2.04 Understanding the Impacts of Climate on Perennial Crops

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Glossary

Chilling requirement The minimum amount of cold temperatures needed for a plant to break winter dormancy and resume growth in the spring.
Dormancy A period of reduced plant activity and growth.
Downscaling The process of adding information at scales smaller than the original spatial resolution or temporal aggregation period.
Fall hardening The gradual process by which a plant becomes tolerant of freezing temperatures.
Growing degree days (GDDs) A measure of heat accumulation, calculated as the difference between the daily mean temperature and a specified base temperature. GDDs are frequently used in agriculture to estimate planting times and approximate dates of crop development stages.
Perennial crops Agricultural commodities with life spans of two or more years.
Phenology The growth stages of a plant.
Poikilothermic Organisms whose growth and development is primarily temperature dependent.
Veraison The onset of ripening.

2.04.1 Introduction

Perennial crops, including the commercial production of fruits and nuts, play important dietary and economic roles at local, regional, national, and international scales. The vulnerability of these commodities to climate has not been as widely studied as compared to annual crops, in spite of their greater relative exposure to fluctuating weather conditions due to their perennial nature. In contrast to many annual crops, the spatial extent of perennial crops across the landscape is relatively limited. Rather, perennial crop production is frequently constrained to areas with unique local or regional climates that are often influenced by topographic position, proximity to water bodies, or the presence of mesoscale atmospheric circulations and weather conditions such as frequent fog that modify the local climate. This limited spatial extent of production regions contributes to the climate vulnerability of perennial crop production. Furthermore, orchards require substantial initial investment and the typical lifetime is on the order of 20–30 years, limiting adaptation options and the time scales at which adaptations can be implemented.

Perennial crops present numerous challenges for climate impact and vulnerability assessments. As summarized by Lobell and Field (2011), multiple critical physiological stages

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must be considered, process-based crop models remain largely unavailable or poorly developed for perennial crops, and the slow growth of perennials makes experimental warming trials less feasible than for annual crops. Also, as pointed out by White et al. (2006), climate assessments for perennial crops must have a fine spatial resolution to resolve subregional scale climate–crop relationships. In spite of these constraints and challenges, a substantial body of literature has evolved on climate impacts on perennial crops that covers multiple production areas worldwide. Based on the frequency of published articles, the fruit crops most investigated are wine grapes, apple, cherry, citrus, peach, and apricot. Numerous other fruit commodities have also been studied including kiwi, mango, pear, pineapple, plum, and strawberry. Almonds and walnuts are the two most widely investigated nut tree commodities.

This chapter reviews prior research examining the impacts of climate on perennial crops. The goals are to (1) highlight vulnerable growth stages and industry components, (2) describe the common methods and analytical techniques used to investigate climate impacts on perennial crops, (3) summarize, based on published literature, the current understanding of temporal trends in freeze risk, heat stress, and the timing of growth stages, and (4) provide our perspective on existing knowledge gaps and recommendations for future research.

2.04.2 Climate Vulnerability of Perennial Crop Production

In general, perennial trees in temperate and cool subtropical climates lose their leaves and begin a cold hardening stage in early fall before becoming dormant in late fall. In some plants, the cessation of growth during fall is triggered by shorter day length, whereas others respond to colder air temperatures. Buds remain dormant or in the stage of 'rest' due to internal physiological blocks (i.e., inhibitors) that prevent their development even under ideal conditions for growth. These physiological blocks are removed when buds are exposed to chilling temperatures above freezing for some weeks. The chilling requirement is often fulfilled in winter for both high- and low-latitude species. After chilling is completed and buds are no longer in a state of 'rest,' they become 'quiescent' and respond to heat accumulation. Cold temperatures during the quiescent period prevent bud growth, whereas buds become active losing much of their hardiness when the temperature becomes favorable for growth. Perennial crops are particularly vulnerable to cold damage at three distinct stages: (1) in the fall before the tree is adequately hardened, (2) during the winter dormant period when severe cold events can cause injury to woody tissue, and (3) during spring when temperatures slightly below freezing may kill flower buds following the loss of cold hardiness (Raseira and Moore 1987). Although cold damage in fall and winter can cause permanent injuries to perennial trees, they are usually less frequent, and have a smaller effect on year-to-year variability in yield, compared to springtime freeze events.

Production is also influenced by other climate factors, such as the amount of plant available moisture in the soil profile, conditions during pollination, the occurrence of prolonged and/or extreme heat or drought events, and the frequency of hail during the growing season. Additionally, weather conditions, including temperature and humidity, contribute to the risk of insect pests and plant diseases, which also affect orchard and vineyard productivity.

An initial step in a climate assessment for perennial crops is the identification of the critical growth stages and related climate factors for the crop in question (Figure 1). Although

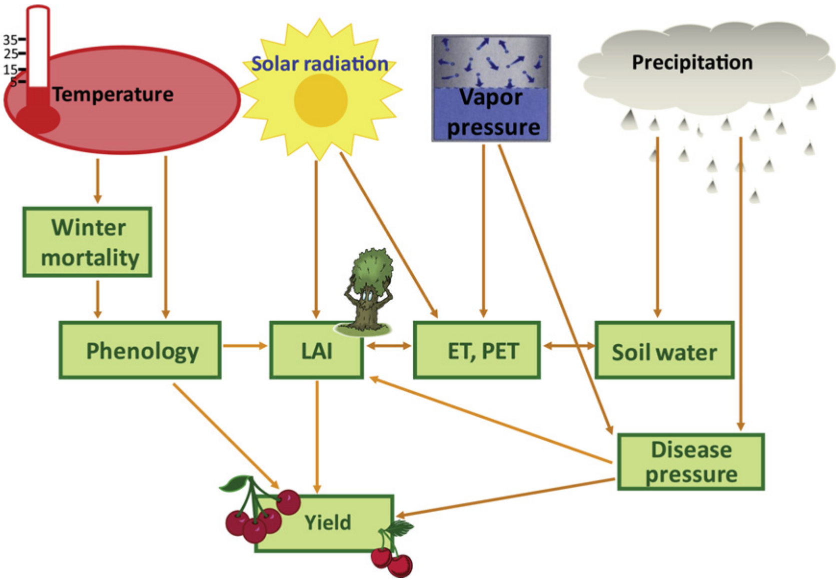

Figure 1 Weather and climate influence a number of aspects of perennial crop development and yield. This cartoon illustrates the potential impacts of four climate variables on sour (tart) cherry production in the Great Lakes region of North America. The cartoon was prepared by Andresen, J. A., J. R. Black, C. Zavalloni, and J. M. Bisanz at Michigan State University for the Pileus Project (http://www.pileus.msu.edu/), and is used here with their permission.

