DEVELOPING A GRAPE SITE SELECTION GIS FOR THE INLAND PACIFIC NORTHWEST

By

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To the Faculty of Washington State University:

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Abstract

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Site selection is of the utmost importance in production of *Vitis vinifera* L. (wine grape) and *Vitis labruscana* Bailey (juice grape). Grape production is a large and expanding industry in the inland Pacific Northwest of the United States. Traditional means of site assessment rely on physical examination of topography, geomorphology, soil characteristics and analysis of long-term observations from weather stations. Through the use of modeled spatial data, this document presents a geographic information system representing environmental features important for predicting vineyard site suitability. Elevation, slope, aspect, solar insolation, heat accumulation, growing season length, soil drainage, available water-holding capacity, depth, pH, calcium carbonate content combine to represent composite topographic, edaphic and overall suitability. Modeled site suitabilities align well with descriptions of existing viticultural areas within the region as well as with perceptions of growers in established vineyards. Comprehensive spatial analysis provides a holistic view of viticultural areas, revealing conditions previously unseen through traditional site examination. Extracted climatic characteristics from vineyards mapped by cultivar begin to inform requirements for premium *V. vinifera* production based on indices developed in other wine regions. Continued validation efforts are underway and will additionally

inform and improve the site selection model. Although this type of spatial analysis will never replace physical site examination for addressing specific site conditions, it allows efficient, spatially extensive, initial assessment of viticultural areas that can focus attention on potentially the most problematic or distinguishing environmental characteristics of a site. This is a valuable database that will help expand and explore the potential of a world-class grape producing region.

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ABBREVIATIONS

AEX	Aerials Express
ATF	Bureau of Alcohol, Tobacco and Firearms
AVA	American Viticultural Area
AWC	Available water-holding capacity
BEDD	Biologically effective degree-days
BLM	Bureau of Land Management
CDL	Cropland Data Layer
DEM	Digital elevation model
ECAD	European Climate Assessment & Dataset
ED	Excessively drained
FFD	Frost-free days
FSA	Farm Service Agency
GCS	Geographic coordinate system
GDD	Growing degree-days
GIS	Geographic information system
GPS	Global positioning system
GSFC	Goddard Space Flight Center
HARN	High Accuracy Reference Network
IAGT	Institute for the Application of Geospatial Technology
IPNW	Inland Pacific Northwest
IUPAC	International Union of Pure and Applied Chemistry
LTI	Latitude-temperature index

MWD	Moderately well drained
MTWM	Mean temperature of the warmest month
NAD	North American Datum
NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NAVD	North American Vertical Datum
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NRCS	Natural Resources Conservation Service
OIV	L'Organisation Internationale de la Vigne et du Vin (International Organization of Vine and Wine)
OK	Ordinary kriging
PAWS	Public Agricultural Weather System
PD	Poorly drained
PLSS	Public Land Survey System
PRISM	Parameter-elevation Regressions on Independent Slopes Model
SED	Somewhat excessively drained
SPD	Somewhat poorly drained
SRS	Statistical Reporting Service
SSURGO	Soil Survey Geographic
TTB	Alcohol and Tobacco Tax and Trade Bureau
UK	Universal kriging
USDA	United States Department of Agriculture

USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VPD	Very poorly drained
WD	Well drained
WGS	World Geodetic System
WRCC	Western Regional Climate Center
WSDA	Washington State Department of Agriculture
y.b.p.	Years before present
ZAMG	Zentralanstalt für Meteorologie und Geodynamik (Central Institute for Meteorology and Geodynamics [Austria])

Dedication

This thesis is dedicated to my mother and father,

蔡瑞華 和 姚德霖

who taught me the value of knowledge

and drive my love of learning.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

The early history of the Washington grape industry began in western Washington with the first planting of European wine grape (*Vitis vinifera* L.) vines by the Hudson's Bay Company at Fort Vancouver in 1825 and the first bonded winery on Stretch Island in southern Puget Sound in 1933 (Peterson-Nedry, 2000). Eastern Washington presently dominates grape production. Sparks of the Washington wine grape industry ignited in the mid-nineteenth century with *V. vinifera* plantings primarily in the Walla Walla and Yakima Valleys, predominately by European immigrants including French fur trappers and traders, German homesteaders and Italian bakers. However, a severe winter in 1883 caused the young wine industry to falter while California's wine industry began to mature (Peterson-Nedry, 2000).

Much of the growth of the grape industry in Washington in the mid-twentieth century came through plantings of the American grape, *Vitis labruscana* Bailey. These grapes are utilized most notably for juice production and tolerate harsh winters experienced in eastern Washington better than *V. vinifera* varieties (Jackson and Schuster, 2001; Peterson-Nedry, 2000). The real proliferation of *V. vinifera* vineyards began in the 1970s with accelerated growth in the following decade (Clarke, 1999). In the 1980s, Washington's climate was perceived to promote high acidity in wine grapes and eastern Washington was thought better for white grapes than for red. This dynamic has changed and the state now produces nearly equal quantities of red and white wine grapes with a current trend of increasing red and decreasing white production (Johnson, 2003; USDA-NASS, 2011; Figure 1).

Many growers and researchers have made substantial contributions to the Washington grape industry. Two outstanding researchers were Dr. Walter J. Clore, 'Father of the Washington Wine Industry,' and Dr. Charles W. Nagel. Clore dedicated much of his career proving quality *V.*

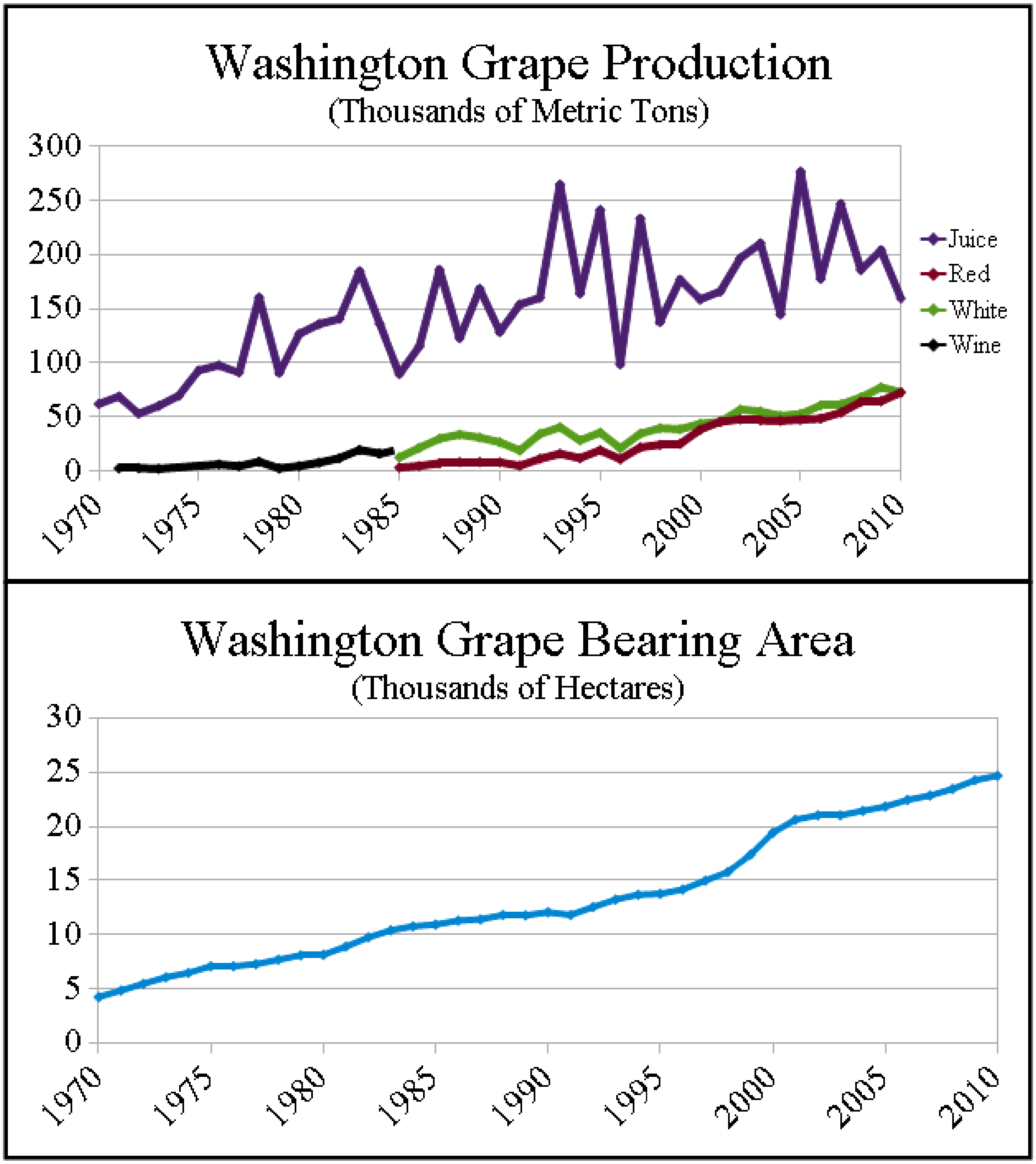


Figure 1: Washington state grape production and bearing area, 1970-2010. Prior to 1985, tonnage by wine grape color were not available (USDA-NASS, 2010a, 2010b, 2011).

vinifera grapes could be grown successfully in eastern Washington, planting over three hundred cultivars by the time he retired from Washington State University in 1976 (Clore et al., 1972; Kaag, 2007). Nagel's work improved wine quality from fruit grown in eastern Washington and introduced trained tasting panels to the region (Kaag, 2007; Nagel et al., 1972). Both researchers' seminal works pioneered the way for the modern inland Pacific Northwest (IPNW) grape industry and must be acknowledged in any discussion on the history of grapes in the region.

Today the state of Washington hosts eleven American Viticultural Areas (AVAs) acknowledged by the Alcohol and Tobacco Tax and Trade Bureau (TTB) on the basis of national or local name recognition, usage and distinguishing features (e.g. climate, geology, soils, physical features and elevation). Ten of these AVAs lie east of the Cascade Mountains and two new AVAs, Ancient Lakes and Naches Heights, are currently under review. Three AVAs, the Columbia Valley, Columbia Gorge and Walla Walla Valley, share some area with Oregon. One more appellation, the Snake River Valley, straddles the border of Oregon and Idaho. These eleven AVAs comprise the major grape growing regions of the IPNW (Figure 2).

The expansive (~4,000,000 ha) Puget Sound AVA is the only Washington appellation found to the west of the Cascade Mountains (Figure 3) and is relatively sparsely planted with grapes (ca. 40 ha, Danehower, 2010). Similarly, the capacious (>2,000,000 ha) Snake River Valley AVA is still a developing region, the eastern portion of which is largely of too great an elevation for successful *V. vinifera* production under current climatic conditions (Gillerman et al., 2006). Therefore, much of this thesis will focus on eastern Washington state grape production.

Washington state now leads the nation in juice grape production, surpassing New York state in 1976, and is second only to California in terms of wine grape production. Juice grape production is predominately of the Concord variety (USDA-SRS, 1977; USDA-NASS, 2011).

