENSA/INRA Montpellier. Gas-exchange was determined with a modified ADC LCA-3 system between 10am and 3pm in July.

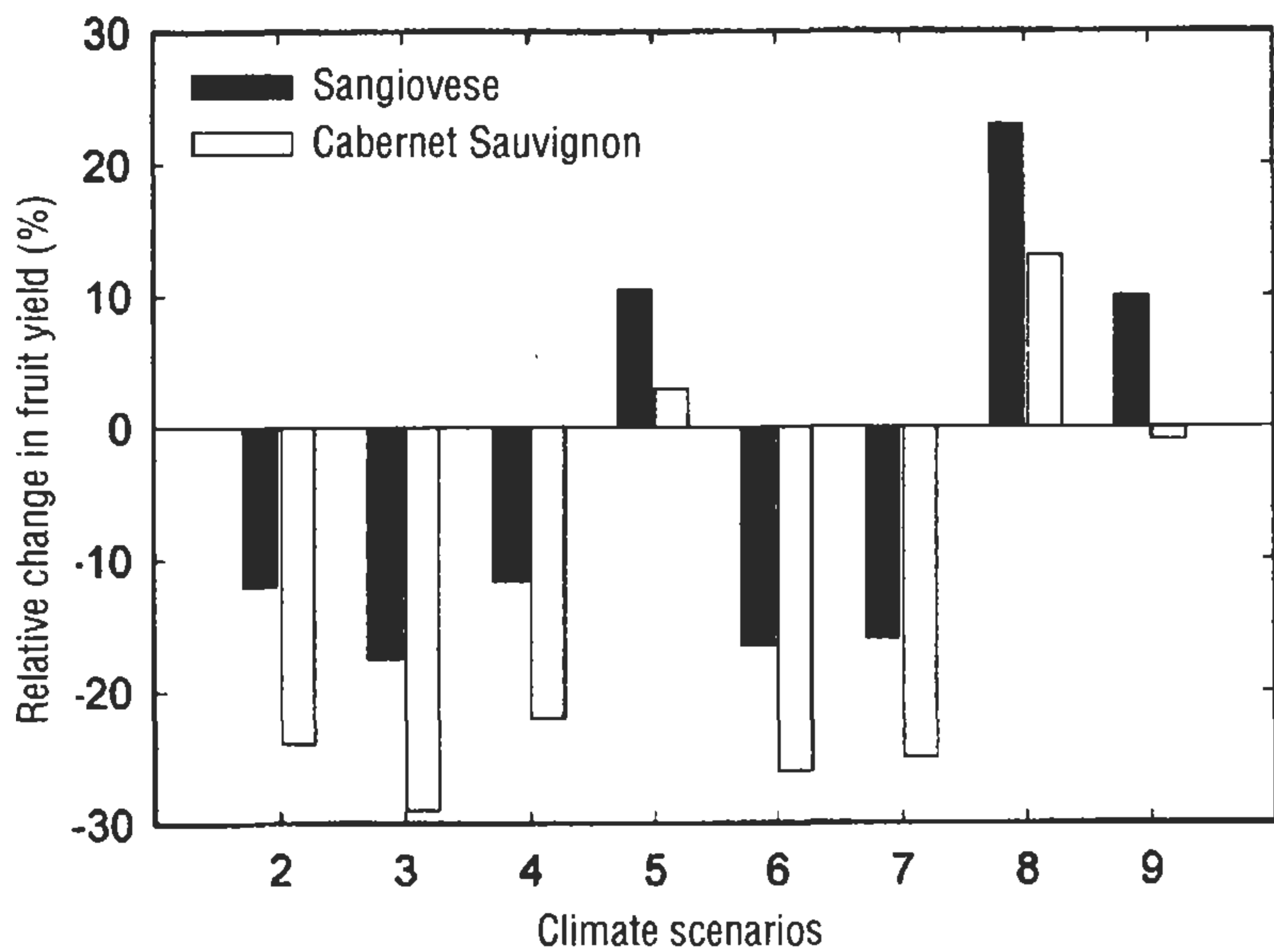


Figure 7. Predicted relative change in fruit yield of varieties Sangiovese and Cabernet Sauvignon under several climatic scenarios based on a model of grape growth and biomass accumulation (based on Bindi et al. 1996b).

Long term exposure to elevated CO_2 may have very different effects at a whole vine or vineyard level. An initial increase in photosynthesis as reported above, may be partly or completely down-regulated if sinks for the manufactured photosynthate are not sufficient. Over a period of days, weeks or months of growth in elevated CO_2 , an acclimation response may be substantial enough for photosynthetic rates of plants grown and measured in elevated CO_2 to match those grown at current ambient concentrations (Bazzaz 1998). Plant respiration and carbon allocation may be altered but this needs to be examined for each species, probably for each variety, separately (Samarakoon and Gifford 1995).

Photosynthetic activity is regulated at a biochemical, physiological and molecular level, and judging from the large differences in vegetative and reproductive development between grape cultivars (Champagnol 1984), it is likely that sink size and activity will largely affect the responses of different varieties to elevated CO_2 . Bindi et al. (1996a) in a study using a FACE-system (free air carbon dioxide enrichment in the field) with the variety Sangiovese over several months, found a stronger increase in leaf area (+35%) and vegetative dry weight (+49%), than in reproductive dry weight (+21%) when CO_2 concentration was increased to 700 ppm. The increase in vegetative dry matter was confirmed when simultaneous changes in temperature and solar radiation were additionally considered in running several climate change scenarios and GCMs, but yield response was negative in most cases and more so for Cabernet Sauvignon than for Sangiovese (Bindi et al. 1996b) (Figure 7). Faster development of larger leaf areas may in turn have important consequences for water consumption and canopy management, which just points to the difficulty in predicting the combined action of several changing environmental factors.