these factors will vary by crop, past studies have highlighted winter chill fulfillment, changes in springtime freeze risk, pollination constraints, heat stress, and enhanced disease and insect pest pressure as particularly contributing to the climate vulnerability of perennial crops.

2.04.2.1 Winter Chill Fulfillment

As noted above, for many commercial perennial tree crops (e.g., apples, cherries, and peaches), a chilling requirement must be met to break winter dormancy and resume growth in the spring (Luedeling and Brown 2011). When chilling requirements are not met, foliation is delayed and flowering is irregular and occurs over a longer period, resulting in varying fruit sizes and maturity stages at the time of harvest and even in poor pollination if synchrony of male and female flowering is required for pollination (Byrne and Bacon; Luedeling et al. 2009). Thus, possible warming raises concerns regarding crop quality and yield, if perennial trees do not fulfill their chilling requirements.

2.04.2.2 Springtime Freeze Risk

For many current areas of perennial crop production, damaging springtime temperatures is the single most important climate-related risk factor (Flore 1994). Springtime freezes can be classified as either an inversion (radiation) freeze or a wind (advection) freeze (Winkler et al. in press). Estimating the temperature at which damage occurs to flower buds is challenging, due to the confounding factors of growth stage and ambient conditions, and published temperature thresholds (e.g., Longstroth 2007) are likely a more appropriate reference for inversion freezes compared to wind freezes. Damages associated with wind freezes may occur at warmer temperatures than the published temperatures, especially if the period of cold temperatures is prolonged and/or the flower buds are wet due to precipitation (Longstroth 2007).

Considerable uncertainty exists regarding the future susceptibility of perennial crops to below freezing temperatures when preceding crop development is considered. Early spring warm-ups may result in greater freeze risk if flower buds are at a more advanced stage of development at the time of the last spring freeze. On the other hand, if the date of the last spring freeze advances to an earlier date in synchrony with bud development, spring freeze risk may not change or even decrease. Thus, a warmer climate cannot be assumed to bring more favorable conditions for perennial crops that currently are vulnerable to springtime freeze damage.

2.04.2.3 Pollination Constraints

Conditions favorable for pollination vary with species. For example, Lobell and Field (2011) argue that below average temperatures during the bloom season lead to a longer pollination period for almonds, as the stigma is receptive to pollen for longer periods of time. Consequently, warming during the bloom period could contribute to reduced yield. On the other hand, pollination of highbush blueberry in the Great Lakes region of North America is negatively impacted by cool, moist conditions (Tuell and Isaacs 2010). Bees are essential for pollination, and their activity is reduced under unfavorable weather conditions such as temperatures below 12 °C and wind speeds greater than 25 km h^{-1} (Thomson 1996). Warmer temperatures, if also accompanied by light winds and dry conditions, could result in greater pollination for this region and crop type.

2.04.2.4 Heat Stress

Heat and drought spells during the growing season are a concern for most perennial crops, as temperature and moisture availability directly influence photosynthesis, fruit size and quality, and harvest time. As summarized by Moretti et al. (2010), more heat can lead to higher sugar content (e.g., apples, grapes), lower levels of tartaric acid (e.g., grapes), lower fruit firmness (e.g., avocado), and higher antioxidant activity (e.g., strawberries). Higher temperatures can additionally reduce vitamin content of some fruit crops (McKeon et al. 2006). Physical damage is also possible including burning of walnuts (Baldocchi and Wong 2008) or sunburn and loss of texture in apples (Ferguson et al. 1999). When wine grapes are exposed to prolonged periods of high temperature, plant heat stress can lead to premature veraison (i.e., onset of ripening), the separation of berries from vines, enzyme inactivation, and failure of flavor ripening (White et al. 2006).

2.04.2.5 Disease and Insect Pest Damage

A confounding factor when considering climate impacts on perennial crop production is the frequency and severity of insect pests and plant diseases. Insect pests are poikilothermic; that is, their growth and development is primarily temperature dependent. Thus, the number of insect generations per year and their timing with respect to plant development stages are sensitive to a perturbed climate. For example, annual monitoring of codling moth (*Cydia pomonella*) in Germany's northernmost apple growing region (Lower Elbe valley) points to the occurrence of a partial second generation during warm years such as 2006, 2008, and 2010, and a climate impact analysis suggests possible future increases in the annual number of codling moth generations in all German fruit growing regions (Chmielewski et al. 2009). Also, increased insect pest populations could lead to early leaf abscission, which in turn contributes to an early loss of photosynthetic capability and therefore lower accumulation of total carbohydrates in perennial organs. For example, in sour cherry early defoliation delayed acclimation in the fall and induced a more rapid deacclimation in the spring, reducing bud survival and fruit set (Howell and Stackhouse 1973).

The severity of plant disease outbreaks is influenced by moisture conditions in addition to temperature. For example, Ladányi et al. (2010) found that rain during the bloom period promotes bacterial and fungal diseases in sour cherries. Further, *Diplodia seriata*, a cause of black rot of apples, is a new pathogen in the Lower Elbe valley whose appearance is probably associated with higher temperatures and more frequent rainstorm events during the the vegetation period (Weber 2009).