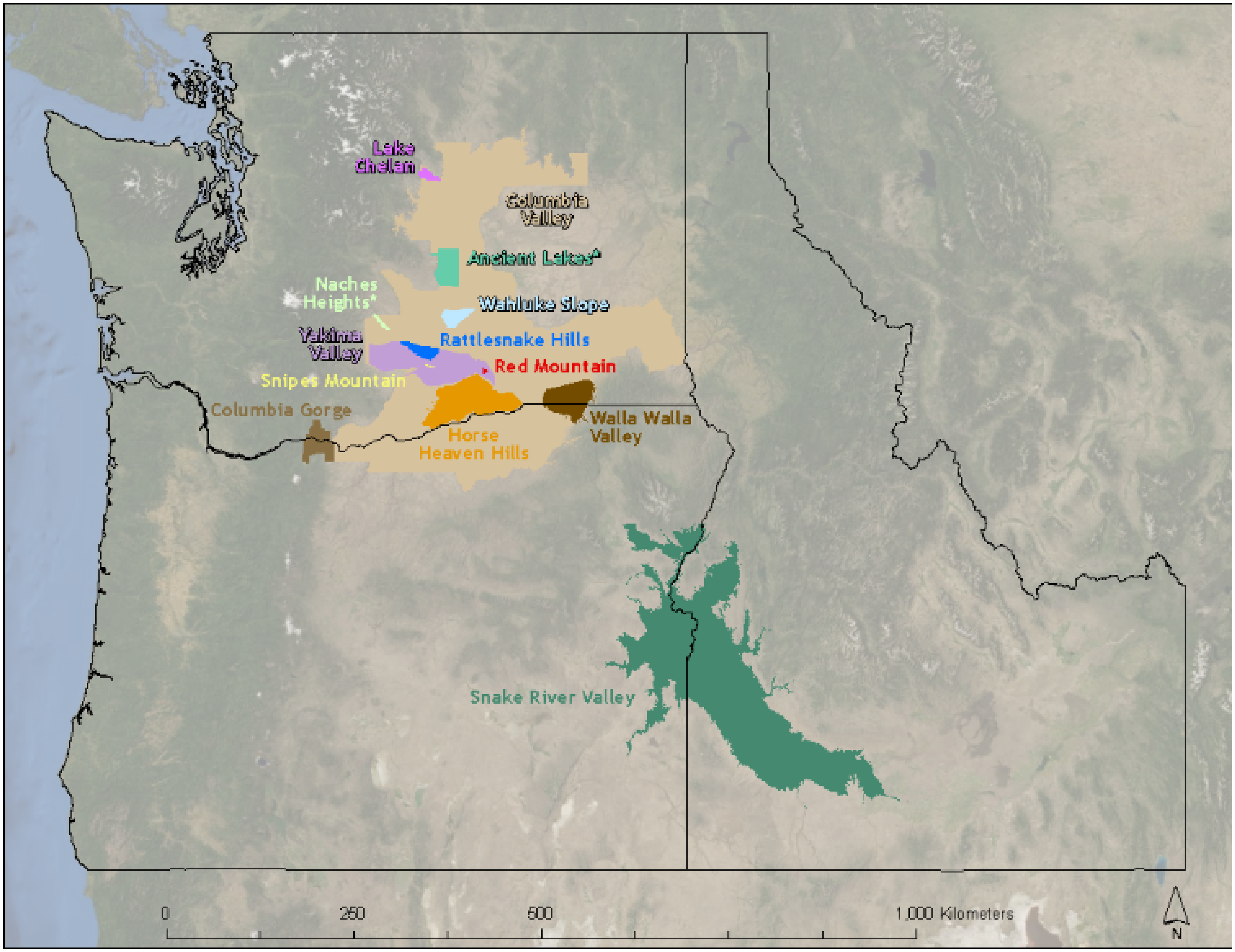


Figure 2: American Viticultural Areas of the inland Pacific Northwest. An asterisk denotes appellations under review as of 1 June 2011.

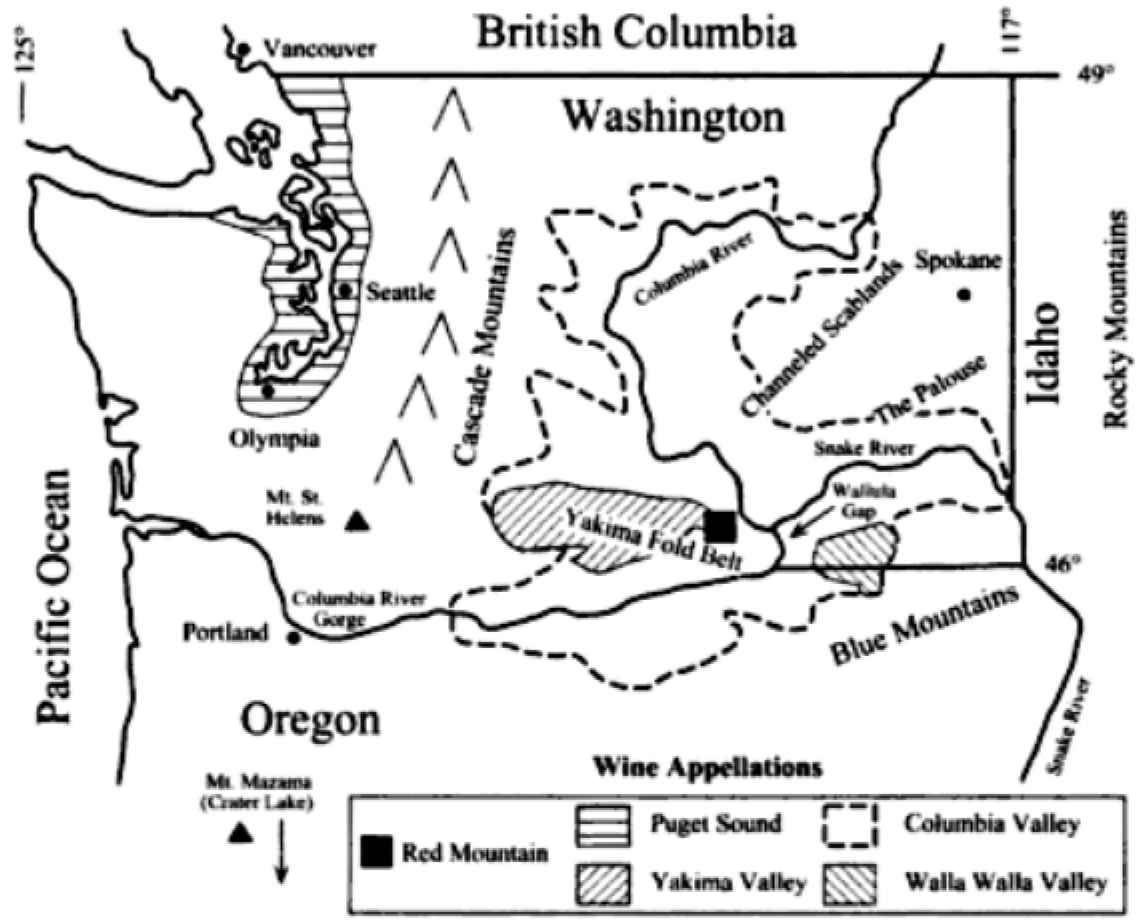


Figure 3: Location map of the Pacific Northwest showing five American Viticultural Areass of Washington and Oregon states and major geographic features. From Busacca and Meinart (2003)

New plantings continue to expand grape production in the IPNW; bearing area has doubled in the last twenty years to nearly 25,000 ha in 2010 (Figure 1). Demand for wine in the United States appears to be increasing in the face of recovery from the 2008 global recession (OIV, 2011).

The grape industry plays a substantial role in the economy of the IPNW. A study by MKF Research (2007), commissioned by the Washington Association of Wine Grape Growers and Washington Wine Commission, among others, reported the Washington grape industry had a total national economic impact of over $4.7 billion (~$3 billion in Washington state). This includes nearly thirty thousand jobs related to grapes and $850 million in wages nationwide (~$580 million in Washington state). The grape juice industry's impact is primarily through production, processing and retail. The wine grape industry provides economic activity in several additional areas, most notably tourism, winemaking equipment and supplies and federal and state taxes.

The IPNW enjoys a climate and geologic history that makes it a unique region for grape production (Meinert and Busacca, 2002). The rain shadow of the Cascade Mountains creates a climate that contrasts sharply with the notoriously moist conditions found in the Northwest on the west side of the Cascades with most grape growing areas receiving 30 cm of annual precipitation or less (Davenport and Horneck, 2011). The Rocky Mountains shield the region from arctic cold fronts, helping to moderate what are often harsh winters. Orographic lift over the Rocky and Blue Mountains dramatically increase precipitation towards the eastern edge of the region (Meinert and Busacca, 2002).

High solar insolation, relatively little cloud cover during the growing season and long day length combine with low relative humidity and large diurnal temperature ranges make the region capable of ripening a diversity of cultivars. Northern portions of the IPNW receive approximately two more hours of summer sunlight than occurs in California grape producing regions (Meinert and Busacca, 2000). The aridity of the region benefits grape production through lowered disease risk, quickly cooling summer nighttime temperatures and a means of managing the vigor of *V. vinifera*. However, it does make irrigation obligatory. Massive irrigation projects along the Columbia, Snake and Yakima Rivers provide plentiful, relatively inexpensive water in a grape producing area that does not legally restrict irrigation practices allowing growers a high level of control over vine growth throughout the season (Jackson and Schuster, 2001).

The geologic history of the region is truly unparalleled. During the early Miocene, between seventeen to fifteen million years before present (y.b.p.), multiple eruptions from north-south fissures roughly paralleling the present-day Washington-Idaho border covered approximately 165,000 km^2, an area now known as the Columbia River Basalt Group. These are the largest documented lava flows in the planet with individual eruptive volumes estimated at 3,000 km^3 or more (Meinert and Busacca, 2000; Figure 4).

More recently and just as spectacularly, the Missoula Floods deposited much of the substrate that supports the IPNW grape industry. Approximately twelve to eighteen thousand y.b.p., during the Last Glacial Maximum, a lobe of the Cordilleran Ice Sheet periodically dammed the Clark Fork River in northern Idaho creating glacial Lake Missoula which covered 7,800 km^2 of western Montana. The ice dam repeatedly failed and rebuilt, unleashing up to 2,500 km^3 of water across the Columbia Plateau with each breach (Smyers and Breckenridge, 2003). These catastrophic floods formed what is known today as the Channeled Scablands. The torrential waters were constricted at Wallula Gap before continuing through the Columbia River Gorge en route to the Pacific Ocean. This led to backflooding and deposition of slackwater sediments that form distinct layers between each successive flood's deposition. These sediments were eroded by the prevailing southwesterly winds and redeposited to form deep loess on the Columbia Plateau (Busacca and Meinert, 2003). A large dust storm swept through portions of eastern Washington on 4 October 2009, offering a glimpse of eolian soil formation processes that took place over recent millennia (Figure 5). Exposures of some of the world's largest and most spectacular flood basalts, dune and loess fields, glacial outburst flood deposits, ice rafted erratic boulders and recent volcanic activity (Mt. St. Helens, 1980; Mt. Mazama, 6,860 y.b.p.) make the

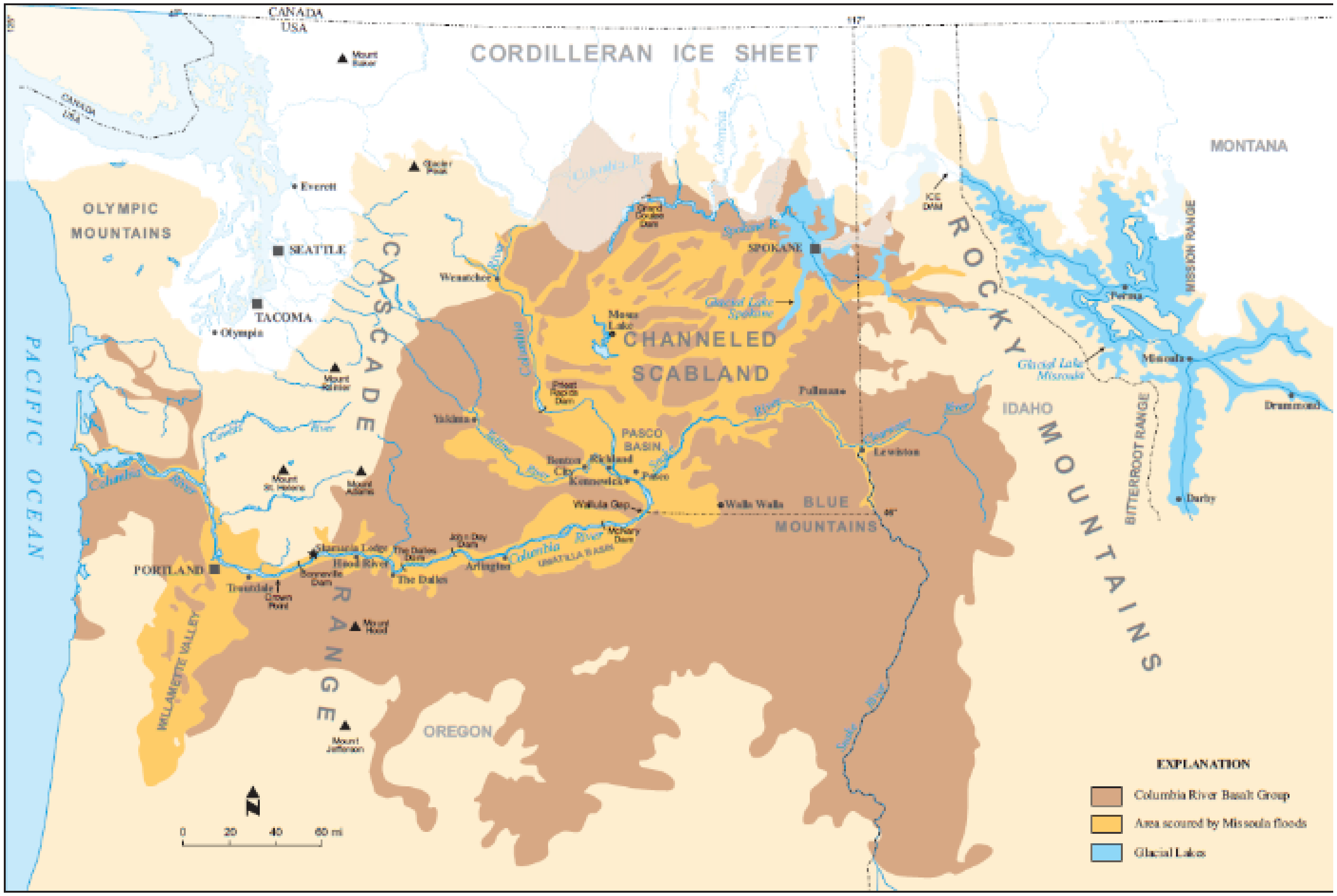


Figure 4: Columbia Plateau and surrounding area, showing the probable extent of the Cordilleran ice sheet, ice-dammed glacial lakes, Missoula floods, and Columbia River Basalt Group. The failure of the ice dam of the Clark Fork River in western Montana released a 600 m wall of water that rushed across eastern Washington repeatedly, eroding a series of intertwining canyons called coulees. This area is known as the Channeled Scabland. The various flood pathways converged in the Pasco Basin, where there was a narrow exit for the waters—Wallula Gap. The narrowness of the gap caused the floodwaters to back up and form a 365 m deep lake covering over 9000 square kilometers. Several other temporary lakes were created by similar events near The Dalles and Portland, Oregon. From Norman et al. (2004)