Partial stomatal closure is likely to occur in a high CO_2 world. Indirectly, this can lead to increased leaf temperatures as a result of reduced cooling. Increased leaf tem-

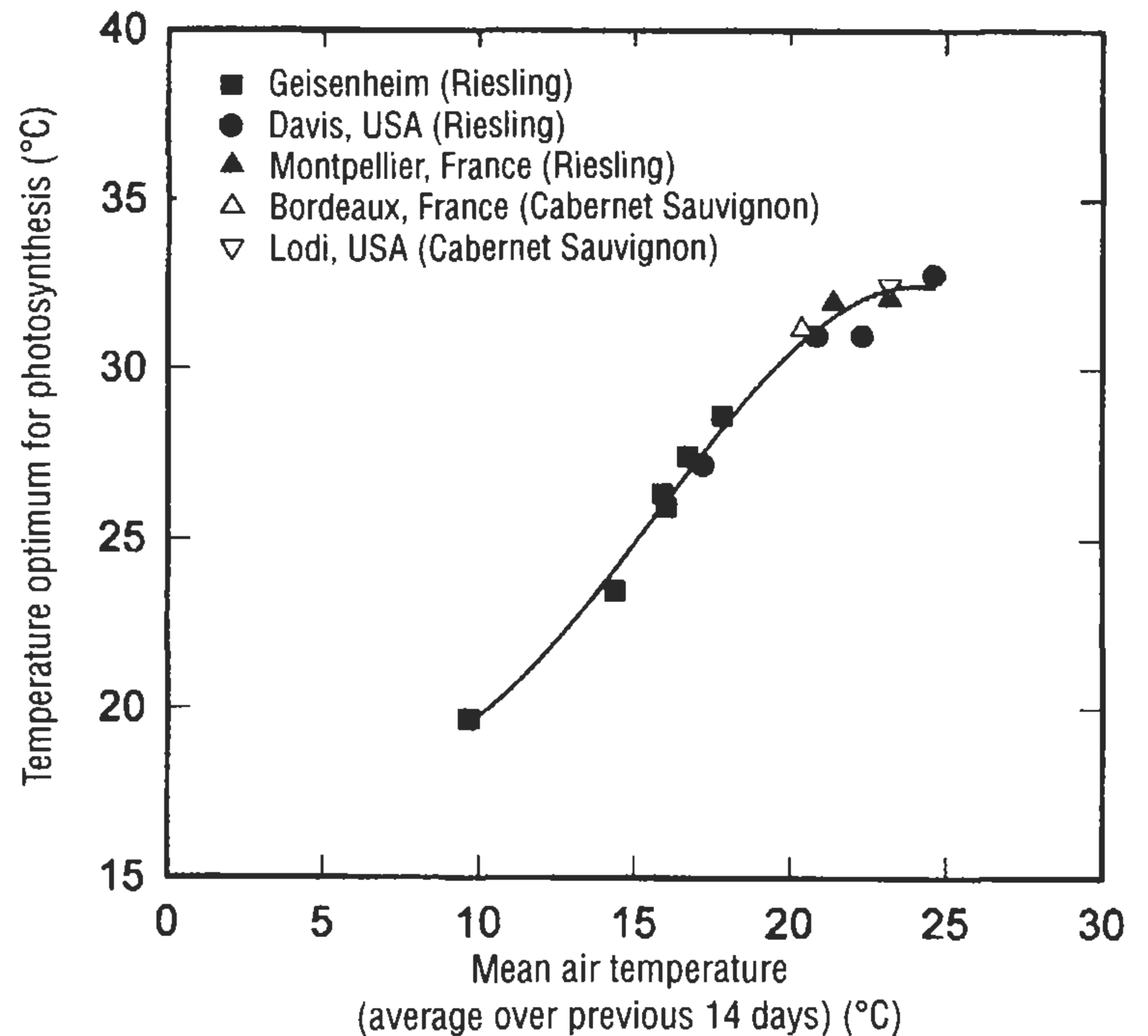


Figure 8. Changes in the temperature optimum of photosynthesis as a function of mean air temperature over the previous 14 days. Measurements were conducted on Riesling in 3 locations, Geisenheim (Germany), Davis (USA), and Montpellier (France), and on Cabernet Sauvignon in 2 locations, Bordeaux (France), and Lodi (USA) in different years and different times of the season. Data from Geisenheim span the period of May to October 1988; data from Davis are for May, June, August and September 1991, data from Lodi are for September 1992, data from Bordeaux are for July 1993, data from Montpellier are for July and August 1994. Measurements were conducted on several days at different temperatures, saturating light, high relative humidity and non-limiting water status. Data were then pooled and the optimum temperature for photosynthesis calculated with a model (Schultz 1993). Gas-exchange systems used were ADC LCA-2 (data USA), ADC LCA-3 (data France) and a Walz $\text{CO}_2/\text{H}_2\text{O}$ Porometer (data Germany).

peratures can in turn alter the relative affinity of the primary enzyme of photosynthesis, ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco), for CO_2 and O_2 . Temperature can also alter the availability of the competing substrates, since the solubilities of CO_2 and O_2 are differentially affected by temperature. Yet photosynthesis (and respiration) can adapt to temperature. This acclimation may occur within a few days, or sometimes hours. It may involve: changes in enzyme activities (Berry and Björkman 1980); interchange between isoenzymes with the same action but different temperature optima; and by chemical and structural alterations in biomembranes, such as fatty acid composition (Berry and Downton 1982).

Acclimation to increasing temperature in grapevines is an adaptive feature that is large but not unlimited, judging from the continuous shift to higher optimum leaf temperatures for photosynthesis up to about 33°C with increasing ambient temperature (Figure 8). Data shown in Figure 8 were measured at different times (and thus external temperatures) during the season within a given climate, and within different climatic regions. Despite the flexibility of the photosynthetic system, average daily air temperatures of $23\text{--}25^\circ\text{C}$ seem to represent the upper limit of adaptation. Above this threshold, leaf temperatures during the course of a day will be increasingly