Future changes in plant development and insect and disease pressure might necessitate different approaches for the use of pesticides and disease protection management strategies

(Khanizadeh 2007). A number of current management strategies, such as chemical sprays, are restricted to certain growth stages or specified times before harvest, and changes in the timing of insect life cycles or disease occurrence with respect to crop growth stages could make these strategies no longer viable Winkler et al. (2002).

2.04.3 Nonclimatic Contributions to Vulnerability

Climate is not the only consideration when assessing the long-term viability of perennial crop production. Economic and social factors must also be considered. Specific concerns will vary with crop type and location, but most industry stakeholders must contend with changes in consumer demand, competing land uses, and competition with other production regions. The sour (tart) cherry industry in the United States is used here to illustrate these concerns.

While relatively small in scope, sour cherry production has major economic impacts at the local and regional levels. Production in the United States occurs primarily in the lake-modified zones surrounding the Great Lakes. In 2009, 292 million pounds of sour cherries, or 80% of the national total, were produced in Michigan, New York, Pennsylvania, and Wisconsin (NASS 2011). Of this amount, 266 million pounds were produced in Michigan alone.

Changes in consumer demand have been a particular concern for the sour cherry industry in the United States. The majority of product exchange is as processed products, with frozen sour cherries an intermediate product destined for use in the further processed ingredient and bakery industries (Thornsbury and Woods 2005). However, changes in American dietary patterns have reduced the demand for sour cherries by the bakery industry, forcing industry stakeholders to search for alternative uses of their product. The Cherry Marketing Institute, located in Michigan, has launched a 'Go red instead' campaign, advertising the high antioxidant content and health benefits of sour cherries (Cherry Marketing Institute), and the health foods industry is becoming an increasingly important commercial outlet for sour cherry production.

Competing land uses are also a concern. Orchards are typically located on hilltops and slopes near the Great Lakes shoreline in a scenic environment and sought after area for vacation homes. Many local planning organizations have recognized the contribution of the orchards to the allure of the local environment with some areas putting in place regulations to limit housing development, but, nonetheless, development pressure contributes to the vulnerability of the sour cherry industry in the Great Lakes region. Furthermore, sour cherry production is competing for orchard sites with wine grape production, which has increased substantially in size over the past several decades.

Competition with other production regions is also a growing concern. Historically, the United States imported very little in terms of sour cherry products, relying instead on a nationally produced product. However, after the near-complete crop failure in northwest Michigan in 2002 due to a springtime wind freeze, sour cherries were imported to the United States to sustain current markets, with most fruit imported from Poland – the current world leader in sour cherry exports and where the sour cherry industry has recently rapidly expanded (Thornsbury and Woods 2005). Although imports from Poland and other producing regions have since declined with improved production in Michigan and other cherry producing states, sour cherry imports remain at a higher level than before the 2002 crop failure (Thornsbury and Woods 2005). Importation remains elevated in part because Schatten Morello, the sour cherry variety grown in Poland and several other European production regions, differs from the cultivar Montmorency primarily grown in Michigan in terms of fruit color, taste, and other physical characteristics. Thus, the two cherry cultivars are not perfect substitutes for each other.

Additional nonclimatic factors that can contribute to the vulnerability of commercial sour cherry production and other perennial crops include uneven changes in wealth effects, influencing patterns of supply and mix of goods demanded, and political actions in response to environmental or trade concerns that lead to changes in subsidies (Winkler et al. 2010). These factors, along with changes in consumer demand, land use pressure, and competition with other production regions, may make investments in perennial crops unappealing to the individual producer.

2.04.4 Methods and Models for Assessing Climate Impacts on Perennial Crops

In contrast to assessments for annual crops, where the focus is often on potential changes in yield as estimated from well-known process-based models, climate assessments for perennial crops heavily rely on empirical relationships developed between climate observations and plant phenology, and, less frequently, between climate observations and yield. A number of empirical approaches have been applied, all of which have strengths and weaknesses that must be considered when interpreting the outcomes of assessment studies. Below we highlight several analysis and modeling approaches that have been frequently utilized for assessments of climate impacts on perennial crops. These methods, along with climate inputs and typical outcomes, are summarized in Figure 2.

2.04.4.1 Critical Thresholds, Growing Degree Days, and Agro-Climatic Indices

Critical thresholds represent perhaps the simplest approach for evaluating climate impacts, and many applications appear in the literature (e.g., Winkler et al. 2002; Zavalloni et al. 2006a,b; Rochette et al. 2004). As a more recent example, Ladányi et al. (2010) argued that the 10 days before and during bloom had the greatest impact on sour cherry quality and yield in Hungary and explored the effect of changes in the frequency of several critical thresholds. These thresholds were selected to assess freeze risk and conditions for pollination, and included the number of days with minimum temperatures below 0 °C and precipitation greater than 5 mm. The advantage of critical thresholds is their modest data requirements and computational costs, whereas a disadvantage is the difficulty in identifying appropriate threshold values. Critical thresholds can vary with variety and cultivar, and field trials and growth chamber

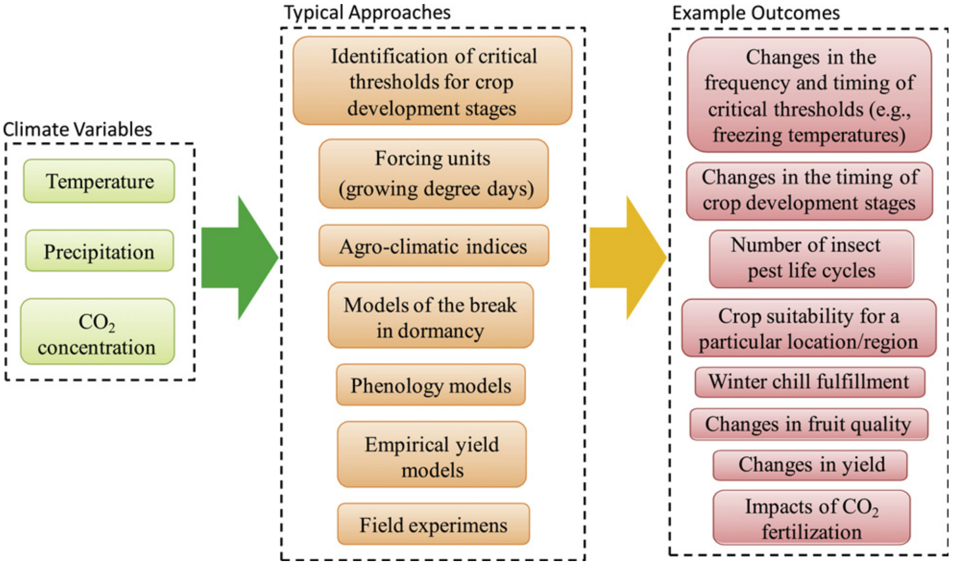

Figure 2 Typical methods and analytical techniques used to investigate climate impacts on perennial crops, along with frequently used climate inputs and example outcomes.