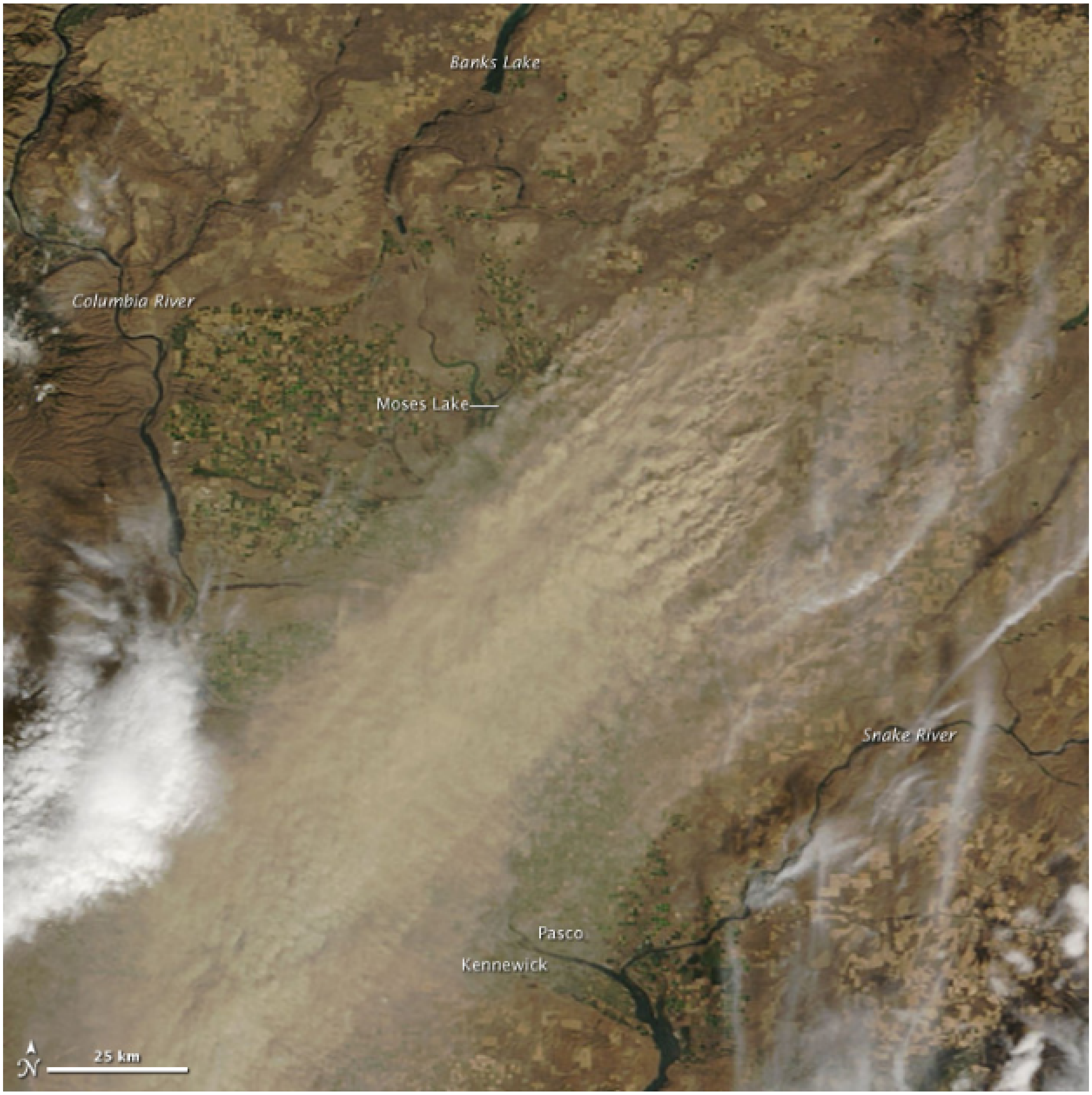


Figure 5: Extensive dust storms on 4 October 2009. Image courtesy of NASA/GSFC, Modis Rapid Response

IPNW unique in its grape production (Meinert and Busacca, 2000, 2002; Smyers and Breckenridge, 2003; Figure 4).

The Snake River Valley AVA was also subjected to prehistoric flooding. The boundary of the appellation is roughly the delineation of prehistoric Lake Idaho, a series of lakes, floodplains and wetlands contained within the rift basin of the western Snake River Plain and structural downwarp of the eastern Snake River Plain. Lake Idaho slowly drained (ca. four to two million y.b.p.) as a divide near Hells Canyon was overrun. The exposed lake bottom was cut away by the Boise River in a stepwise fashion leaving gravel terraces upon which modern vineyards are planted (Gillerman et al., 2006). More recently (ca. 14,500 y.b.p.), Lake Bonneville, ancestor to modern-day Great Salt Lake, eroded the northern portion of its confinement at Red Rock Pass and surged through the Snake River for six months depositing materials of different sizes as flows varied (Jarrett and Malde, 1987). During stages of high flood discharge, water backed up behind Hells Canyon and fine, slackwater sediments settled. Surficial loess, sand and Bonneville Flood deposits are the primary substrate upon which vineyards now grow (Gillerman et al., 2006; Figure 6).

Perhaps the most unique feature of grape production in the IPNW is the lack of problematic populations of grape phylloxera (*Daktulosphaira vitifoliae* Fitch), the root louse that devastated European vineyards in the late nineteenth century. *D. vitifoliae* feed on roots and leaves of susceptible grapevines eventually girdling roots and killing the vines (Watson et al., 1990). In much of the grape producing world, *V. vinifera* scions must be grafted onto resistant rootstock in order to produce quality wine (Jackson and Schuster, 2001). Although the absence of dangerous numbers of *D. vitifoliae* is not well understood, the advantage bestowed upon growers is enormous. Not relying on phylloxera resistant rootstock, most grapes are planted with their own roots, avoiding the expense of grafting and allowing retraining without grafting following catastrophic damage to the vine (Olmstead and Keller, 2007).

1.1.1 Importance of site selection

The selection of a site is probably the single most influential decision determining the

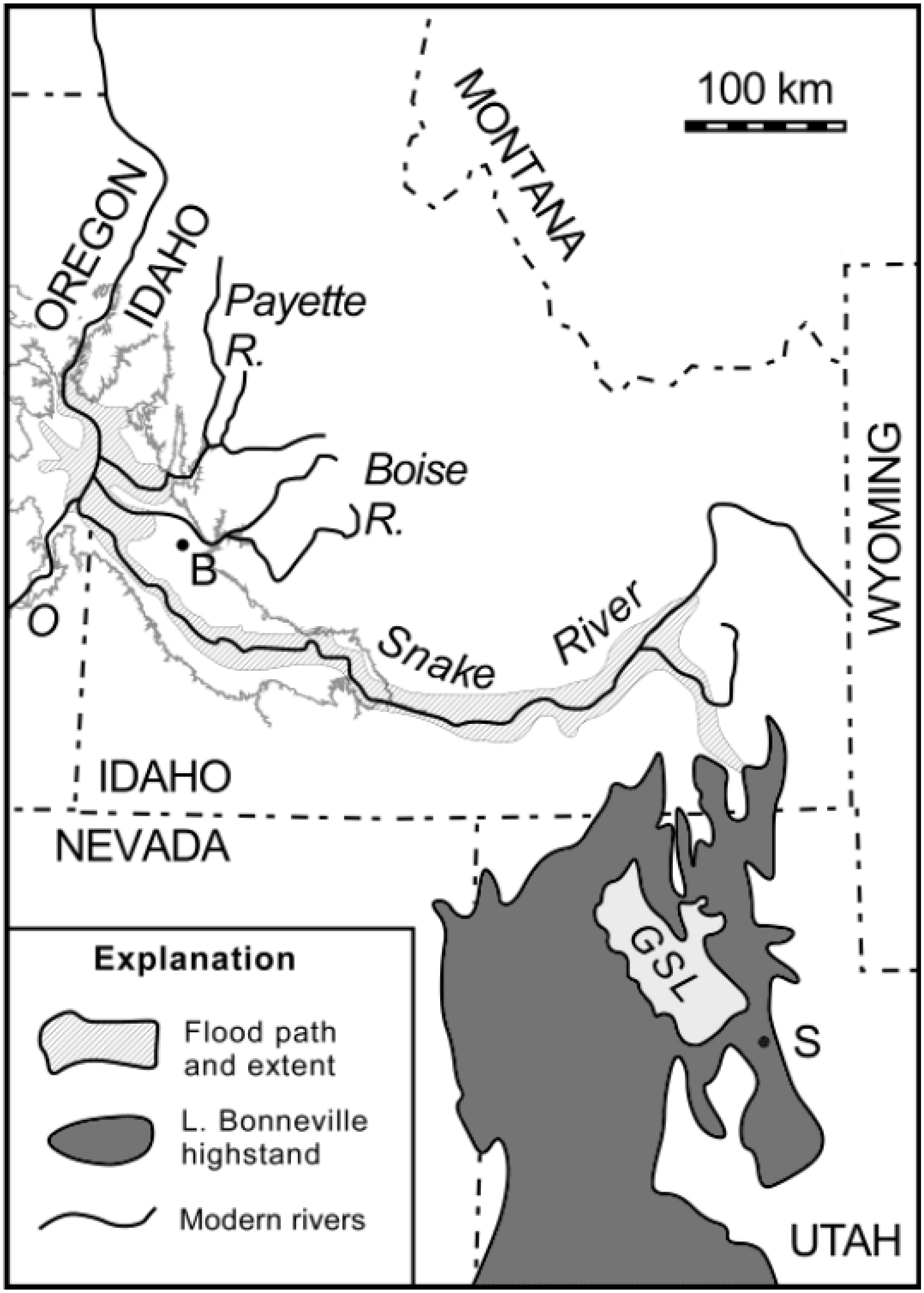


Figure 6: Regional map of the Snake River Plain showing modern river drainages and outline of Pleistocene Lake Bonneville with its associated outburst flood (flood path and extent). Abbreviations: O (Owyhee River), B (Boise), S (Salt Lake City), GSL (modern Great Salt Lake), H (Hells Canyon). Modified from Gillerman et al. (2006)

ultimate success or failure of a vineyard (Smith, 2002). This statement is not intended to marginalize other decisions and costs necessary during foundation and ongoing management of a vineyard (e.g., choice of viticulturist(s), partnership with enologist(s) for wine grape growers, labor, pest control). The price of land and expense of infrastructure and its installation, most prominently trellises and irrigation, during a period when the vineyard is most economically vulnerable make site selection the critical decision determining both initial success and longevity of a vineyard (Ball et al., 2004; Klonsky and De Moura, 2009; Seavert et al., 2007).

A relatively narrow range of environmental conditions, specifically climatic conditions, are conducive to prosperous production of specific grape varieties. Therefore, site selection and matching appropriate grape species and cultivars to the site are much more important than in other crops (Smith, 2002). It is rare to find a site that is ideal in all facets of consideration; site selection is about compromises and understanding the canvas upon which the work begins. Nearly all specific factors given serious consideration have complex interactions with one or more other factors. In this sense, site selection modeling over an extensive area can be seen as a rating of site suitability with many areas falling within a general continuum of suitability from which growers can identify specific, desirable factors. Finding a site with the right mesoclimate (vineyard scale climate) within the larger, regional macroclimate is integral for perennial vineyard performance. A good site ought to moderate climatic extremes of a region and consistently produce high-quality crops (Gladstones, 1992; Jackson and Lombard, 1993).