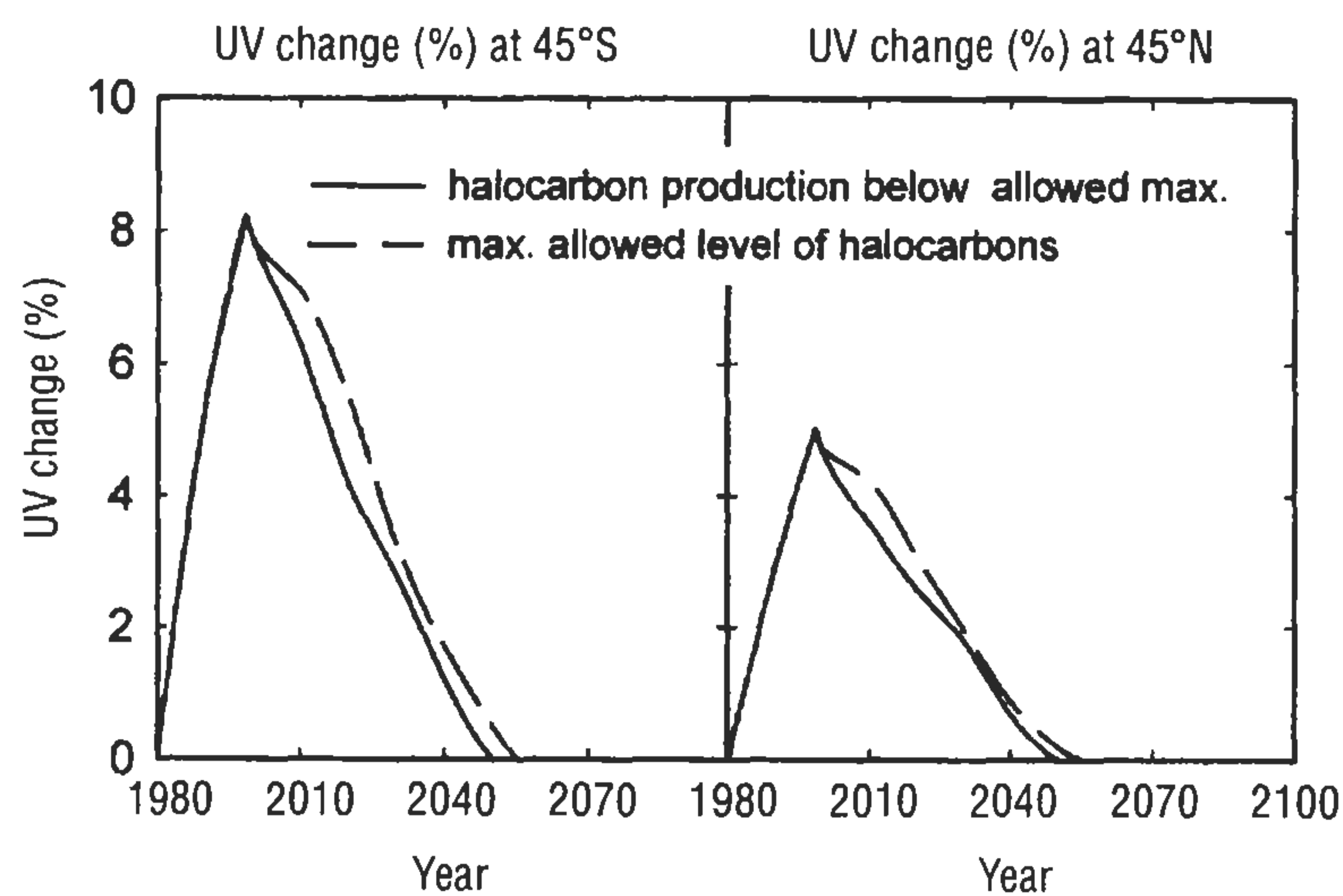


Figure 9. Scenario for future changes in erythemally (sunburn-causing) – weighted UV radiation at the Earth's surface, at 45°N and 45°S. UV radiation changes are estimated from ozone changes, which in turn are estimated from changes in atmospheric amounts of ozone-destroying substances (halocarbons). Scenarios shown are based on current control measures (Montreal 1997 amendments) with one scenario (solid curve) recognising that production of some ozone-depleting substances is currently already below the allowed maximum. For the second scenario (dashed curve) production is at maximum allowed level (modified from Madronich et al. 1998b).

outside the optimal range of photosynthesis (i.e. > 33°C) and productivity will decrease.

Ultraviolet (UV-B) radiation

Increased UV-B radiation could damage terrestrial organisms. The UV-B wavelength band ranges from 280 nm to 320 nm, although only wavelengths greater than 290 nm can reach the Earth's surface. In sunlight, the ratio of UV-B to photosynthetically active radiation (PAR; 400–700 nm) fluctuates, primarily caused by changes in solar angle and thickness of the ozone layer.

Depletion of the ozone layer results from emissions of halogenated chemicals, such as chlorofluorocarbons (also called halocarbons). Such depletion decreases UV-B screening (Tevini 1996). Stratospheric ozone levels are near their lowest point since measurements began, so current UV-B radiation levels are thought to be close to their maximum (Madronich et al. 1998b) (Figure 9).

Changes over the past decades are difficult to quantify because of a lack of suitable historical data. Estimates range from an average increase of about 8% per decade (Blumthaler and Ambach 1990) at high altitudes to 4–7% since 1970 for the Northern Hemisphere and 130% for the Antarctica in spring (Madronich et al. 1998b). However, temporal and spatial variation due to cloud cover, atmospheric pollutants and surface albedo is very large. Based on satellite observations monthly deviations from these mean values can approach +40% under clear sky conditions for latitudes between 30° and 45° North (McPeters et al. 1996), where almost all grapes are grown in Europe (Figure 10).

Thinning of the ozone layer also results in a shift of the spectral UV-composition towards shorter wavelengths, which are more biologically damaging (Jansen et al. 1998). Calculations of ozone and UV radiation (for latitude 45° N and S), based on halocarbon loading of