experiments are often unavailable for the crop variety or cultivar of interest.

Growing degree days (GDD), typically calculated as the difference between the daily mean temperature and a specified base temperature, have also been widely used in assessment studies for perennial crops, particularly to estimate the timing of different phenological stages (e.g., Nemani et al. 2001; Winkler et al. 2002; Zavalloni et al. 2006a,b) (Figure 3). For example, the Baskerville-Emin method (1969) was used to calculate growing degree days (base value 5 °C) beginning from 1 January for the sour cherry production regions of Michigan (USA), and early bud development (e.g., 'side green') was estimated to occur when ~150 growing degree days was reached (Winkler et al. in press). The degree day concept can also be used to evaluate changes in cold intensity and duration, as shown by Rochette et al. (2004). In this case, 'cold' degree days were defined as the degree days below a base value of −15 °C and were accumulated for the period 1 August–31 July. Additionally, some authors have employed modified degree day calculations, such as the Huglin Index (Duchêne and Schneider 2005) which weights daily maximum temperature more than minimum temperature in order to better represent species-specific development requirements, or biologically effective degree days (BEDD) that restrict the maximum heat accumulation for a particular day to emulate the reduction in growth rate at high temperatures (Hall and Jones 2008). Blümel and Chmielewski (2012) found that incorporating a day length term into a GDD model markedly improved projections of the timing of fruit tree blossom. Often times critical thresholds and heat accumulation are considered jointly; for example, growing degree day accumulation at the time of the last spring freeze (e.g., the last occurrence in spring of minimum temperature ≤0 °C) can provide an indication of temporal changes in crop susceptibility to damaging cold temperatures (Winkler et al. 2012, in press).

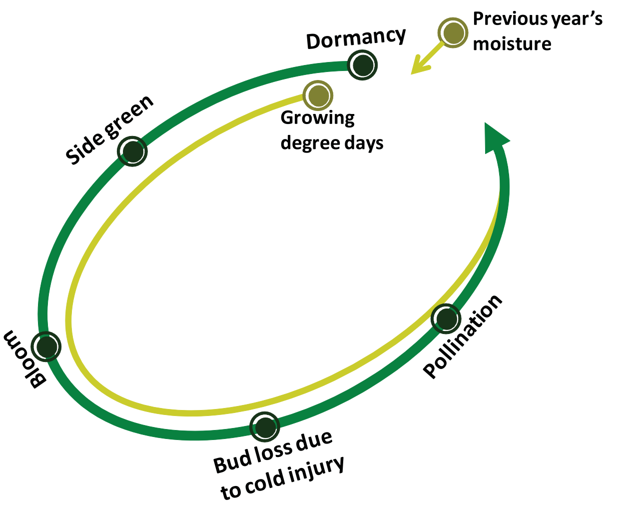

Figure 3 Growing degree days (also referred to as forcing units) are frequently used to estimate growth stages of perennial crops. In this example for sour cherry production, growing degree days are used to estimate the (1) timing of side green (a critical growth stage that occurs soon after bud swell), (2) the timing of flower bloom, (3) crop development at the time of last spring freeze and consequent bud loss, and (4) the timing of pollination. This image was prepared by Andresen, J. A., J. R. Black, C. Zavalloni, J. M. Bisanz, and H. K. Min at Michigan State University for the Pileus Project website (http://www.pileus.msu.edu/) and used here with their permission.

Agro-climatic indices are simply the expression of one or more climate variables in terms reflective of conditions important to crop development. These indices are often used to judge the suitability of a particular region for crop production, and have been a particularly popular approach for assessing suitable areas for quality wine production (e.g., Jones and Davis 2000; Hall and Jones 2008). As an example, White et al.

(2006) developed a nominal, four-category index for identifying premium wine grape producing areas in the United States based on the frequency of hot and cold days, diurnal temperature range in the growing and ripening seasons, and average temperature and heat accumulation during the growing season.

2.04.4.2 Modeling the Break of Dormancy

Models used to estimate whether perennial crops have met their chilling requirement for break of winter dormancy are collectively referred to as 'chill models.' Several chill models currently exist, although all are based on the concepts of growing degree days and critical thresholds. A commonly used but relatively simple model is the Chilling Hours Model, also referred to as the Weinberger Model (Weinberger 1950). This model requires hourly temperature measurements as input, and chilling is simply calculated as the sum of hours when the temperature falls between the thresholds of 0 and 7.2 °C. The user needs to fix the time period for the summation, which can vary by location and variety, although a frequent summation period (for Northern Hemisphere locations) is 1 November–1 March (Luedeling et al. 2009). In contrast, the popular Utah Model (Richardson et al. 1974) assigns different chilling efficiencies to different temperature ranges (Luedeling and Brown 2011), and includes the concept of negative chilling accumulation or chilling negation with temperatures above 15.9 °C assigned negative chill units (Byrne and Bacon). The Dynamic Model (Erez et al. 1990) represents a more complex formulation. The underlying assumption is that dormancy completion depends on the level of a dormancy-breaking factor that accumulates in flower buds (Erez et al. 1990). As summarized by Luedeling et al. (2009), initially an intermediate accumulation product is formed in a process promoted by cold temperatures, with warm temperatures able to destroy this product. Low temperature efficiency in releasing buds from rest follows an optimum curve where the maximum efficiency is between 6 and 10 °C (Erez and Lavee 1971). Higher temperatures produce negative effects and result in negation of a certain amount of hours of chilling units depending on the species and cultivar (Erez et al. 1979). Once a critical level of the intermediate product is amassed, it is irreversibly transformed into a Chill Portion, which can no longer be destroyed (Luedeling and Brown 2011.) An advantage of the Utah Model and the Dynamic Model over the older Chilling Hours Model is that end and start dates for chilling accumulation do not need to be prescribed, as both models can account for the reversibility of the chilling process when temperatures are high (Luedeling et al. 2009).