1.1.2 *Terroir*

There is a French concept, originating in Burgundy during the fourteenth century, known as *terroir*. It is claimed by some in its country of origin to be untranslatable, but it relates to the environmental and cultural factors that bestow unique characteristics upon an agricultural product. Most often it refers to wine production, but is also commonly used in regards to coffee (*Coffea arabica* L.) and tea *(Camellia sinensis* (L.) Kuntze). Interestingly, the French consider *terroir* the intersection of the *vigneron*, the 'wine grower,' with the land (Haynes, 1999; Wilson, 2001). The idea of a *vigneron* differs from the New World notion of a viticulturist or grape grower, a distinct entity from the enologist or wine maker. *Terroir* is a relatively recent addition to the New World wine lexicon introduced to mainstream audiences with James E. Wilson's *Terroir: the Role of Geology, Climate and Culture in the Making of French Wines*, published in 1998 (Haynes, 1999).

Perception and reception of the *terroir* concept in the New World has varied tremendously. Moran (cited in Haynes, 1999) of New Zealand claimed the concept is simply a myth designed to inflate land values. Australian wine expert Busby (cited in Hugget, 2006) also levied an accusation of the exploitation of the *terroir* concept when a perceived marketing advantage in correlating a wine with a soil existed. John Michael 'Jake' Hancock (cited in Hugget, 2006), British geologist and scholar of viniculture, criticized one study correlating geology to cognac quality so harshly that he went so far as to say the conclusions drawn went beyond poor science to deliberate fraud. Hancock (cited in Hugget, 2006) also took a shot at not only the concept, but also its country of origin, declaring *terroir* a typical product of base French thinkers combining the obvious notion that the quality of a grape is related to where it is planted with the mystical.

Not all scholars approach *terroir* with such cynical skepticism. Most notably, there have been attempts to elevate geology to the pinnacle of environmental factors contributing to *terroir*. Haynes (1999) discusses areas in France where geologists have correlated legally defined hierarchies of quality with stratigraphy, something *vignerons* have learned through centuries of trial and error in site selection. Haynes (2000) also advocates revision of delineation of Designated Viticultural Areas in Canada, originally based primarily on climate, to a process based primarily on differences in geology. One study attempted to correlate wine origins with geologic and soil chemistry through intensive chemical analysis (Taylor et al., 2002). This study found strontium and rubidium may serve as discriminating elements for wines produced in the Okanogan Valley, BC, but the picture is complicated by disparate soil genesis regimes, glacial till mixing over parent materials and minute contributions of trace elements that may be added during winemaking procedures.

On the other hand, Gladstone and Smart (1994) downplay the role of geology in terroir. They claim it only contributes indirectly through weathering of parent material, geomorphology, selective root penetration of parent materials (chalk, alluvial deposits, etc.) and instead focus on the effects of soil and mesoclimate. Meinert and Busacca (2000, 2002) note the unique geologic history of the IPNW have created disparate *terroirs* within the same general climatic region and in relatively close proximity due to different soil formations, contrasting Aridisols and Entisols found on Red Mountain with Mollisols in the Yakima River floodplain, less than one kilometer outside the Red Mountain appellation boundary. It is also not uncommon to see adjacent vineyard blocks planted to Bordeaux Cabernets, Rhone Syrahs and Mosel Rieslings in the IPNW. Here, the cultural component of *terroir* comes into play. There are no regulations dictating which cultivars may be grown in the region as there are in European viticultural regions (Jackson and Schuster, 2001) and the entrepreneurial, creative spirit of growers in the region drive experimentation with different cultivars and wine styles.

The discipline of viticulture is not enhanced by myopic focus on any single category of physical site characteristics contributing to *terroir* nor dismissal of certain disciplines, sometimes seemingly on the basis of professional bias. Wilson (2001) sees the spread of the concept of *terroir* as a comprehensive, albeit elusive, description of site potential and, as a whole, beneficial in encouraging study and improved understanding of the effects of geology, soil, climate, culture and their interactions on grape quality. Ultimately, there are myriad factors that have all been demonstrated to affect fruit quality and it does not appear there is one or even several specific elements that will guarantee successful grape production. Meinert and Busacca (2000) regard the concept holistically, acknowledging the diverse array of environmental variables influencing grape quality, that no one factor is insignificant and at the same time no one specific factor is transcendent. On top of it all, temporal variability, especially of climatic parameters, makes *terroir* dynamic and fluid.

Madame Bize-Leroy, head of Maison Leroy and co-owner of Domaine de la Romanée-Conti (Grand Cru estate of Burgundy), in a letter to James E. Wilson, states her belief that *terroir* factors are too dynamic, almost alive, to ever pin down. However, she goes on to say her conviction is that the fundamental character of each wine depends on the nature of its subsoil (Haynes, 1999). It is a debate that will continue and this thesis attempts to make a small contribution to the discourse by exploring site characteristics of grape growing regions of the IPNW. Using a geographic information system (GIS) to explore environmental factors that contribute to different senses of *terroir* is superior to acknowledged approaches using only point measurements and allows users to examine differences at various scales depending on resolution and quality of the data and the users' understanding of interactions between the environmental variables considered (Vadour, 2002).

1.1.3 Geographic information systems

A GIS utilizes computer software to store spatial data and related attribute data for the purposes of retrieval, display and analysis to assist decision-making processes. It creates a dynamic map environment which can produce answers to complex, detailed questions (Kennedy, 2009). It is difficult to imagine a dataset that does not contain a spatial component, especially in agriculture. Advances in computational technology, data storage and ever-expanding sources of spatial data make GIS an incredibly powerful, fundamentally intuitive tool for site selection.

Traditional approaches to examining viticultural suitability utilize a finite number of stationary weather station observations, a broad understanding of pedological processes and on-site examination of geomorphology (Gladstones, 1992; Jackson and Schuster, 2001). For sites lacking a nearby weather station with a climatically relevant period of record, additional knowledge of often complex meteorological mechanisms is also necessary. Work examining viticultural areas in the western United States note the spatial diversity of climate patterns within AVAs and the fact that single weather station observations cannot adequately define a growing region (Jones et al., 2010). Site selection with a GIS offers continuous surfaces of relevant data and a more holistic, efficient approach to understanding a viticultural region's capability than traditional approaches. This is particularly true of climatic data which exhibits much greater variability than topographic or edaphic features and functions on a temporal scale difficult for humans to observe even with multiple site visits at different times of the year.

Relatively young grape growing regions, like the IPNW, typically face a trial and error process of finding what works in terms of site and cultivar selection. Initial efforts are often based on work performed in other, established regions (Prescott, 1965). However, imitation can only get a grape growing region so far and cultivar trials like those conducted by Walter Clore are required to unlock a region's potential (Shellie, 2007). Californian cultivar trials began after information from European growing regions proved limited in their utility. Currently, active pursuit of determination of suitable cultivars for the Snake River Valley area is underway, primarily at the University of Idaho Parma Research and Extension Center (43º47'N, 116º57'W, 750 m elevation, Shellie, 2007). Clore's (1972) trials took place at the present-day Washington State University's (originally Washington State College) Irrigated Agriculture Research and Extension Center (originally Irrigation Experiment Station, 46º15'N, 119º44'W, 260 m elevation). A GIS can extrapolate results from such cultivar trials as well as from established, successful vineyards to continue exploration of unplanted areas within a larger region.

It must be stated that understanding sources of spatial data, standards recognized in creation of the datasets, scale, temporal variability and resolution are of the utmost importance in the correct use of a GIS. Many spatial datasets interpolate or extrapolate information from point measurements based on knowledge of physical processes in the real world and subsequent modeling (Daly et al., 2008; Hartkamp et al., 1999; USDA-NRCS, 2011b). While a level of expertise needed to recreate datasets is not necessary to utilize the data, cognizance of assumptions made is critical for appropriate analysis and acknowledgments of limitations in the data. One example is found in soil maps. Soil unit boundaries are displayed in spatial datasets as discrete units, each with their own sets of attributes. These strict delineations do not reflect what one would see on the ground in soil surveying where changes in soil characteristics most often occur along gradients.

This thesis focuses specifically on site selection, but there are many other possible applications of GIS in viticulture. There are obvious uses for precision agriculture, a field which aims to manage land not as implied homogenous blocks, but as areas with spatially and temporally variable climate, soil characteristics, etc., in order to achieve less variability in crops and/or optimize returns on inputs (Bramley, 2001). Intense, gridded soil samples, yield data and color infrared aerial imagery were utilized to guide management decisions for liming, phosphorus and potassium fertilization in corn (*Zea mays* L.) in Central New York (Magri et al., 2005). Similarly, global positioning systems (GPS), yield and crop quality data and interpolations of soil and tissue sampling paired with GIS could inform decisions for variable rate applications of nitrogen in Concord grapes (Davenport et al., 2003), numerous nutrients in *V. vinifera* (Davenport and Bramley, 2007) and non-homogenous irrigation practices (Davenport et al., 2008). As technologies improve, become less expensive and understanding of the interactions between inputs and outputs in grapes advances, precision viticulture, powered by GIS, will become more feasible and widespread (Bramley, 2001).

1.2 Major factors influencing likelihood of success

The following is a discussion of the factors considered in this thesis and their effects on grape production. As stated before, a plethora of environmental variables contribute to the overall performance of a vineyard and many of them interact with one another. A major limitation of GIS analysis is the availability of data relevant to the question being posed. For regional evaluation, computational requirements and storage space necessitate the utilization of datasets created at a relatively broad scale. Although more detailed, higher resolution spatial data would be preferable in many ways, it is generally not wholly available for an area as expansive as the IPNW.

1.2.1 Climate

Although it was previously stated that no one *specific* factor is transcendent in assessment of a site's viticultural suitability, climate, as a broad category, is probably the greatest determinant factor in a region's ability to produce quality grapes (Jones and Duff, 2007). The importance of climate on grape production is so profound and persistent that work has been done reconstructing twentieth century climate based on grape harvest dates (García de Cortázar-Atauri et al., 2010). Some even advocate the hedging of systemic risk of potentially shifting and detrimental climatic conditions on viticultural performance (Cyr et al., 2010).

Grapevines have relatively specific climatic requirements. They demand heat and perform best under high radiation intensities for both vegetative growth and berry development (Jackson, 2008). They require a period of chilling to induce dormancy and promote storage of carbohydrates in perennial organs and are highly susceptible to frost damage outside of such dormancy periods (Keller, 2010). Conversely, temperatures above 40 to 45ºC may irrevocably damage some physiological processes (Malheiro et al., 2010). Climate is the leading environmental factor influencing grapevine yield, quality and global distribution. Additionally, numerous cultivars exist which vary considerably in their climatic requirements (Schultz and Jones, 2010). Matching cultivars to an appropriate climate is crucial for quality grape production.

Nearly all quality grape growing regions fall between 10 and 20ºC annual mean temperature isotherms, between 30 and 50º latitude in the northern hemisphere or between roughly 12 and 22ºC growing season (April through October in the northern hemisphere) mean isotherms (Malheiro et al., 2010; Schultz and Jones, 2010; Figure 7). The IPNW is often compared, based solely on latitude, with famed wine grape growing regions of Europe, but latitude is deemed a good predictor of ripening potential only within the context and vicinity of proven grape growing regions and should not be used alone to speculate on suitability of disparate regions (Jackson and Cherry, 1988).