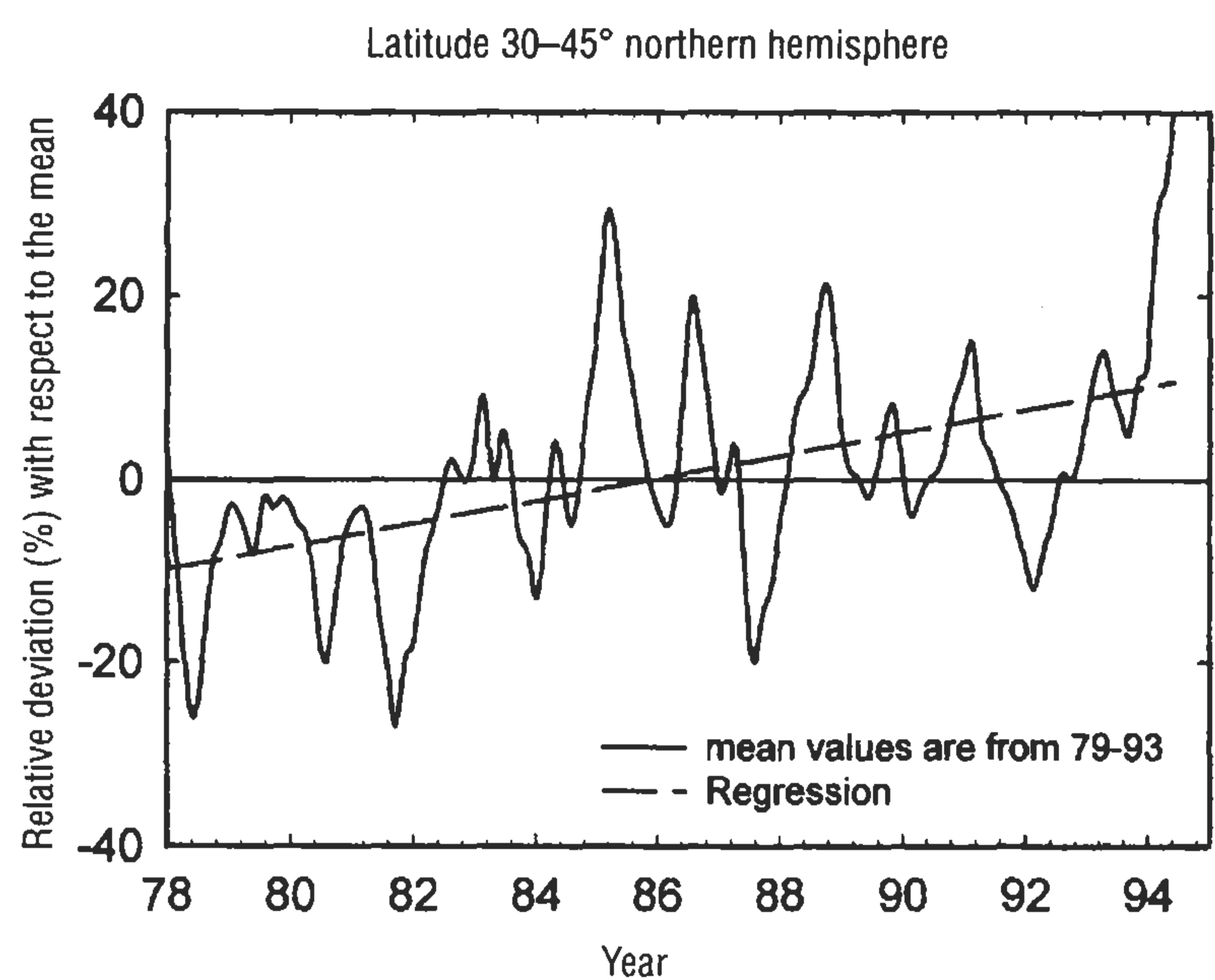


Figure 10. Changes in daily surface spectral irradiances at 310 nm, computed for cloud-free conditions from satellite-based ozone observations (TOMS, version 7, McPeters et al. 1996). Values given are percent deviations from the 1979–1993 means for the latitude band 30–45° North. (Redrawn from McPeters et al. 1996).

the atmosphere under various scenarios (see Figure 9 for details), indicate that maximum values may have already been reached or will be reached in the near future. Moreover, those levels are likely to remain high for several decades (Figure 9, adapted from Madronich et al. 1998b). Additionally, seasonal fluctuations may largely exceed the average increase in UV-radiation and are likely to cause significant biological damage (Figure 10).

Increased UV-B can be damaging to terrestrial organisms including plants and microbes, but these organisms do have both protective and repair mechanisms. Terrestrial ecosystem responses to increased UV-B are evident primarily in interactions among species, rather than the performance of individual species (Figure 11) (Tevini 1996, Madronich et al. 1998a). Yet the possible interactions with respect to life cycle timing, changes in plant form and production of plant chemicals not directly involved in primary metabolism, are very complex (Tevini 1996). The impact of UV-B on the morphological, physiological and biochemical features of higher plants has been extensively studied. Decreases in leaf expansion (Tevini and Teramura 1989), fresh and dry weight, total biomass and photosynthetic capacity have been noted (Krupa and Jäger 1996). Research in the past few years indicates that increased UV-B exerts effects more often through altered patterns of gene activity rather than gene damage (Madronich et al. 1998a). While UV-B responses are immediate, effects can accumulate from year to year in long-lived perennial plants such as trees (Musil et al. 1998, cited in Madronich et al. 1998a)—grapevines might follow a similar pattern.

While reports of plant responses to such UV-B alterations have varied according to species or cultivar sensitivity, as well as the experimental system used (Krupa and Jäger 1996), increases in UV-absorbing compounds seem to be a general reaction to increased UV-B radiation (Tevini 1996, Jansen et al. 1998). Accumulation of these compounds reduces UV-radiation penetration into plants