A major concern of all chill models is their applicability outside the region for which they were initially developed, especially as the models are often extrapolated to other locations with little or no change in the original parameters and critical temperatures. Luedeling and Brown (2011, p. 411) recently expressed their concern that users "assume that the choice of chill model is not important and that estimates of species chilling requirements are valid across growing regions." This concern is particularly critical for climate assessments, as biases resulting from the misapplication of chill models may provide a misleading interpretation of plausible future changes in the spatial distribution of production regions. Recent comparisons of the output of the chill models at multiple locations worldwide provide credence to this concern and suggest that site-specific correction factors are likely needed in order to facilitate spatial comparisons (Luedeling and Brown 2011).

Another constraint when applying chill models is the need for hourly temperature data. Hourly observations are available for a much smaller subset of climate observing stations compared to daily temperature observations. Consequently, subregional variations in chill units often cannot be captured by the coarse spatial resolution of hourly observing networks, particularly in areas of complex topography where temperature is highly associated with landscape position (i.e., aspect, elevation).

2.04.4.3 Estimating the Timing of Growth Stages

Phenological modeling is an important component of many climate assessments for perennial crops. Some phenological models are purely statistical in character such as the model developed by Zavalloni et al. (2006a) that relates flower bud phenological stages for sour cherries to growing degree accumulations. Others are somewhat more mechanistic in concept and attempt to simulate the processes of chilling and subsequent heat accumulation (e.g., Chuine et al. 1998). Recently, Chmielewski et al. (2011) evaluated the ability of five representative phenological models to estimate apple blossom in Germany. The comparison included a phenological model that assumes chilling is completed by 1 January and estimates blossom time based on a temperature forcing rate function, a slightly more complex model that assumes forcing temperatures are not effective until chilling is met and estimates both chilling rates and a forcing rate function, two 'parallel' models that assume chilling and forcing can occur simultaneously but differ in terms of how the chilling and forcing rates are calculated, and a simple statistical model employing mean temperatures for the period February–April as predictors of apple blossom. All five models were found to satisfactorily simulate the beginning of apple blossom for a wide range of apple cultivars, although the error was smallest for the combined chilling–forcing models. Furthermore, all five models performed well even though daily, rather than hourly, temperature series were used as model input. These findings suggest that at least some phenological models can be employed to estimate the beginning of blossom for multiple cultivars and geographic regions, although further evaluation for a larger number of crops and locations is needed. Recently developed phenological models that incorporate day length, in addition to chilling and heat accumulation (Blümel and Chmielewski 2012), appear to perform well in different geographic regions and have utility for climate assessments (Matzneller et al. 2012, manuscript submitted to *Agric. Forest Meteorol.*).

2.04.4.4 Empirical Yield Models for Perennial Crops

As previously noted, few process-based yield models exist for perennial crops. One exception is the CropSyst modeling system, a relatively simple generic (i.e., multi-crop) daily time step simulation model that includes an orchard–vineyard module (Stöckle et al. 2010). As noted by the developers, the extension of CropSyst to perennial crops is still in its early stages, and its performance across a wide range of perennial crops and locations remains largely untested. Empirical methods continue to be the primary approach for estimating yield for perennial crops, although the resulting models are specific to an individual location and crop type (or even cultivar). The development of empirical yield models has proven to be a demanding, often frustrating, undertaking. Two recent papers, describing the development of state-level (Lobell et al. 2006) and county-level (Lobell and Field 2011) empirical yield models for perennial crops in California, highlight the many challenges in empirical yield model construction. Yield models were developed at two very different spatial scales, since, as pointed out by Lobell and Field (2011), the spatial scale (e.g., station, county, state) for model development is not intuitive, and is often dictated by the availability and spatial coverage of weather, production, and yield measurements rather than by theoretical and statistical considerations. An advantage of the county-level models is the greater range of values for the predictor variables (monthly temperature and precipitation for the California models), whereas an advantage of the state-level models is that they are not as susceptible to omitted variable bias compared to the county-level models, where variations between counties may be a function of other factors (e.g., soil) besides climate (Lobell and Field 2011). Another challenge is that the explained variance of the empirical yield models is often very modest. In fact, Lobell and Field (2011) found that the county-level empirical relationships were significant for only 8 (almonds, wine grapes, strawberries, hay, walnuts, table grapes, freestone peaches, and cherries) out of the 20 perennial crops for which models were developed. Even for these eight crops, the explained variance when the models were applied to a test period hovered only around 20%. One reason for the low explained variance is that mean values of temperature and precipitation, which are commonly used predictors, are not sufficiently capturing the physical processes contributing to yield variations. Furthermore, the spatial aggregation masks considerable spatial variability in climate conditions and in the quality of orchard and vineyard sites. The choice of spatial aggregation level can also result in different interpretations of the impacts of climate on yield. Lobell and Field (2011) found, for instance, that the county-level model for almonds suggested a small beneficial effect of warming temperatures on yield, whereas the state-level model suggested a negative effect. These differences led Lobell and Field (2011) to argue for greater effort to verify the signs of model coefficients, including surveying growers to obtain their input on the importance (and direction) of weather variables on yield.