There have been many approaches to quantifying climatic suitability for grape production. Tonietto and Carbonneau (2004) propose a multicriteria climatic classification combining a latitude-corrected heliothermal index, cool night index and dryness index. They

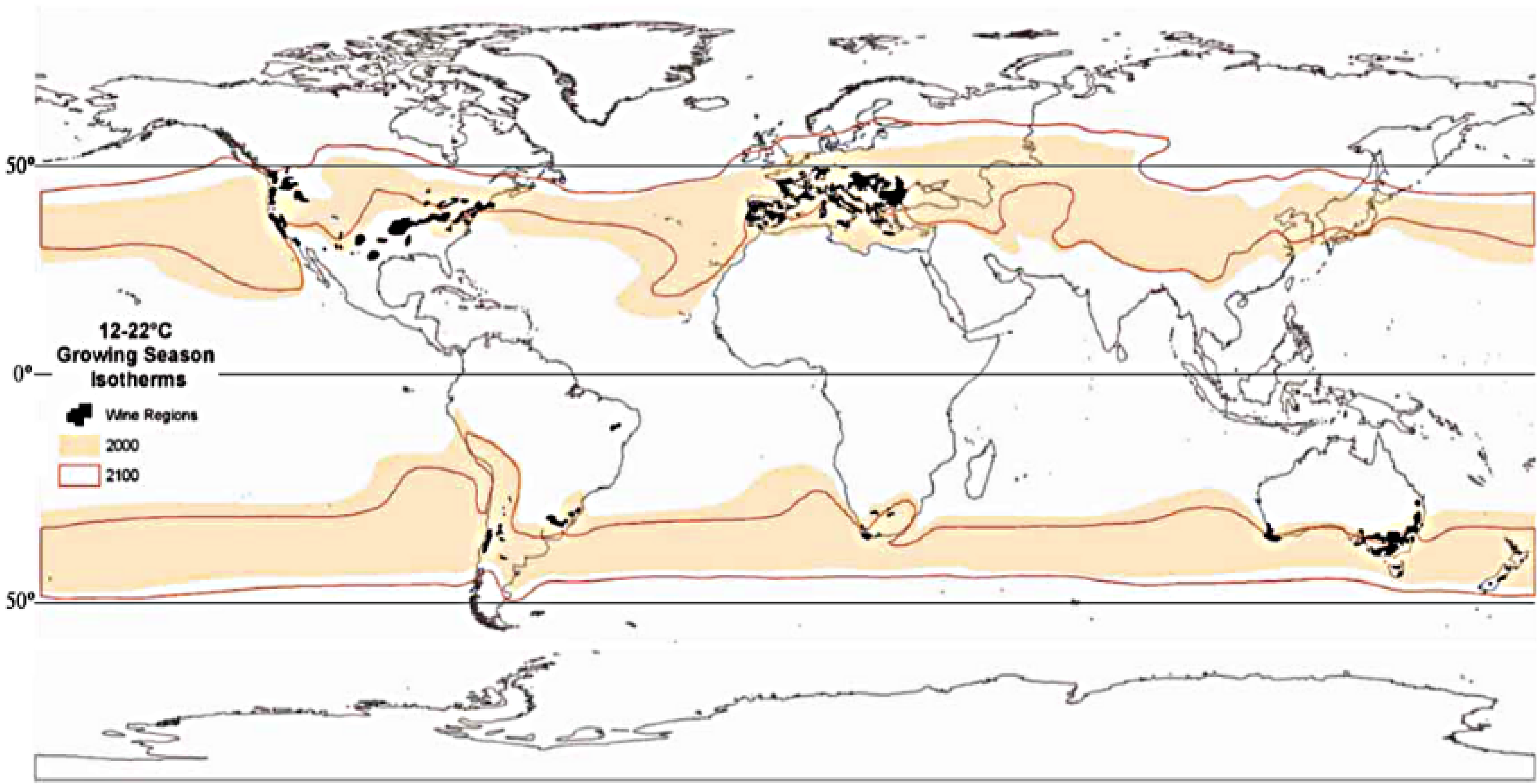


Figure 7: Worldwide distribution of wine grape growing regions. Future projections are based on model runs from the Community Climate System Model and predictions based on moderate levels of warming. From Schultz and Jones (2010)

found the heliothermal index and cool night index accounted for much of the climatic variability in grape producing regions worldwide. However, the dryness index is problematic to calculate, particularly in a region where irrigation is ubiquitous, requiring soil moisture status and evapotranspiration, which are very difficult to model and interpolate over large areas.

Jackson and Cherry (1988) compared fourteen climatic classification indices in more than sixty wine grape regions in seven countries. Their study found a latitude-temperature index (LTI) and latitude-corrected degree-days showed the best differentiation of wine grape ripening groups based on knowledge of heat requirements for different cultivars. The LTI is calculated by multiplying the quantity of sixty minus the latitude of a site by the mean temperature of the warmest month (MTWM).

Climatic suitability and cultivar recommendations are most commonly based on some measure of heat accumulation throughout the growing season (Gladstones, 1992; Jones and Duff, 2007; Moulton and King, 2005). An oft-performed calculation is one of growing degree-days (GDD), a summation of temperatures exceeding some base temperature over a specified period of time. For grapes in the northern hemisphere, the most popular method is to sum degrees of daily mean temperatures greater than a base temperature of 10ºC at a daily interval from 1 April to 31 October. Any days with a mean temperature below 10ºC neither contribute nor detract from the sum of GDD. The mean daily temperature is most often determined simply as the mean of the daily maximum and minimum temperatures because these are the most readily available observations available from weather stations. Most famously, five regions were delineated for wine grapes in California based on GDD by Amerine and Winkler (1944). These ripening groups have been cited and utilized well outside the region from which they were developed.

It is important to note that GDD calculations are but one index of heat accumulation.

They describe neither temporal distribution of heat accumulation over the growing season, which can be very important for different stages of fruit development, nor variability from year to year. It can be presumed that heat accumulation over the growing season follows a near normal distribution with a peak in the middle of the season, July to August, and tapering off in either direction. Some studies examine regions based on the MTWM (Jackson and Cherry, 1988). Others have found strong correlations between the average temperature of the growing season and GDD (Jones et al., 2010).

It should also be noted that temperature fluctuation and ranges at specific times of the growing season may have greater influence on berry development than at other times (Caprio and Quamme, 2002). Heat accumulation during specific portions of the growing season may inform growers of the timing of phenological events; e.g., October (analogous to April in northern hemisphere) GDD correlated with flowering dates and November (analogous to May in northern hemisphere) GDD correlated with duration of flowering in New Zealand (Tesic et al., 2002a). Jackson and Lombard (1993) provide a good discussion of climatic effects on grape quality, including grapevine responses to certain temperature thresholds during different stages of maturation. These are generalizations and responses vary by cultivar amongst other variables. One broad acknowledgment particularly pertinent to a discussion of the IPNW is the conservation of acid, primarily malic acid, in berries exposed to greater diurnal temperature ranges typically due to lower nighttime temperatures in cool climate grape producing areas. This keeps juice pH low, providing a balance winemakers deem desirable. Cool nighttime temperatures are one of the hallmarks of IPNW *V. vinifera* production.

There are variations in how GDD are calculated. Some prefer the use of biologically effective degree-days (BEDD, Gladstones, 1992). The base temperature of 10ºC used in GDD calculations is founded in the generalization that there is little productive development that occurs below this temperature. Similarly, it has been observed that increasing productivity with heat is not indefinite and slows dramatically around 19ºC (Gladstones, 1992). Therefore, BEDD often limit daily heat accumulation to 9ºC.

The temporal structure of data used to construct GDD calculations also varies. With daily weather station observations, it is possible to take the average of daily maximum and minimum temperatures and make the calculation in 24-hour steps. However, climatic data is not always available in daily increments. It is common to find long-term analysis provided as monthly means or monthly average maximums and minimums. Subtracting 10ºC from these monthly means and multiplying by the number of days in the month gives a monthly incremental calculation of GDD. At the other end of the spectrum, modern weather stations with improved data storage and transmission can record conditions at hourly or even smaller intervals. One example is Washington State University's AgWeatherNet (http://weather.wsu.edu/). Finer temporal resolution arguably represents the thermal effects on grapevines better. Hourly data tends to result in heat accumulation values lower than either daily or monthly approximations while monthly data can slightly underestimate heat accumulation, specifically at the beginning and end of the growing season (Jones et al., 2010). It is also noted that GDD calculated from daily temperatures correlated better with ripening capacity than those calculated from monthly means based on an examination of cultivar groupings in many wine grape regions worldwide (Jackson and Cherry, 1988).

Matching cultivars to a site is very largely dependent on heat accumulation necessary to ripen a quality crop. Our focus is on GDD calculated from daily and monthly data without an upper limit of daily heat accumulation for two reasons. First and foremost is the availability of data. While AgWeatherNet is a valuable resource, the period of record is still lacking with many relatively new stations in the network. AgWeatherNet stations are also limited to Washington state. Although the coverage of current grape production areas is decent, exploration of areas outside of those already established is limited and there are no stations in the portions of Oregon that share appellations with Washington nor any in the Snake River Valley AVA. Secondly, the coarseness of even daily summations of heat accumulation begs the question of accurate portrayal of physiologic processes in the calculation of BEDD. The lack of temporal resolution in monthly summations leaves BEDD completely out of the question.

In one study of Concord grapes in Arkansas, Morris et al. (1980) found that from peak bloom to harvest at 16% soluble solids, 1,400 GDD (ºC) were required. For the coolest of wine grape cultivars, it is recommended that a site receive a minimum of 900 to 1,000 GDD or experience 19 to 20ºC MTWM and a minimum monthly mean temperature in excess of -1ºC (Jackson and Cherry, 1988; Moulton and King, 2008; Prescott, 1965). Jones et al. (2010) propose that GDD in excess of 2,700 are too hot for grape production and a minimum of 850 GDD. Gladstones (1992) provides contrasting recommendations for the coolest wine grape cultivars, 1,050 BEDD. BEDD should be, at most, equal to traditional GDD and, in almost all cases, less than GDD for a specific site due to the daily accumulation limitation.

Such discrepancies point out that recommendations of heat required to ripen quality crops of different cultivars depend heavily on the region(s) from which they were developed and/or predominate wine styles of those regions. Additionally, different clones of the same named cultivar may have dissimilar heat requirements (Moulton and King, 2008). Desired wine styles also influence recommendations as noted by Gladstones (1992) with distinctions between requirements for ripening grapes for red wines versus rosé. Cultivars also vary in their ranges of acceptable heat accumulation with some potentially spanning multiple climatic groupings and others restricted to relatively narrow ranges (Figure 8). Generally, existing climatic indices used in viticulture function well in differentiating wine regions at a global scale and delineating macroclimates, but subregion mesoclimatic conditions are often too subtle for existing indices and modeling techniques to discriminate (Tesic et al., 2002b).

Growing season length, generally the period between the last spring and first autumn frosts, is another frequently examined climatic index. Recommendations for growing season length vary. Roper et al. (2006) advise a minimum of 155-160 frost-free days (FFD) for Concord grapes in Wisconsin. Generally, early-ripening varieties require 150 days and late-ripening varieties 180 or more in Indiana (Bordelon, 2009), a minimum of 160 days is suggested for New York (Magarey et al., 1998), 180 days for Virginia (Wolf and Boyer, 2003) and broadly speaking, cool-climate viticulture requires 180 days (Jackson and Cherry, 1988; Prescott, 1965). There are other definitions of growing season, so it is important to understand the criteria used. Malheiro et al. (2010) examine an index corresponding to GDD calculations where growing season length is defined by the number of days in which mean air temperature is greater than 10ºC. These recommendations should not be examined in isolation, but within the context of heat accumulation within the growing season.

In higher latitude, cool climate viticulture, late spring frosts, early autumn frosts and extreme cold events are a major limitation in site selection. Growing season length is one predictor of frost risk, but the picture is much more complicated than number of FFD. Frequency of extreme events and their timing and interactions with cultivar-specific phenological events, specifically periods of dormancy in which vines can survive much colder temperatures, determine site risk. In very cold regions, cultivar selection is often viewed in terms of cold