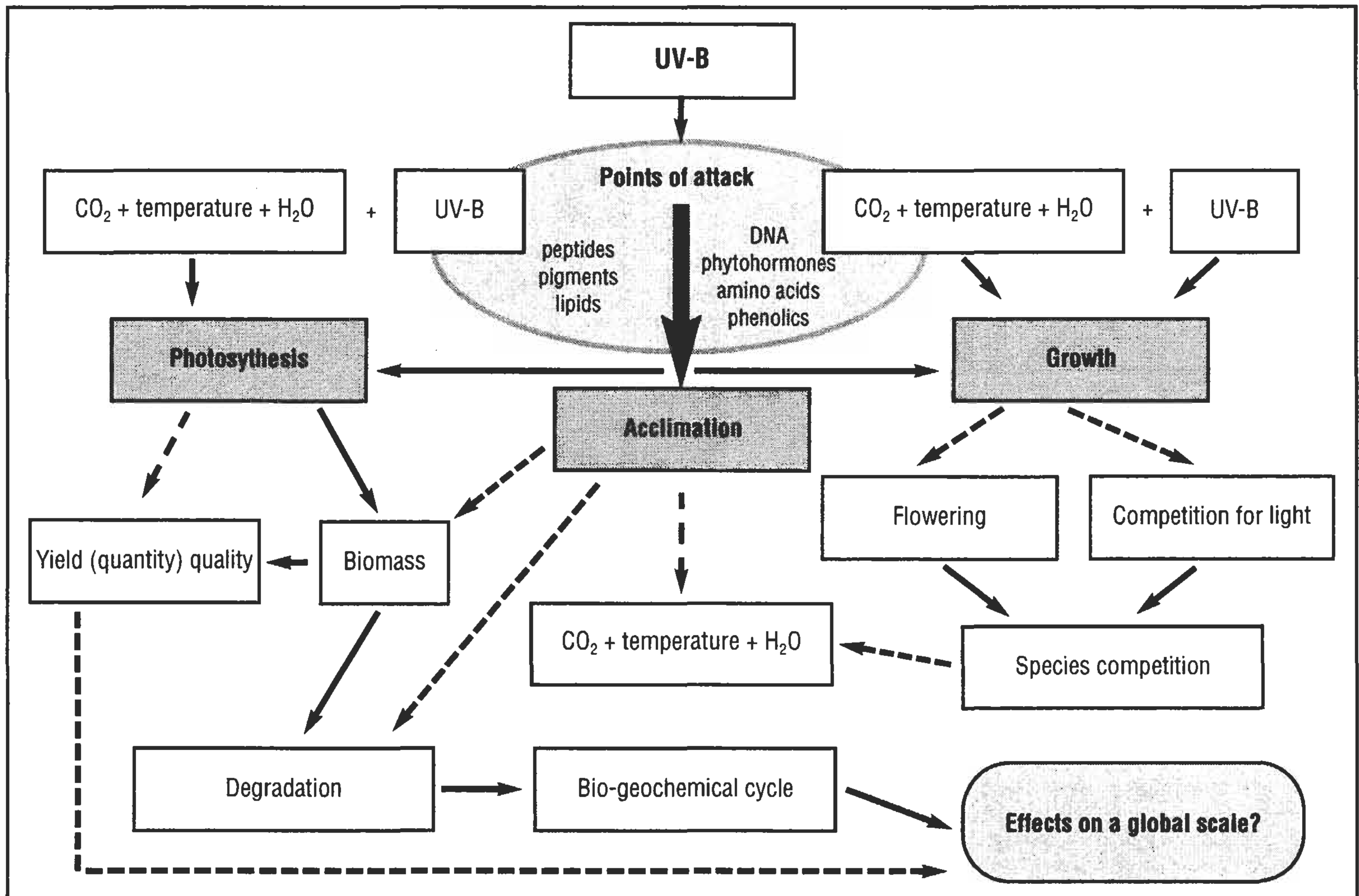


Figure 11. Potential consequences of increased UV-B radiation for plant functioning as a result of the destruction of earth's ozone layer. Dashed lines: little or not yet sufficient experimental results; continuous lines: qualitative and quantitative data existing (modified from Tevini 1996).

Table 1. Some known effects of UV-B radiation and their possible relevance for grape production.

| UV-B effects | Possible relevance for grape production |
|--|--|
| • activation of genes of the phytopropanoid pathway | ➔ accumulation of flavonoids and anthocyanins (colour formation, wine composition) |
| • inactivation (damage) of photosystem II and of photosynthetic enzymes | ➔ decreased photosynthesis |
| • reduced chlorophyll and carotenoid concentrations | ➔ decreased photosynthesis, ➔ altered aroma compounds? (vitispirane, 1,1,6-trimethyl-1,2-dihydronaphthalene, TDN, β -damascenone)? ➔ xanthophylls, leaf and berry energy balance? |
| • effects on nitrogen metabolism (via carbon supply or direct effects on key enzymes) | ➔ decreased amino acid concentration (yeast metabolism, fermentation kinetics, higher alcohol formation, secondary aromatic compounds) |
| • thicker leaves, wax composition | ➔ more disease resistance |
| • photo-oxidation of indole acetic acid (IAA, auxin), UV-B absorption by tryptophan | ➔ possible formation of <i>o</i> -aminoacetophenone (off-flavour in white wines) |
| • increase in ascorbic acid and glutathione content through the formation of free radicals | ➔ photoprotection, sulfur metabolism, induction of enzyme activities (important for yeast metabolism)? |
| • flowering and phenology | ➔ may be affected in some varieties |
| • alterations in soil microflora and fauna | ➔ nutrient availability |

and other organisms. For instance, formation of yellow and red pigments significantly reduces penetration of UV-light into nectarine fruit (Blanke 1996). Some key enzymes involved in flavonoid biosynthesis (chalcone synthase) and the phenyl-propanoid pathway (phenylalanine ammonium-lyase) have been shown to be up-regulated by UV-radiation, as are levels of key antioxidants glutathione and ascorbate (Jansen et al. 1998), whereas carotenoid pigment formation and the incorporation of nitrogen into amino acids can be inhibited (Döhler et al. 1995, Jansen et al. 1998).

Since components such as flavonoids, amino acids and carotenoids are important constituents of grapes with a marked effect on flavour development, some influence of UV-B radiation on grape composition can be expected (Schultz et al. 1998) (Table 1). Additionally, at a molecular level, UV-B can destroy peptides and lipids and can photo-degrade the plant hormone auxin (Figure 11), which absorbs in the UV-B range and may play a significant role in the formation of an off-flavour in white wines increasingly found over the last decade in Central Europe (Geßner et al. 1999) (Table 1).

To study these possible effects, a large-scale field experiment was initiated in 1996 (Figure 12) using 19-year-old Riesling grapevines (*Vitis vinifera* L.) clone 198 on 5C rootstock with an east-west row orientation. UV-B absorbing polyester film and UV-B and UV-A absorbing diacetate film (both 1.1 m width, 0.1 mm thickness, Jürgen Rachow, Hamburg, and Schlußner KG, Dreieich, Germany) were installed on the south-facing side of the canopy at an angle of 35° with respect to the foliage to cover the fruiting zone (lower 75 cm of the canopy) three weeks after flowering (Figure 12). Complete coverage of the plants was not possible because that caused substantial alterations in vineyard microclimate. As an additional control a neutral film completely transparent at all wavelengths was installed.

In 1996, 20 vines were covered by the films in 4 replicates of 4.8 m length to allow free air circulation. In 1997–1999, the experiment was extended to several hundred square metres of protected canopy. The spectral characteristics of the films (bandwidth 300–1100 nm) were measured with a portable spectro-radiometer (LI-COR 1800, Lincoln, Nebraska, USA). There was only a small fraction of UV-B light transmitted in the waveband near 320 nm and a relatively clear-cut absorptance below 400 nm for the UV-B and UV-A attenuation treatment, whereas the neutral film did not substantially absorb at any wavelength tested (Figure 13). Light attenuation in the photosynthetic active region of the spectrum (400–700 nm) was only 3–4% after an entire season in the field (Figure 13). Maximum and minimum air temperatures under the cover differed by less than 1°C from ambient.

One of the striking features we observed after shielding fruit from UV-radiation was the near absence of visible pigmentation of berries. Since pigments have a large effect on absorptance, transmittance and reflectance characteristics of any organism (Gates 1970), the reflectance spectra of intact berries were measured over the