Empirical yield models have numerous additional constraints – management practices are usually considered constant, temporal trends in yield due to improved technology need to be removed, CO_2 fertilization is rarely included, linking statistical relationships to physical processes is difficult, and, like all empirical models, the validity of the yield models is questionable outside the range of the data used in the model development (Lobell and Field 2011). This latter issue is of particular concern for climate studies, as the range of values of the predictor variables, particularly maximum and minimum temperature, could shift in the future.

2.04.4.5 Field and Greenhouse Experiments

In addition to the empirical and modeling approaches described above, a limited number of field and/or greenhouse experiments have been conducted for perennial crops, particularly to investigate the impacts of changes in carbon dioxide (CO_2) concentrations on crop growth and development. For example, Idso et al. (1991) exposed sour orange trees to elevated CO_2 concentrations to investigate changes in photosynthesis rate, whereas Allen and Vu (2009) considered the impact of CO_2 enrichment on leaf and root development for sweet orange trees.

2.04.5 Perennial Crop Production and Historical Climate Variability

Synthesis of the numerous studies that have investigated the impacts of historical climate on perennial crops is challenging as differences are expected by geographic region and crop type. Most analyses of the influence of historical climate variability focused on the timing of phenological stages, and, in general, these studies found that crop growth has advanced earlier in the year. For example, an increase of 0.06 °C per annum in average springtime temperatures appears to be associated with an earlier and shorter period between budburst, flowering, and harvest of wine grapes in France (Duchéne and Schneider 2005). Similar results were found by Jones and Davis (2000), who observed a shortening of growth intervals and lengthening of growing season for wine grapes.

Additionally, warming trends in Japan appear to have contributed to an advancement in phenology for apple and cherry trees (Fujisawa and Kobayashi 2010; Primack et al. 2009) and to earlier flowering dates for apricots (Doi 2007). Similarly, earlier flowering times for apples and pears in France have been observed (Atauri et al. 2010). Noticeable advances in leaf unfolding, flowering, and fruiting have been observed in recent decades for fruit trees in the western Mediterranean, which have been accompanied by an increase of over 2 weeks in the length of the growing season and less spatial variability in the timing of phenological stages (Gordo and Sanz 2009). Advanced timing of springtime phenophases for apple and sweet cherry trees in Germany is correlated with an earlier beginning of the growing season (Chmielewski et al. 2004), while cherry trees in Switzerland have displayed an earlier appearance of springtime phenological phases, and although less pronounced, later phases in autumn (Defila and Clot 2001). Warming trends were also associated with observed advances in spring phenology ranging from 2 to 8 days for the period 1965–2001 for apples and grapes in the Northeastern United States (Wolfe et al. 2005). As a consequence of warming, suitable climate conditions for apple production have moved inland and northward in Finland, as the risk of extreme low temperatures decreased from ∼1980 to 2000 (Kaukoranta et al. 2010). Several studies indicate that damage accruing from spring frost is decreasing. For example, there has been a general reduction in the risk of spring frost in recent decades for apples in Trentino, Italy (Eccel et al. 2009). In the western United States, both late spring and early fall freeze events are becoming less common, and the area is now more conducive to the ripening of wine grapes (Jones 2005).

Negative consequences of observed warming have also been reported. All major wine grape growing regions across the world have experienced warming during the growing season, but 12 out of the 27 regions experienced a decline in production associated with optimum growing season temperatures above vintage ratings (Jones et al. 2005). Ramos et al. (2008) reported that a warming of 1.0–2.2 °C during the growing season led to an increase in heat accumulation for wine grapes in Spain and resulted in a 6–14% increase in water demand.

Winter damage is another factor that may affect the productivity of perennial trees. Studies of grapes, peach, apricot, sweet cherry, pear, and apples in the Okanagan Valley of British Columbia reveal that poor fruit production was due to winter freeze events caused by more frequent Arctic airflow in November–December than in the past (Quamme et al. 2010; Caprio and Quamme 1999, 2006). Modeling experiments conducted by Marshall et al. (2003, 2004) suggest that land use change might have exacerbated freeze risk in the citrus production regions of south Florida, as minimum temperatures were warmer, and below freezing temperatures persisted for a shorter period, for the model simulations that employed pre-1900s land cover compared to those with near present day land cover.

Analyses of the impact of historical climate trends on the break of dormancy for grapes, kiwi, peach, and sweet cherry in California indicate that most locations experienced a significant negative trend in winter chill hours (Baldocchi and Wong 2006). In a later study, trends in winter chill in the Central Valley of California for fruits and nuts were observed to range between −50 and −260 chilling hours per decade (Baldocchi and Wong 2008). Hennessy and Clayton-Greene (1995) analyzed a number of high-chill fruits in Australia (e.g., plum, apple, pear, cherry, peach, and apricot) and demonstrated that warming causes greater reduction in chilling at sites with a higher mean temperature and a wider diurnal temperature range.

Although not as widely studied, precipitation variability also plays a role in the productivity of perennial fruit trees. For example, a slight decrease in precipitation during the bloom to veraison period resulted in plant water stress in a study involving wine grapes in Spain (Ramos et al. 2008). In contrast, Zavalloni et al. (2008) found that the amount of precipitation preceding the end of the previous growing season helped to explain historical yield variations of sour cherries in Michigan (USA).

2.04.6 CO_2 Fertilization

A modest number of studies have investigated the potential impacts of CO_2 enrichment on crop growth and development. In a relatively early study, photosynthesis rates were found to increase when sour orange trees were exposed to elevated CO_2 concentrations (Idso et al. 1991). More recently, Allen and Vu (2009) found that young sweet orange trees grown in greenhouses displayed increased photosynthetic rates, but decreased leaf development and fine root biomass, with elevated CO_2 concentrations. A 2-year FACE (Free Air CO_2 Enrichment) experiment for wine grapes suggested that elevated CO_2 concentrations have an early season effect on fruit dry weight and concentrations of tartaric acid and total sugar, but by the time the grapes reach maturity there was little evidence of any impact of CO_2 fertilization on grape quality (Bindi et al. 2001). In terms of yield, a 3-year open top chamber study found grape yields increased under elevated CO_2 concentrations in the Mediterranean (Moutinho-Pereira et al. 2009). These short-term experiments suggest a complex relationship between CO_2 fertilization and perennial crop growth and development, although the impacts of CO_2 fertilization over the entire lifetime of an orchard are still largely unknown. Furthermore, differences in the impacts of CO_2 fertilization by species and cultivar are not well documented.