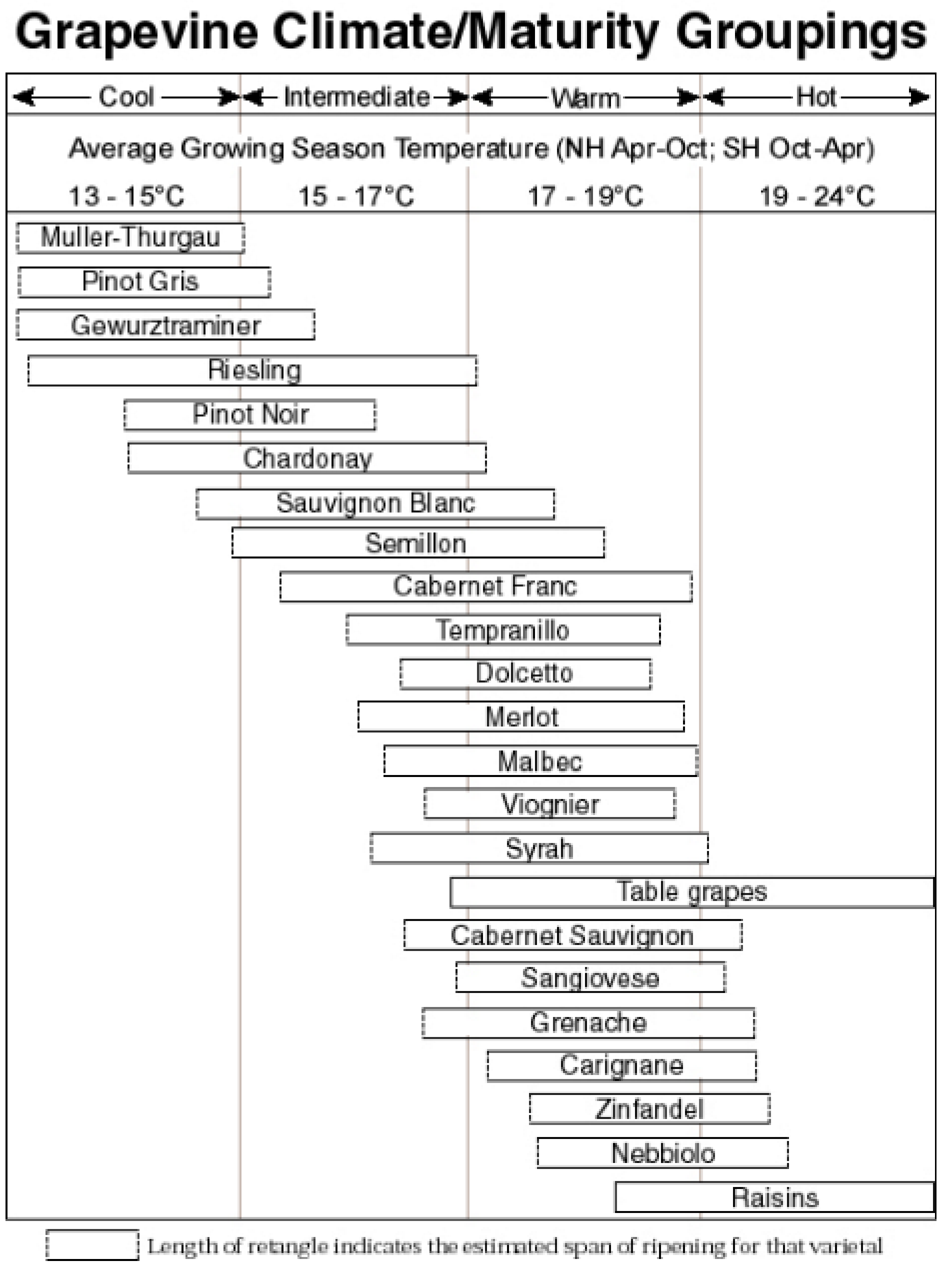


Figure 8: The climate-maturity groupings given in this figure are based on relationships between phenological requirements and climate for high to premium quality wine production in the world's benchmark regions for each variety. The dashed line at the end of the bars indicates that some adjustments may occur as more data become available, but changes of more than +/- 0.2-0.6°C are highly unlikely. From Jones (2007)

hardiness (Roper et al., 2006).

Vine cold acclimation and hardiness is complicated by the dependence of the extent of hardiness on environmental factors, namely temperatures preceding potentially damaging low-temperature events, photoperiod, vine water status leading up to cold acclimation and surface moisture, which can raise damage thresholds by up to 4ºC (Keller, 2010; Mills et al., 2006). The presence of osmotically active solutes and low water content within tissues allows supercooling of bud, cane and trunk tissues and survival of temperatures well below -10ºC. Damaging temperature thresholds vary by cultivar and deacclimation can occur rapidly during brief periods of warmer temperatures. Timing of phenological events, namely budbreak and fruit and shoot maturation, can help mitigate a vine's risk to damaging temperatures (Keller, 2010).

Rating frost risk not only requires data from a climatically relevant period of record, but phenological data or modeling of the bud break period and the period leading up to dormancy (Stafne, 2007). Dynamics of cold hardiness present great challenges in predicting when and what temperature thresholds will result in significant cold damage to different cultivars. One approach examines number of occurrences of specified low temperature thresholds within some time frame; e.g., frequency of temperatures below -20.5 to -23.3ºC in a ten-year period in New York (Magarey et al., 1998), sites with more than three occurrences of temperatures below -22.2ºC over a decade were deemed too risky for *V. vinifera* production in Virginia (Wolf and Boyer, 2003) and similarly, Concord grapes in Wisconsin have been noted to suffer damage at temperatures below -29ºC during dormancy (Roper et al., 2006). Continuous monitoring systems like that described by Mills et al. (2006) have the potential to be incorporated into GIS decision support systems for a dynamic, spatial prediction of frost damage.

One more facet of site selection largely climatically driven is disease risk. Powdery mildew (*Uncinula necator* (Schwein.) Burrill [syn. *Erysiphe necator* Schwein.]) is the most serious fungal grape disease in the IPNW. Epidemics in the mid-1990s resulted in 20 to 25% losses in susceptible cultivars. These were seasons characterized by abnormally high rainfall between budburst and the immediate postbloom period (Grove, 2004). Infection of immature fruit causes tissue scarring and berry splitting rendering it unmarketable as fresh fruit, potentially impairing quality for wine making and increasing risk for bunch rot. Long-term, infection reduces vine size, bud fruitfulness and increases risk of winter cold damage (Chellemi and Marois, 1992; Wilcox, 2003).

In grape growing areas, periods of high humidity often accompany the moderate temperatures (21-30ºC) which are favorable for *U. necator* development while higher temperatures are often associated with high radiative load and low humidity, conditions inhospitable for *U. necator* proliferation (Sall, 1980; Schnathorst, 1965). Extended temperatures above 33°C can kill colonies and the fungus is completely destroyed at temperatures above 35°C for durations of 12 hours or more, a process exacerbated by exposure to ultraviolet light (Gubler et al., 1999). Although humidity favors the spread of *U. necator*, free moisture severely inhibits infection. Where excess moisture excludes *U. necator*, low temperatures often work in conjunction to limit the pathogen's virulence (Schnathorst, 1965).

Literature often indicates berries are vulnerable to new infection until they reach 8% sugar content, that colonies on infected berries continue to produce spores until berries reach 12 to 15% sugar and colonies become inactive and berries are less susceptible when sugar content is greater than 15% (Gubler et al., 1999; Sall, 1980). A study of *V. labruscana* and four cultivars of *V. vinifera* showed severe powdery mildew symptoms only when inoculated within two weeks of bloom, six weeks before the 8% sugar benchmark was achieved, indicating ontogenic resistance may be expressed more rapidly than what is widely reported in the literature (Gadoury et al., 2003).

In either case, *U. necator* control early in the season is critical to keep infection in check throughout the season. Severe infection is usually the result of poor control during or shortly following the prebloom period (Wilcox, 2003). In California, generally speaking, the degree of success of powdery mildew control is largely dependent on environmental conditions; when moderate conditions favorable for powdery mildew proliferation persist, even the best control programs may fail (Gubler et al., 1999).

The climatic future for grape production in the inland Pacific Northwest holds both challenges and possibilities. Climate change modeling has predicted a shift in U.S. wine production to a narrow West Coast region and the Northwest over the next century (White et al., 2006). Warming trends may expand suitable growing area in the near future (Figure 7), but predicted increasing variability, increased frequency of extreme events and shifting ripening period conditions will prove challenging for continued production of consistently high-quality crops (Jones, 2007). Much of predicted warming is attributed to increasing minimum temperatures, not maximum, as well as warming in the winter and spring. These effects may be detrimental to conserving acid levels in ripening berries. Warming during the dormancy period coupled with more extreme events may also dramatically increase frost risk (Jones et al., 2005 ; Jones and Webb, 2010; Schultz and Jones, 2010). Databases such as the one built for this thesis respond to an increasing call for research to amplify resilience, flexibility and adaptability of grape-growing regions, specifically in the face of climate change (Jones and Webb, 2010; Kenny, 2010; Schultz, 2010).

1.2.2 Topography

Topographic suitability can be viewed in two ways: physical ability to manage a vineyard and influence over mesoclimatic conditions. Mechanization of vineyard operations represents a major economic consideration. Mechanical harvesters have been estimated to reduce costs by up to 75% compared to manual harvesting in some regions (Jackson, 2008). Modern vineyard machinery readily operate on slopes of up to 15% if vine rows are parallel to the slope (Bergmeier and Striegler, 2011) and high-end, self-leveling equipment can handle side slopes of 30 to 35% (Greenspan, 2008). Viticulture on steeper slopes occurs, but requires more expensive and time-intensive manual labor. Generally speaking, steeper slopes are subject to greater risk for soil erosion. In the arid IPNW this largely depends on wind patterns, soil type and structure, vineyard floor management and row orientation (Jackson, 2008).

Marginal mesoclimate can be mitigated to some degree with favorable geographic features, primarily slope, solar insolation, proximity to large water bodies and cold air drainage (Jones et al., 2004; Meinert and Curtin, 2005; Whitesell, 2005). The so-called 'lake effect' depends on factors such as surface area, depth and salinity of the proximal water body and site position relative to the water. On the leeward side of water bodies, cold air warmed over the heat sink can prevent winter injury. Warmer air moving over the cool body of water in the spring can also retard plant development and reduce risk of late frost (Wolf and Boyer, 2003).

Two readily quantified topographic characteristics are slope and aspect. Slope is widely regarded as more important than aspect; grapes are often grown successfully on so-called 'undesirable' aspects (Wolfe, 1999). Moderate slopes are considered the best sites for grape production (Jones et al., 2004). Katabatic cold air flow can be severely limiting to shoot development, flowering, pollen formation, flower fertilization and damaging to fruit. Sloped sites tend to avoid cold air pooling. Sites above frost pockets may also benefit from additional elevation through lower daytime temperatures, potentially promoting fruit quality (Wolf and Boyer, 2003). Slope alone cannot predict mesoclimate conditions and sites must be considered within the greater context of surrounding topography, obstructions to air flow and prevailing winds (Figure 9).

Southerly facing slopes are often given greatest preference in the northern hemisphere due to higher levels of solar insolation and consequently heat accumulation. Solar insolation is important for photosynthesis, anthocyanin and phenolic development in berries and microclimatic effects, namely heat accumulation and relative humidity. In a trial with Traminette, fruit from fully exposed clusters had 30% greater concentrations of potentially volatile terpenes compared to heavily shaded (>3 leaf layers) fruit, improving an 'aroma reservoir' to release into wine (Skinkis et al., 2010). Potential photosynthetically active radiation and elevation also play significant roles in determining budbreak and flowering dates (Failla et al., 2004). Exposed Pinot Noir berries developed significantly greater levels of eight flavonol compounds, including quercetin glucoside, as well as caftaric acid and resveratrol, compared to shaded berries (Price et

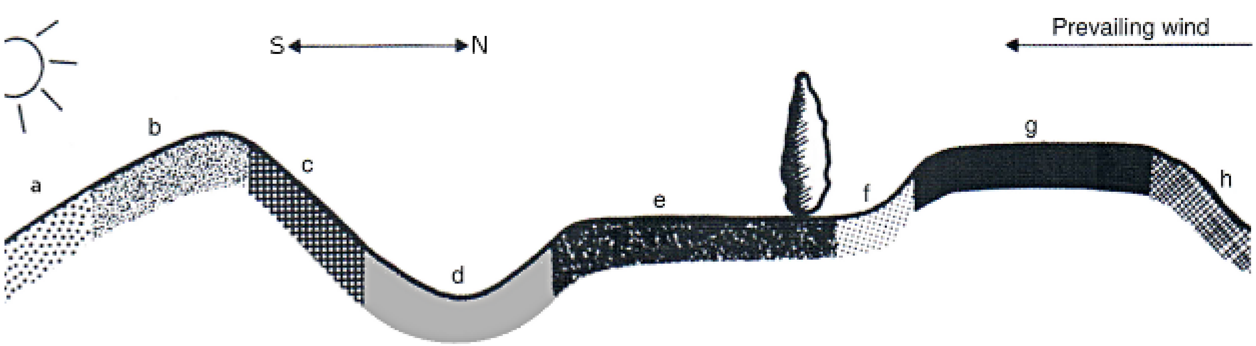


Figure 9: Mesoclimates on hypothetical sites. (a) warm site receiving greater solar radiation due to aspect, avoids frosts with cold air draining below; (b) advantages of site (a) counteracted by cold associated with increased elevation; (c) although avoiding frost, a cold site due to unfavorable aspect; (d) very cold site most susceptible to frost, cold air from surrounding areas drain into this area; (e) still frosty, but less than site (d), some shelter from wind obtained from wind row and hill; (f) wind row at the base of hill prevent cold air from draining and potential frost avoidance is lost; (g) less frost than site (e), but prevailing wind may prevent heat accumulation; (h) similar to site (c). From Jackson and Schuster (2001)

al., 1995).

Studies of the effects of solar radiation on fruit development have had varied results and there is likely a complex interaction between radiation and temperature on anthocyanin synthesis in berries, especially at higher temperatures (Chorti et al., 2010; Tarara et al., 2008). Smart (1987) notes anthocyanin content is increased by light exposure, although the response depends on cultivar. A study of Emperor grapes showed anthocyanin concentrations and soluble solids were significantly greater in berries ripened at field temperatures under full sun (66.5 to 100% sunlight) compared to berries placed under black Saran shade canopies (8.9 to 9.5% sunlight, Kliewer, 1977). Price et al. (1995) found anthocyanin levels were not significantly different in exposed versus shaded Pinot Noir berries. However, exposed berries were smaller in larger clusters, increasing surface area to juice volume ratio, increasing extractable compounds. North-facing slopes may be suitable for cooler climate cultivars, a cooler site in a hot macroclimate or white grape varieties which do not accumulate anthocyanins in fruit.