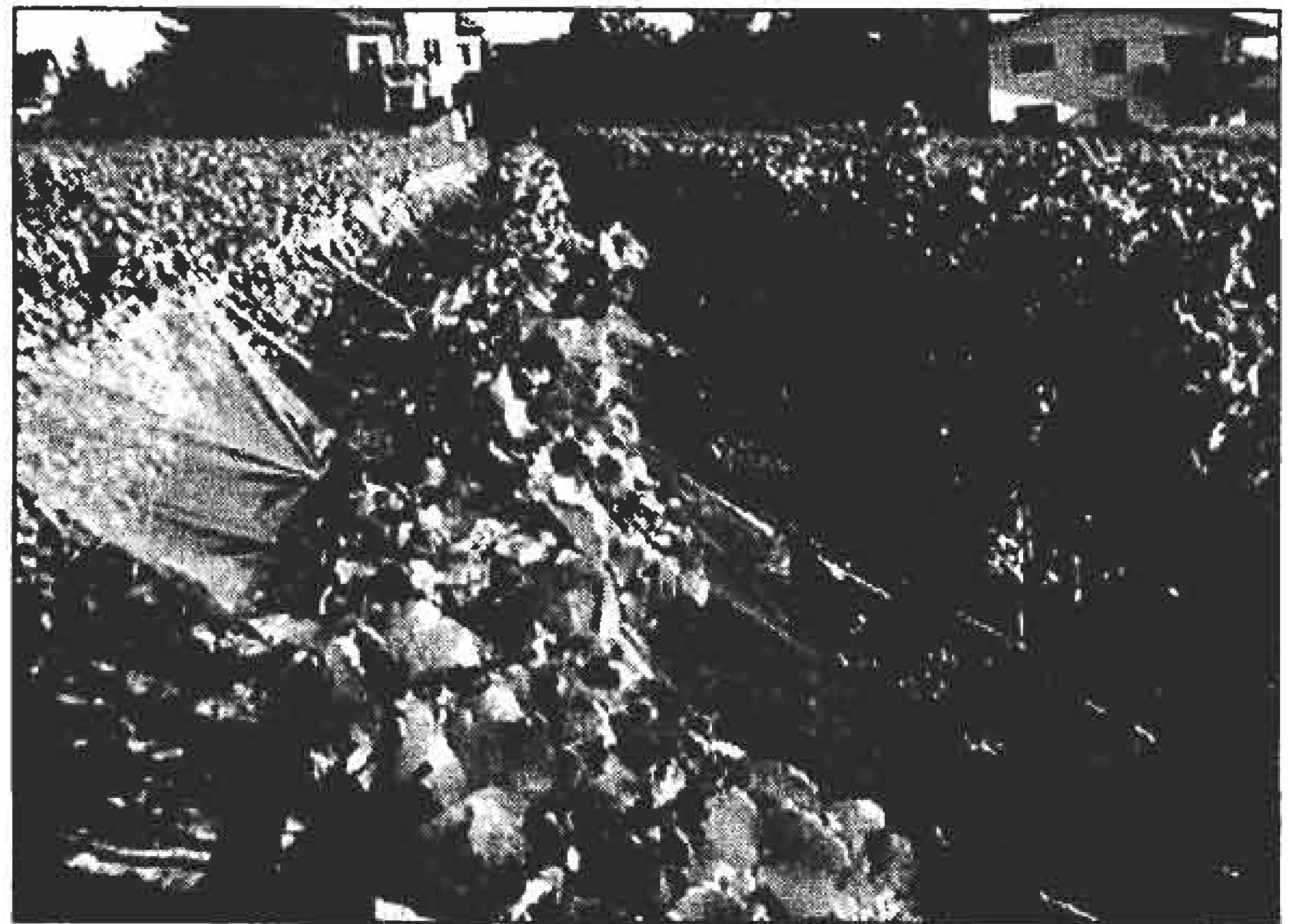


Figure 12. Field experiment to study the effects of UV-B radiation on Riesling fruit composition and leaf photosynthesis in Geisenheim, Germany (photo H. Schultz).

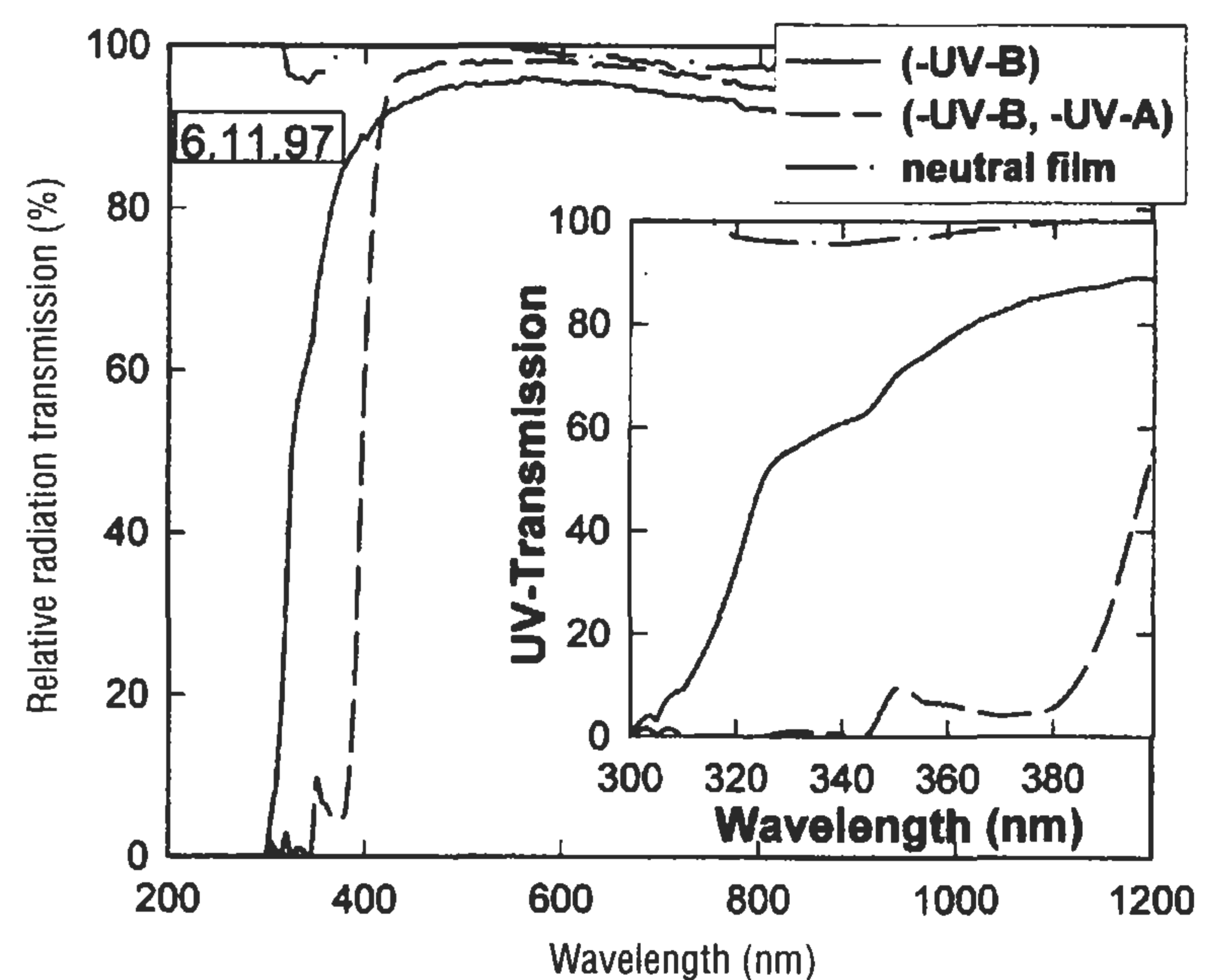


Figure 13. Transmission spectra (300–1100nm) of films used in the UV-experiment at Geisenheim, Germany. The inset graph shows specific percentage transmission of the films in the UV-radiation range. Measurements were made with a LI-COR 1800 Spectroradiometer after the films had been used for an entire season in the field.

wavelength range between 330–1100 nm (Figure 14). In the UV-B exclusion treatment, reflectance was reduced by about 15% over the entire visible range (400–700 nm) and into the near infrared (> 700nm) (Figure 14B). Reflectance seemed to be even lower in the longer UV range between 350–400 nm (Fig 14B).