2.04.7 Potential Impacts of Climate Change on Perennial Crops

In addition to CO_2 fertilization, future changes in temperature, precipitation, humidity, wind, thunderstorm and hail frequency, and other climate variables could have a substantial impact on perennial crop production. The majority of studies that have investigated potential future impacts for perennial crops have applied a 'feed-forward' assessment strategy, as illustrated in Figure 4. Commonly, climate scenarios (also referred to as climate projections) were substituted in place of observations as input to chill, phenology, and yield models or to calculate heat accumulation, agro-climatic indices, water budgets, or pest and disease frequency. A climate scenario is simply an internally, consistent, and plausible future state (Carter et al. 1996). A climate scenario should be carefully distinguished from a 'prediction' or 'forecast,' as it involves numerous assumptions that may or may not be realized (Mearns et al. 2001). Furthermore, climate scenarios only provide a subset of possible future climate conditions (Jones 2000). For the most part, the climate scenarios that have been used for climate assessments of perennial crops were obtained by 'downscaling' coarse-scale output from global climate models to the local or regional scale. In the discussion below,

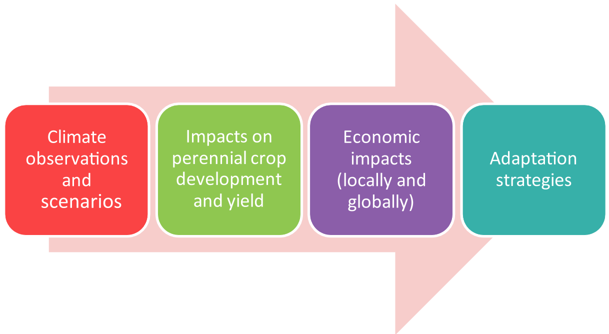

Figure 4 An idealized feed-forward approach to the investigation of plausible impacts of climate on perennial crops. The vast majority of previous impact assessments have included only the first two steps shown in the figure. Potential economic impacts and adaptation strategies are infrequently addressed and represent a substantial gap in the understanding of climate impacts on perennial crops.

we focus on potential future impacts on perennial crop development and yield. Ideally, a feed-forward approach also includes an evaluation of potential economic impacts and adaptation strategies (the third and fourth steps shown in Figure 4), although only a few previous studies of climate change impacts on perennial crops have included an economic component and little research has been conducted on future adaptation options.

Some perennial crops, including apples, could cope better with cold winter temperatures if warmer temperatures linger later into the autumn (Rochette et al. 2004) and the frequency of extreme cold events decreases (Baraer et al. 2010). Consequently, since bud hardening is in part a function of a photoperiod, cold temperatures might not occur until after trees and vines are sufficiently protected by fall hardening (Rochette et al. 2004; Jones 2005). However, despite such an increase in cold hardiness, the risk of winterkill could increase, as suggested by impact analyses for various tree fruits and grapes in eastern Canada (Rochette et al. 2004) and apple production in Finland (Kaukoranta et al. 2010). If there are greater fluctuations in winter temperatures, warm spells might cause a break in dormancy and leave trees at a higher risk of damage by subsequent extreme cold temperatures.

Chilling hours would be reduced with warmer winters, and chilling requirements might not be met as quickly as they have been in the past. Fulfillment of chilling hour requirements has been identified as a potential problem for grape production in Australia (Webb et al. 2007), apple production in Britain (Cannell and Smith 1986), and the production of various fruits in southern Australia (Hennessy and Clayton-Greene 1995) and the Central Valley of California (Baldocchi and Wong 2008). However, one of the greatest concerns for perennial crops is the possibility for warmer temperatures in late winter and early spring. Bud break is strongly related to heat accumulation, and with warmer temperatures in late winter and early spring many fruit and nut trees might reach bud break earlier than they do at present (Cannell and Smith 1986; Rochette et al. 2004; Webb et al. 2007; Kaukoranta et al. 2010; Blümel and Chmielewski 2011). With earlier bud break and flowering, tree fruit may have an increased risk of frost damage as is suggested by analyses of apple production in Finland (Kaukoranta et al. 2010), and apple, pear, peach, apricot, sweet cherry, plum, and grape production in eastern Canada (Rochette et al. 2004). Others have suggested that plants may physiologically acclimate to a warmer climate and thus reduce the plant's risk of frost damage (Eccel et al. 2009).

Higher temperatures during the warmest part of the growing season also might have substantial impacts on perennial crop production. Impact studies investigating grape and wine production in the western United States (Jones 2005), Italy (Bindi et al. 1996), and across the globe (Jones et al. 2005) suggest that temperatures could become too warm for optimal fruit growth or that wine quality may be affected. Warmer temperatures have also been found to speed the phenology of perennial crops, sometimes resulting in earlier harvest dates (Webb et al. 2007).

Regional variations in potential climate impacts also occur and will continue. For example, warmer temperatures could, depending on location and current conditions, negatively or positively impact wine quality (Jones et al. 2005). In more northerly production areas, citrus crops might benefit from warmer temperatures in winter because the risk of frost decreases, but more southerly production areas may see a decrease in productivity due to temperatures that are warmer than optimal (Rosenzweig et al. 1996; Tubiello et al. 2002). Additionally, if the spatial patterns of temperature and precipitation change, it is possible that the distribution of the varieties that are grown would shift; several authors have already indicated that this is a distinct possibility for wine grape production in some regions (Kenny and Harrison 1992; Hall and Jones 2008).