At greater latitudes, favorable aspect works in conjunction with sloped sites to increase solar insolation because of the lower angle of the sun compared to lesser latitudes (Fitzharris and Endlicher, 1996; Huggett, 2006). Longer day lengths at greater latitudes during much of the growing season may also increase growth potential by offsetting cooler temperatures (Jackson and Cherry, 1988; Malheiro et al., 2010). There are additional considerations for aspect besides north and south. Eastern aspects offer earlier initiation of photosynthetic activity, drying of canopy moisture and providing shelter from direct solar radiation during hotter afternoon hours, potentially protecting volatile aromatic compounds. Western exposure may benefit late-season cultivars (Wolf and Boyer, 2003). Ultimately, there is no ideal aspect and suitability depends on cultivar selection and desired wine style.

1.2.3 Soils

Grapevines, as a whole, tolerate and even thrive in a wide range of soil conditions and no one factor or soil type can be proven superior. Nutrient availability and moisture management are the two major areas of importance governed by soil characteristics (Jones et al., 2004). Soils capable of growing quality grapes vary widely in their geneses, rooting depths, textures and available water-holding capacities, all important features contributing to the ability to manage vigor and induce water stress to ensure wine grape quality (Busacca and Meinert, 2003). Van Leeuwen and Seguin (2006) found it was generally not possible to correlate regional soil maps with maps of quality potential for grape production. However, Seguin (cited in Jackson, 2008) correlated the ranking of Bordeaux *cru classé* estates with deep, coarse-textured soils near rivulets or drainage channels, features promoting rapid drainage and believed to permit deep root penetration.

The IPNW hosts a predominance of vineyard sites on Quaternary sediments overlying Miocene basalt. These are commonly Aridisols with upper horizons composed of loess or sand sheets and lower horizons consisting of stratified silty to gravelly flood sediments (Busacca and Meinert, 2003). Rankine et al. (cited in Jackson and Lombard, 1993) concluded that soil is tertiary to climate or cultivar selection, but those soil characteristics most important to grape growth are depth, water-holding capacity and drainage rather than soil composition.

Drainage is widely considered of the utmost importance for soil characteristics (Bordelon, 2001; Gladstones, 1992; Jones et al., 2004; Roper et al., 2006). It is so important that it is often recommended that expensive deep ripping and installation of drainage tiles be considered in vineyard establishment (Jackson, 2008; Gladstones, 1992). Waterlogged soils retard vine growth, favor the development of chlorosis in calcareous soils and several root pathogens and hinder mechanical operations in the vineyard. Saturated soils reduce oxygen availability, increase concentrations of carbon dioxide, ethylene and, under prolonged saturated conditions, can accumulate toxic levels of hydrogen sulfide from anaerobic metabolism of soil bacteria (Jackson, 2008). Free draining soils maintain good oxygen concentrations near roots and also facilitate moderate water stress with proper irrigation management (Foss et al., 2010).

In arid areas, insufficient drainage, often coupled with low-quality irrigation water, commonly leads to salt accumulations due to the inability of salts to leach through the soil profile and their upward movement from capillary action (Ben-Gal et al., 2008). Irrigated, well-drained soils provide consistently extensive volumes of plant available water giving grapevines the incentive to develop large, deep, continuously functioning root systems. During dormancy, when precipitation rates in the IPNW are greatest, good drainage remains relevant by continuing to prevent waterlogging (Gladstones, 1992).

It is recommended that vineyard soils have unrestricted drainage to a depth of at least two to three meters in most situations and ripping of restrictive layers or soil slotting are commonly recommended (Gladstones, 1992; Jackson, 2008). Failla et al. (2004) found grapevine roots at over three meters in depth during soil surveys and vines may grow roots to depths of thirty meters or more if no impenetrable barriers are present (Keller, 2010). Shallow soils where root penetration is problematic are considered unsuitable for grape production and increase the likelihood of waterlogging (Foss et al., 2010; Jackson, 2008). Research with potted vines in sand and nutrient culture showed restrictive rooting area without limitation of water or nutrients can also modify grape composition (Jackson and Lombard, 1993).

Good drainage, along with greater depth increases grapevines' incentive to grow robust, perennial root structures, storage organs for carbohydrates, water and other nutrients, which are important for initial growth of shoots and roots when vines break dormancy (Keller, 2010; Tesic et al., 2002b; Wolf and Boyer, 2003). There is an assumption that depth to any restrictive layer is the depth to root impermeability, but grapevines have an incredible ability to work their way through openings in the soil substrate. An understanding of subsoil structure and hydrology is necessary to complete the picture of soil depth. Duteau et al. (cited in Tesic et al., 2002a) found water from bedrock layers comprised 20 to 40% of evapotranspiration in grapevines in the Bordeaux area, a non-irrigated grape region.

Only under severe water stress will grape vines access substantial water from greater than two meters. Vines draw most of their nourishment from down to a depth of 50 to 100 cm and readily transpire water from depths up to two meters, but root concentrations may shift to greater depths under conditions such as competition with vineyard floor cover crops (Huggett, 2006; Keller, 2010).

One of the most well known and readily measured soil characteristics determining potential nutrient availability is pH (Jackson, 2008; Jones et al., 2004). *V. vinifera* generally absorb many nutrients best at approximately neutral to somewhat acidic pH. *V. labruscana* can thrive at lower pH (Meinert and Curtin, 2005). Overly alkaline soils lead to deficiencies of phosphorus, iron, manganese, boron and zinc (Gladstones,1992; Figure 10). Acidic soils can generate toxic aluminum, copper and manganese levels and induce phosphorus deficiency, restricting root growth and leading to nutrient and soil microbial imbalances (Bargmann, 2003; Foss, et al. 2010; Gladstones, 1992).

Under ubiquitous irrigation, IPNW vineyards offer the most flexibility to consistently ripen quality crops when the available water-holding capacity of soils is relatively low to moderate. Moisture needs of grapevines vary throughout the growing season and the ability of

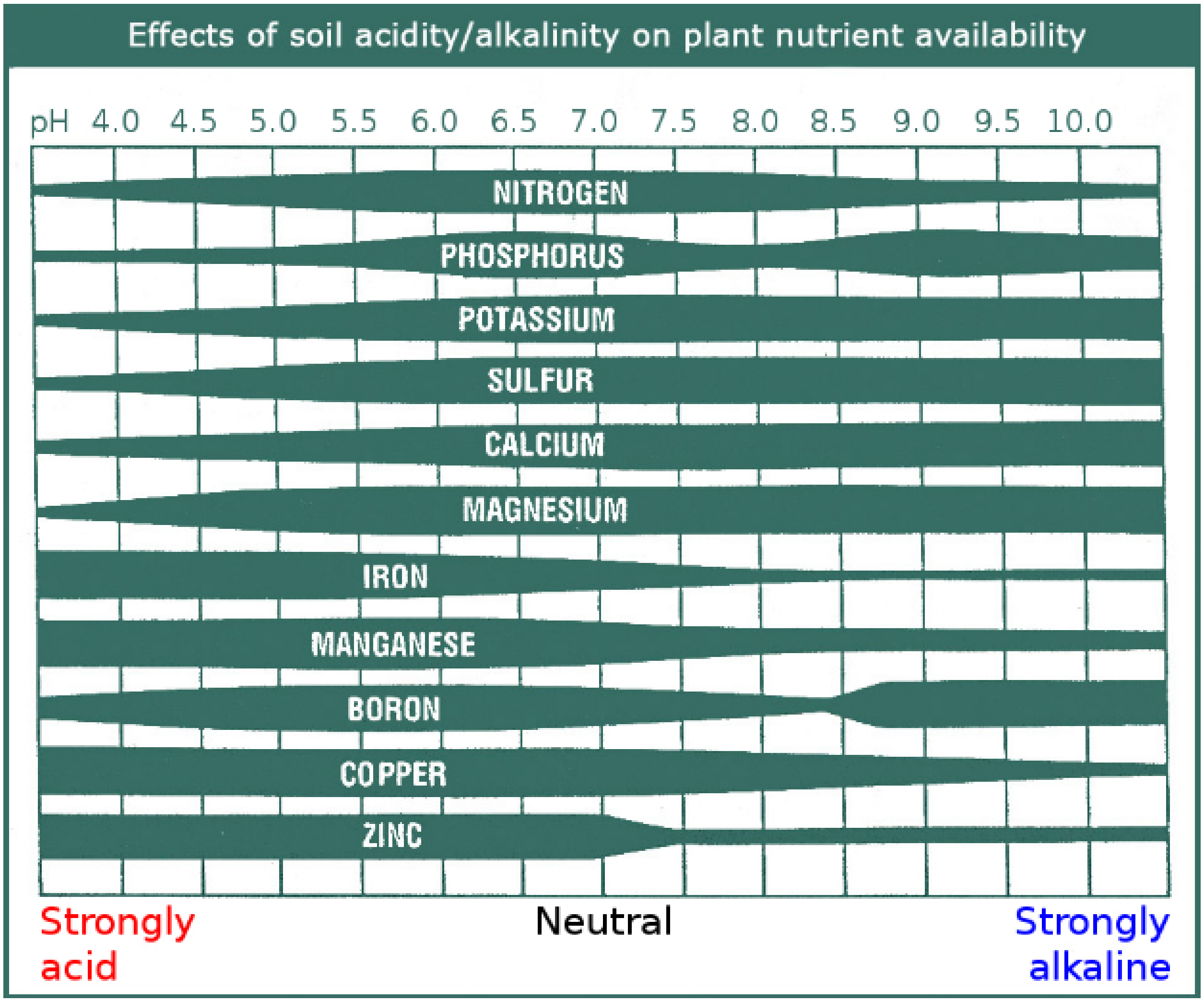


Figure 10: General relationship between soil pH and availability of plant nutrients. The width of each band representing an element indicates the potential availability of the nutrient at a particular pH value. Modified from Jackson (2008)

soils to maintain plant available levels of water without constant irrigation as well as induce some level of water stress within relatively short time frames is desirable. Water stress must be avoided during flowering and fruit set to ensure fruitfulness. Moderate water stress is recommended following early fruit development to manage berry size and vegetative growth, harden the vine for future stress and improve fruit quality (Gladstones, 1992; Malheiro et al., 2010). Severe water stress early in the growing season and after véraison can lead to low levels of titratable acidity. Excessive moisture late in the ripening period can lead to low soluble solids, phenols, flavor and aroma compounds and high titratable acidity and methoxypyrazines (Jackson and Lombard, 1993).

Finally, lime-induced chlorosis is frequently observed in grapes on calcareous soils. Soil pH may limit iron solubility and availability. However, iron content alone does not correlate with chlorosis. There appear to be numerous, complex interactions contributing to lime-induced chlorosis including bicarbonate accumulation disrupting cellular use of iron, young root growth and distribution, acidification of the rhizosphere and production of Fe^{3+} reductase, which reduces ferric iron to the more soluble ferrous (Fe^{2+}) state (Jackson, 2008; Sabir et al., 2010). Davenport and Stevens (2006) found low soil temperature and high soil moisture pre-bloom were strongly correlated with chlorosis in Concord grapes, suggesting inhospitable conditions for root growth and/or function and again emphasizing the importance of good soil drainage and moderate water-holding capacity. Free calcium in soil is also known to inhibit vine uptake of essential nutrients such as nitrogen and potassium (Meinert and Busacca, 2002). *V. labruscana* is much more sensitive to lime-induced chlorosis than own-rooted *V. vinifera* varieties (Jackson, 2008; Sabir et al., 2010).

1.3 Past work in GIS grape site selection

There have been many approaches to vineyard site selection using GIS. Foss et al. (2010) explored viticultural potential in southeast England using Boolean logic. They assigned minimum thresholds or acceptable ranges to eleven parameters represented by raster datasets and overlaid the layers. Pixels rated as acceptable for all parameters are deemed suitable for wine grape production. The eleven factors were GDD, total annual rainfall, frost days during the growing season, average wind speed over growing season, slope, aspect, elevation and soil pH, depth, drainage and organic matter. Sites were generally found to be constrained not by climatic conditions, but by more variable soil and topographic characteristics. While the datasets chosen cover many of the same factors we are considering in the IPNW, the Boolean approach does not permit differentiation between marginal and more ideal sites as defined by the acceptable ranges of parameters. Variable classifications of heat accumulation and other factors could also inform cultivar selection decisions.

Magarey et al. (1998) made an early effort to publish site selection maps online for New York. They examined soil drainage, depth and pH, commercially produced climatic data, including FFD and frequency of extreme low temperatures, and masked the layers to exclude urban areas and water bodies. Researchers noted the difficulty of differentiating site differences with coarse climatic data, modeled at a resolution of one square kilometer, while simultaneously noting high variability associated with high-resolution modeling, which incurs excessive cost and would require impractically extensive sampling. This suggests climatic modeling should be approached with a moderate resolution product in mind. Online access to the data no longer appears to be available.