Reflectance spectra are indicative of the type of pigments present and/or the amount of certain nutrients and water (Gausmann et al. 1982, Myers et al. 1970, Carter et al. 1989, Peñuelas and Filella 1998). From the spectra in Figure 14, some reflectance indices proposed by Peñuelas and Filella (1998) for remote sensing purposes were calculated. In the presence of UV-B radiation, the structural independent pigment index representing the ratio of carotenoids to chlorophyll *a* ($R_{800\text{ nm}} - R_{445\text{ nm}} / R_{800\text{ nm}} - R_{680\text{ nm}}$, R =reflectance) (Peñuelas et al. 1995) was increased, which is often observed when

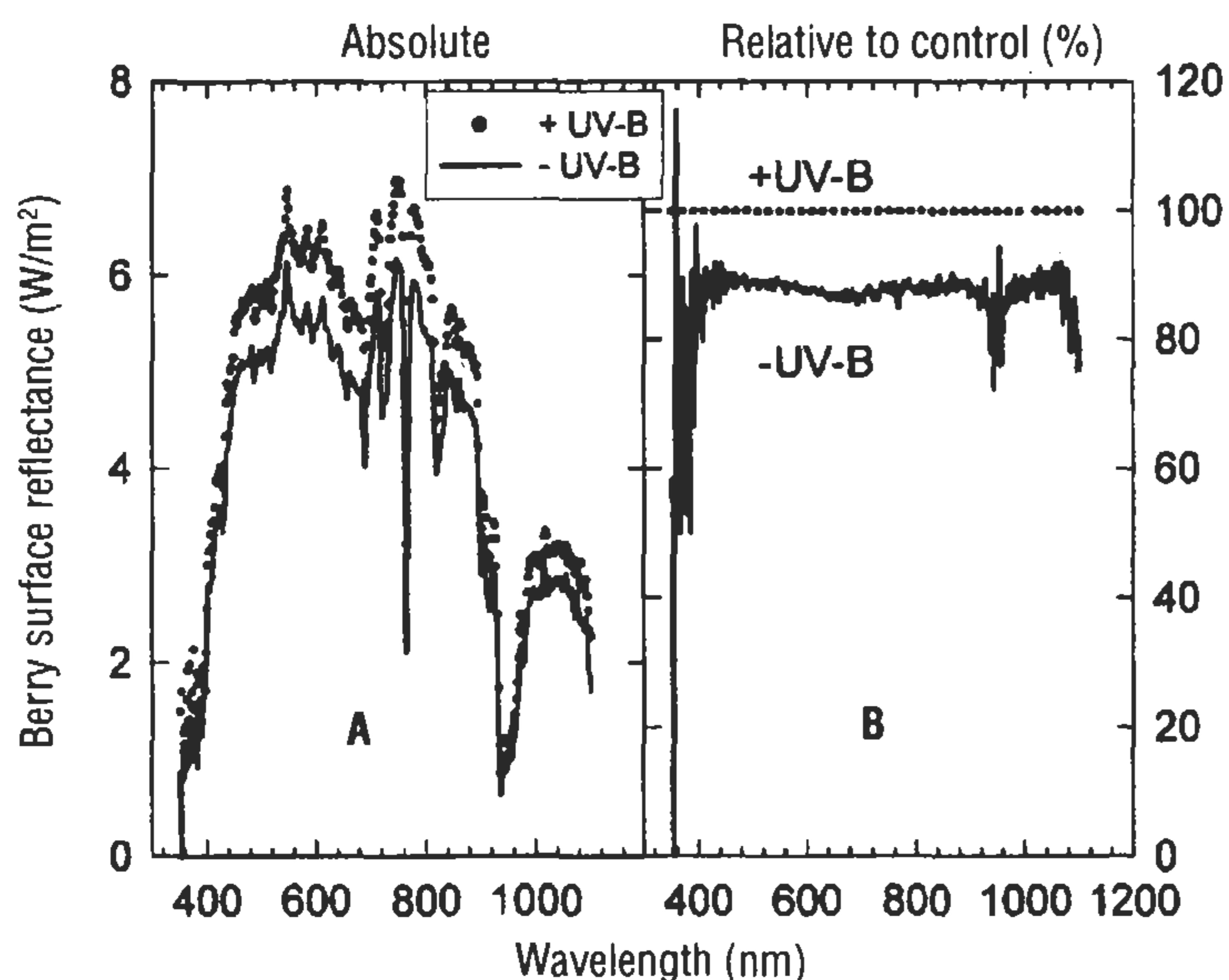


Figure 14. (A) Reflectance spectra from Riesling berries previously exposed to natural UV-radiation and from berries shielded with a UV-B absorbing film. (B) Reflectance expressed as a percentage of control fruit (i.e. exposed to natural UV-B radiation). Data in panel B were calculated from those shown in panel A. Measurements were conducted with a LI-COR 1800 Spectro-radiometer on excised berries placed in a petri dish at full maturity (Schultz, Váradi and Bálo unpublished data).