A limited number of studies have investigated the sensitivity of future changes in yield to climatic conditions. Increased temperatures might increase wine production in Portugal, although decreases in rainfall may limit production in some regions (Gouveia et al. 2011; Santos et al. 2011). Some locations may be relatively insensitive to changes in local and regional climatic conditions with only very small changes in yield, as is suggested by an analysis of the productivity of grapes, oranges, and avocados in California (Lobell et al. 2006). Similarly, an assessment conducted by Stöckle et al. (2010) suggests that apple production in eastern Washington might only decrease slightly with perturbed climatic conditions.

Warmer temperatures might also have indirect impacts on perennial crop production in the form of diseases and pests. With longer and warmer growing seasons, it is possible that the number of insect generations during a given season would increase and that the timing of insect infestations might differ significantly from what they are presently, as suggested for apple codling moth in the Great Lakes region of North American (Winkler et al. 2002). An increase in wet weather during the blooming period might reduce the effectiveness of pollination in plants and also cause increased problems with bacterial and fungal diseases (Ladányi et al. 2010).

2.04.8 Adaptation Options

Climate significantly influences perennial crop development, quality, and yield, and this clearly points to the need to consider options for adapting to a spectrum of future climate conditions. Numerous options have been proposed for adapting to climate-related risk. For example, low chill cultivars and dormancy-breaking chemicals are two possible adaptation options for areas where chilling requirements may not be met in the future (Luedeling et al. 2009). Cold-resistant cultivars and frost protection (e.g., sprinklers) are potential adaptation strategies where springtime freeze hazard may increase, and breeding for heat resistance cultivars is one strategy for locations where warmer temperatures might occur during the growing season. Irrigation may be a feasible adaptation strategy for some areas where water stress increases, and hail nets are options if thunderstorms frequency increase (Figure 5). More generically, management practices that influence an orchard's microclimate (e.g., planting density and pruning; Luedeling et al. 2009) can help adapt to a number of climate-related risks. A more extreme adaptation option is a switch in land use, either to another crop type or to a nonagricultural use. Although most of the studies that we reviewed acknowledged

Figure 5 Example adaptation options for perennial crops. Upper left: An irrigated sour cherry orchard in Hungary. Upper right: Workers installing supports for hail nets in a sour cherry orchard in Hungary. Lower left: Hungarian orchard with both irrigation and supports for hail nets. Lower right: Deployed hail nets in a sweet cherry orchard at Cornell University (USA). Photo credit: Dr. Geza Bujdosó, Research Institute for Fruit Growing and Ornamentals, Budapest, Hungary.

that adaptation options need to be considered, none systematically evaluated the feasibility and economic consequences of alternative adaptation options. In other words, previous research on future perennial crop production has stopped well short of a formal adaptation assessment.

2.04.9 Next Steps

The majority of the research discussed above focused on a location or a region. Recently, Winkler et al. (2010) highlighted the need for assessment strategies for international market systems that go beyond the local–regional focus of traditional climate assessments but that incorporate more detail than the broad, but often overly simplistic, approach of many cross-sectoral integrated assessments (e.g., Nordhaus 1994). Using the international sour cherry industry as an example, Winkler et al. (2010) called for an 'expanded impact assessment' that treats perennial crop systems as an international rather than local industry and that considers variations in climate-related risk between production regions. They further argued that temporal dynamics need to be included in the assessment process including changes in patterns of international trade, consumption, and production along with evolving adaptation strategies by industry stakeholder groups. To do this requires advances in crop modeling, preferably the development of process models that can be applied to multiple species and cultivars, improved availability and international exchange of climate and phenological observations for model development, the modification of currently available trade models for use in climate applications, improved models of individual decision making, and methods for evaluating adaptation options. Additionally, strategies need to be improved for communicating the 'meta-uncertainty' (Winkler et al. 2010) of the assessment outcomes to industry stakeholders. All these present considerable challenges but challenges that are more likely to be addressed with greater involvement of industry stakeholders throughout the assessment process.

2.04.10 Summary

Climate-related risk is large for perennial crops given their exposure to fluctuating weather conditions throughout the year. Key vulnerabilities include the fulfillment of winter chill requirements, springtime freeze risk, climate-related constraints on pollination, heat stress, and disease and insect pest pressure. A myriad of methods have been employed to evaluate the past and future climate vulnerability of perennial crops. Temporal and spatial changes in the frequency and timing of critical thresholds and heat accumulation have been particularly popular approaches to assessing past trends and potential future risk. Agro-climatic indices have been widely applied to evaluate the spatial distribution of suitable production regions. Modeling efforts remain largely empirical, although quasimechanistic phenological models exist in addition to empirical models. Impact assessments for perennial crops are handicapped by the lack of process-based crop development and yield models.

Analyses of the influence of historical climate variability on perennial crops, while varying by crop type and location, suggest earlier dates of bloom and other phenological stages and, for some locations, a reduction in spring and early fall freeze risk. Fruit quality appears to have suffered in some growing regions, and winter injury has increased in high latitude growing regions. Additionally, a negative trend in chilling hours has been observed for a number of species and production regions. Plausible future impacts under a warmer climate include fewer chilling hours, earlier bud break and bloom, changes in fruit quality as temperatures surpass crop-specific optimal temperatures, and reduced frequency of winter, but not necessarily springtime, cold temperature damage. Several analyses suggest that pest and disease risk could increase in the future, with an increase in the number of insect generations per season and the frequency of bacterial and fungal diseases.

Climate assessments for perennial crops need to move beyond the local and regional scales, and recognize that perennial crops constitute an international market system with multiple production regions with varying climate-related risk and that market systems respond to changes in demand, as well as changes in supply. Additionally, grower decision making and adaptation options need to be more formally addressed. Climate assessments for perennial crops will benefit from greater stakeholder input.

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Confronting Climate Change: A South African Fruit & Wine Initiative: http://www.climatefruitandwine.co.za/.
GPM (Global Phenological Monitoring): http://gpm.hu-berlin.de/.
Oregon Climate Change Research Institute: http://occri.net/climate-science.
Pileus Project website: http://www.pileus.msu.edu/.