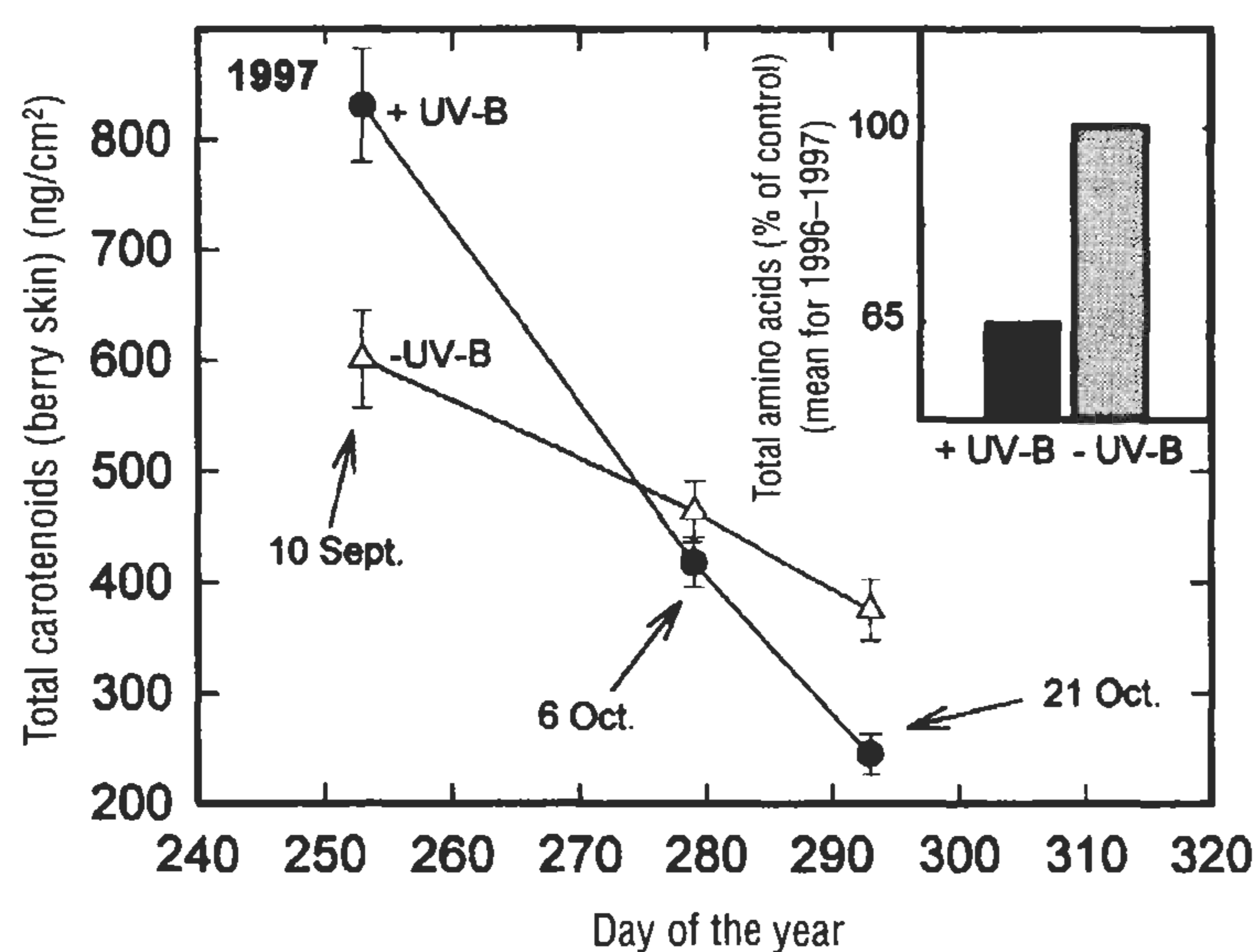


Figure 15. Effect of current level UV-B radiation on the density of the total carotenoid pool in berry skins ($n = 5$) during the grape maturation phase 1997, and on the relative concentration of amino acids (% of control, mean 1996–1997, inset) (adapted from Schultz et al. 1998).

plants are subjected to stress and in senescing leaves (Young and Britton 1990). Ratios of reflectances in the blue domain (where carotenoids and chlorophylls absorb) and the red domain (where only chlorophylls absorb) have been found to be highly correlated with this pigment ratio in different plant species (Peñuelas and Filella 1998). The higher reflectance of UV-B exposed berries in the near infrared wavebands up to 1100 nm (Figure 14B) may be related to a stronger accumulation of brown pigments such as phenolics (Walter-Shea and Norman 1991). From this indirect method it became clear that chemical alterations in berry composition occur under natural UV-B compared with fruit from vines shielded from UV-B.

When berry skin samples were analysed, both amino

acid and carotenoid concentration at harvest were substantially reduced under current level ambient UV-B radiation especially in 1997, a year with a high incident radiation level and low soil moisture content during fruit maturation (Figure 15) (Schultz et al. 1998). Additionally, amino acid composition was altered under UV-B radiation, exhibiting lower levels of arginine and glutamine, the main sources of amino acids for yeast metabolism. Effects of UV-B on both amino acid and carotenoids have been reported for other plants (Jansen et al. 1998) but never for fruits.

However, it seems to be important to study specifically the interactions between UV-B and fruit composition, since many UV-B responsive components of secondary metabolic pathways, such as carotenoids, are constituents and/or precursors of important fruit and wine flavours or ingredients. Several authors suggested that the difference between the carotenoid level at the onset of ripening and that at harvest indicates formation of norisoprenoids (Razungles et al. 1993, Bureau et al. 1998). These compounds have been linked to the ageing flavour of wines (vitispirane, 1,1,6-trimethyl-1,2-dihydronaphthalene, TDN) and the fruity character of must and wine (damascenone), and can be influenced by climatic factors (Marais et al. 1991) (Table 1).

Under natural, UV-B exposed conditions, the degradation of carotenoids was more pronounced than when UV-B was excluded, suggesting a larger build-up in norisoprenoids (Figure 15). Equally possible is a link between low amino acid concentrations in grapes and must and disturbed fermentation processes and off-flavour formation through UV-B sensitive compounds such as indoleacetic acid or tryptophan giving rise to *o*-aminoacetophenone (Table 1) (Christoph et al. 1996, Jansen et al. 1998, Geßner et al. 1999). Aside from direct effects on grape composition, indirect effects through impaired photosynthesis are possible but remain to be demonstrated in future studies.

Concluding remarks

The seven warmest years of global records have all occurred since 1990, indicating a rapid warming trend. In Europe, continued warming will increase the margins of suitability for grape production to the North and East through higher effective temperature sums and longer growing seasons and will alter the 'picture' of varietal distribution. Increased evaporation rates from soils and higher transpiration rates from plants will accompany the rise in temperature and may lead to more frequent drought events and the necessity to adapt soil management systems and/or scion and rootstock choice.

Changing precipitation patterns could aggravate the problem. Irrigation may become a more common practice in Europe, although for most areas, water availability will be the limiting factor. A rise in CO₂ concentration will inevitably continue. Consequences for grape production throughout the world remain unclear because there are very few data available on how grapevines respond to high CO₂. Grapevines have a large adaptive potential to changes in the environment, at least with respect to

temperature and possibly to CO₂. Nevertheless, such adaptation towards higher temperature optima for photosynthesis or higher water use efficiency will not necessarily translate into improved yields or enhanced wine quality.

Current levels of UV-B radiation are probably close to their likely maximum, provided global restrictions on release of ozone-destroying substances are honoured. If not, UV-B radiation will continue to increase, with serious implications for wine quality via effects on fruit composition. These effects may not be exclusively negative, but our current knowledge on this subject is still very limited. The great challenge in the future will be to predict the responses of grapevines to simultaneously changing climatic components and to develop adequate strategies to overcome potential problems.

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