Jones has performed the most work on GIS site selection for vineyards in the Pacific Northwest. His work has focused on the Umpqua Valley (Jones et al., 2004) and Rogue Valley (Jones et al., 2006) AVAs in western Oregon and the North Olympic Peninsula (Jones and Duff, 2007), which is partially contained within the Puget Sound AVA in western Washington. These projects use various combinations of slope, aspect, hillshade, solar insolation, elevation, GDD, FFD, precipitation, climatic variability, land use and soil drainage, depth, available water-holding capacity and pH. Suitability for every parameter except land use is divided into three or more rankings, often with lower and/or upper thresholds, resulting in a gradation of suitability in contrast to a Boolean approach. The factors are then added together to produce a composite surface of relative site suitability. Climatic classifications differentiate sites into ripening potential groups primarily based on heat accumulation.

Elevation rankings are region-specific and vary with geography and macroclimate. Relative elevations (i.e. height above a valley floor) are more important than absolute elevation above mean sea level (Smith, 2002; Wolf and Boyer, 2003). Calculations of solar insolation provide a continuous assessment of site exposure that traditional delineations of aspect do not. They account for shading from adjacent topography and include consideration for latitude, which influences day length and solar angle (Jones et al., 2006). Suitability surfaces are masked with parcel information to include those zoned for agriculture, farm/forest transition and rural residential where agricultural operations of five acres or more are allowed (Jones et al., 2004; Jones et al., 2006; Jones and Duff, 2007).

Site suitability in the Umpqua Valley AVA found existing vineyards fell into the fifth and sixth deciles of topographic suitability and sixth and seventh deciles for soil suitability (Jones et al., 2004). Selected sites were found around and above the median of rated suitability, implying some degree of validity in this approach of modeling. Obviously, results are complicated by available land within the AVA, conflicting land use, land planted to other crops, etc.

The study of site suitability on the North Olympic Peninsula also incorporated climate change modeling and predicted increasing and expanded viticultural suitability in a very cool region (Jones et al., 2006). It has also been suggested that monitoring of some varieties like Pinot Noir can serve as an indicator of climatic shifts in viticultural areas in the face of climate change due to their relatively limited range of climatic tolerance (Jones and Webb, 2010).

Bowen et al. (2005) compiled an extensive inventory of wine grape vineyards in the Okanogan and Similkameen Valleys in British Columbia. They examined site suitability as well as management practices through in-depth questionnaires and site evaluation. Vineyard performance was gauged through regional wine competition awards, a method which authors note is complex and difficult to discern clear patterns with. Topographic features were measured as a site average and represented spatially with contour maps, which can miss subtle geomorphologic features. Soil analysis focused on depth, surface stoniness, texture, perviousness, drainage, shear strength, pH, salinity, and cation exchange capacity. Climatic assessment consisted of macroclimatic measurements based on widely spaced weather stations as well as high-resolution monitoring with radio-transmitting sensors and data loggers. One vineyard of approximately 40 ha was monitored with 24 sensors revealing the high degree of spatial and temporal variability possible within a small area. An area as small as one hectare can exhibit temperature ranges of 8ºC or more.

Lakso and colleagues at the Institute for the Application of Geospatial Technology have recently published site selection data for New York in a publicly accessible website featuring an interactive map (VSSA, 2011; http://arcserver2.iagt.org/vll/Default.aspx). The site includes layers of climatic data featuring GDD, FFD, extreme temperature thresholds, slope, aspect, hillshade and soil drainage, pH, depth to restrictive layers and texture with recommendations on preferred ranges of each. Datasets cover the Lake Erie, Finger Lakes, Hudson Valley, Lake Ontario and Lake Champlain regions overlain on Bing™ maps and the site features educational information supporting recommendations.

1.4 Objectives

My study objectives were to: 1) compile a GIS database of existing grape production areas in the IPNW, 2) establish a GIS for grape site potential and selection, 3) evaluate IPNW production areas for site suitability for different grape species/cultivars and 4) begin preliminary validation of site selection model by mapping existing vineyards by block and obtaining qualitative perceptions of vineyard performance from viticulturists. These databases will serve to assist extension agents and educators in providing information efficiently to neophyte and struggling growers as well as contribute to the understanding of viticultural potential in the region.

CHAPTER TWO

MATERIALS AND METHODS

2.1 Materials and Methods

Spatial data sources are summarized in Table 1. Geographic information system (GIS) software packages used were ArcGIS 9.3.1 and 10.0 (Esri, Redlands, CA). Tabular data were spatially represented using geographic coordinates provided by responsible organizations. Spatial data were projected to Universal Transverse Mercator (UTM) Zone 11 North, North American Datum, 1983 using bilinear sampling for continuous data. Thematic maps were created from Soil Survey Geographic (SSURGO) databases using Soil Data Viewer 5.2 (NRCS). Data layers and composite suitability surfaces were divided by county for organization and increased operability.

Slope, aspect and solar insolation were calculated using the 1/3 arc second (ca. 10 m) National Elevation Dataset (NED) digital elevation model (DEM). A higher resolution, 1/9 arc second (ca. 3 m) NED DEM is available in limited portions of the study area, but mostly in western Washington and Oregon and in the vicinity of Spokane, WA (Figure 11). The NED has been shown to have high relative vertical accuracy, an important metric for calculation of derivative topographic products, and should perform well for initial site assessment (Gesch, 2007). Slope calculations were made in units of percent rise.

Solar insolation calculations were performed using the mean latitude of each DEM to 10^{-12} decimal degrees, a sky size of 40,000 cells, fourteen-day and two-hour intervals. Calculations were made from ordinal day 91 (1 April) to 304 (31 October). Thirty-two azimuth directions were used to calculate viewshed. Eight zenith and azimuth divisions were used to calculate the sky map. A uniform sky diffuse radiation model was used. A diffuse proportion of 0.3 and transmissivity of 0.5 were used, presumptive of generally clear sky conditions (Esri, 2010; Fu and Rich, 2002). Solar insolation surfaces do not represent actual solar accumulation over a climatically relevant period of record and are intended to represent sites' topographic

Table 1: Summary of data sources used in development and analysis of grape site selection geographic information system for the inland Pacific Northwest. Abbreviations: AEX (Aerials Express), FSA (Farm Service Agency), NAD (North American Datum), NAVD (North American Vertical Datum), PRISM (Parameter-elevation Regressions on Independent Slopes Model), USDA (U.S. Department of Agriculture, USGS (U.S. Geological Survey), WGS (World Geodetic System).

	Source	Data Type	Resolution/Scale	Native Coordinate System	Datum
Topography					
National Elevation Dataset	USGS	Raster	1/3 arc second (ca. 10 m)	Geographic	NAD 1983; NAVD 1988
Soil					
Soil Survey Geographic Database	USDA – Natural Resources Conservation Service	Vector	1:12,000 to 1:63,360	variable	variable
Climate					
PRISM	PRISM Climate Group, Oregon State University	Raster	30 arc second (ca. 800 m)	Geographic	NAD 1983
Western Regional Climate Center	Desert Research Institute	Tabular	n/a	Geographic	WGS 1984
European Climate Assessment & Dataset	European Climate Support Network	Tabular	n/a	Geographic	WGS 1984
Krems	Central Institute for Meteorology and Geodynamics	Tabular	n/a	Geographic	WGS 1984
Imagery					
Esri	Esri, i-cubed, USDA FSA, USGS, AEX, GeoEye, AeroGRID, Getmapping	Raster	≤1 m; ≥1:1,128*	Mercator Auxiliary Sphere	WGS 1984

*Aerial imagery resolution and source is dependent upon the scale at which it is viewed.

Table 1 (cont.): Summary of data sources used in development and analysis of site selection geographic information system for the inland Pacific Northwest. Abbreviations: HARN (High Accuracy Reference Network), NAD (North American Datum), NAVD (North American Vertical Datum), WGS (World Geodetic System).

	Source	Data Type	Resolution/Scale	Native Coordinate System	Datum
Imagery					
Topographic Maps	U.S. Geological Survey	Raster	1:24,000; 1:100,000	Universal Transverse Mercator	NAD 1927; NAVD 1929
Land Cover					
CDL	U.S. Department of Agriculture – National Agricultural Statistics Service	Raster	30 m	Universal Transverse Mercator	WGS 1984
Ag. Land Use	Washington State Department of Agriculture	Vector	variable	Washington State Plane South	NAD 1983 HARN
NHD	U.S. Geological Survey	Vector	1:24,000	Geographic	NAD 1983
Cadastre					
Atlas	U.S. Geological Survey	Vector	1:2,000,000	Geographic	NAD 1983
PLSS	Bureau of Land Management	Vector	variable	Geographic	NAD 1983
AVA	Richard Rupp, Joan Davenport, *Federal Register*, U.S. Geological Survey topographic quadrangle maps	Vector	variable	variable	variable

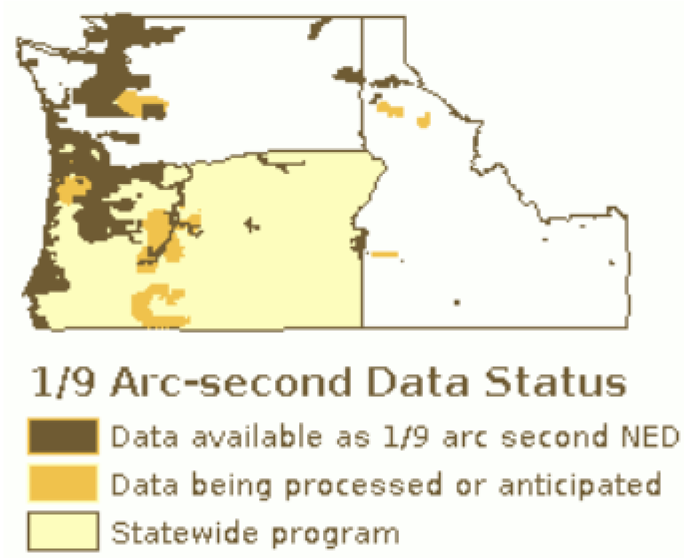


Figure 11: Status of the National Elevation Dataset 1/9 arc second layer, June 2011 release. Available and anticipated high-resolution digital elevation models are largely unavailable in the study area. Modified from USGS (2011)

exposure. Output surface units are Watt hours per square meter (Wh/m^2). Ratings were determined by taking the mean of five-quantile divisions for mid-latitude counties within the study area.

Calculation guidelines recommend the extent of input DEMs be less than one degree latitude (Esri, 2010), but calculations of adjacent surfaces with combined extents of much less than one degree latitude showed notable differences in continuity. Most DEMs masked by county were too large for a single calculation of solar insolation. DEMs were divided vertically whenever possible to maintain relatively constant mean latitude for each county. Vertical divisions were made with overlap to account for effects of adjacent topography and improved continuity. Divided surfaces were later mosaicked using a blend of overlapping areas.

Thematic maps of soil characteristics were created for drainage class, depth to any restrictive layer, available water-holding capacity (AWC, 0 to 50 cm), pH (0 to 50 cm) and calcium carbonate ($CaCO_3$, 0 to 60 cm). Dominant component or condition were the aggregation methods used. Counties represented with multiple SSURGO databases were merged and clipped to county boundaries. Vector data was converted to raster data with a resolution of ten meters.

Effervescence tests were performed on 5 g samples of Quincy fine sand mixed thoroughly with finely powdered $CaCO_3$ added by mass at 0, 1, 2.5, 5, 7.5 and 10 percents. Hydrochloric acid was prepared and applied as described in Schoeneberger et al. (2002). Observations of effervescence were used to correlate quantities of $CaCO_3$ with common field soil profile sampling and description.

Portions of the study area are currently not represented by the SSURGO database (Figure 12). Soil survey data for the Yakama Indian Reservation is not publicly available at the request of the Yakima Tribe, the Hanford Nuclear Reservation is a highly restricted federal installation with no public data and soil surveys are currently in progress for the Umatilla National Forest (R. Myhrum, personal communication, 2010). Soil surveys are also currently in progress for Malheur County, OR (C. McGrath, personal communication, 2011).

Surfaces of GDD were calculated using three methods: Parameter-elevation Regressions on Independent Slope Model (PRISM) monthly normal summations and two interpolation methods, ordinary and universal kriging, utilizing Western Regional Climate Center (WRCC) daily normals for the period of 1971 to 2000. PRISM produces official climate datasets for the U.S. Department of Agriculture (USDA) utilizing a vast network of weather stations, relying on a large community of climate experts and modeling numerous environmental factors influencing climate including elevation, aspect, coastal proximity and moist boundary layer heights (Daly et al., 2008). WRCC daily normals offer greater temporal resolution. Ordinary kriging is a method commonly used for interpolation of climatic variables and universal kriging attempts to account

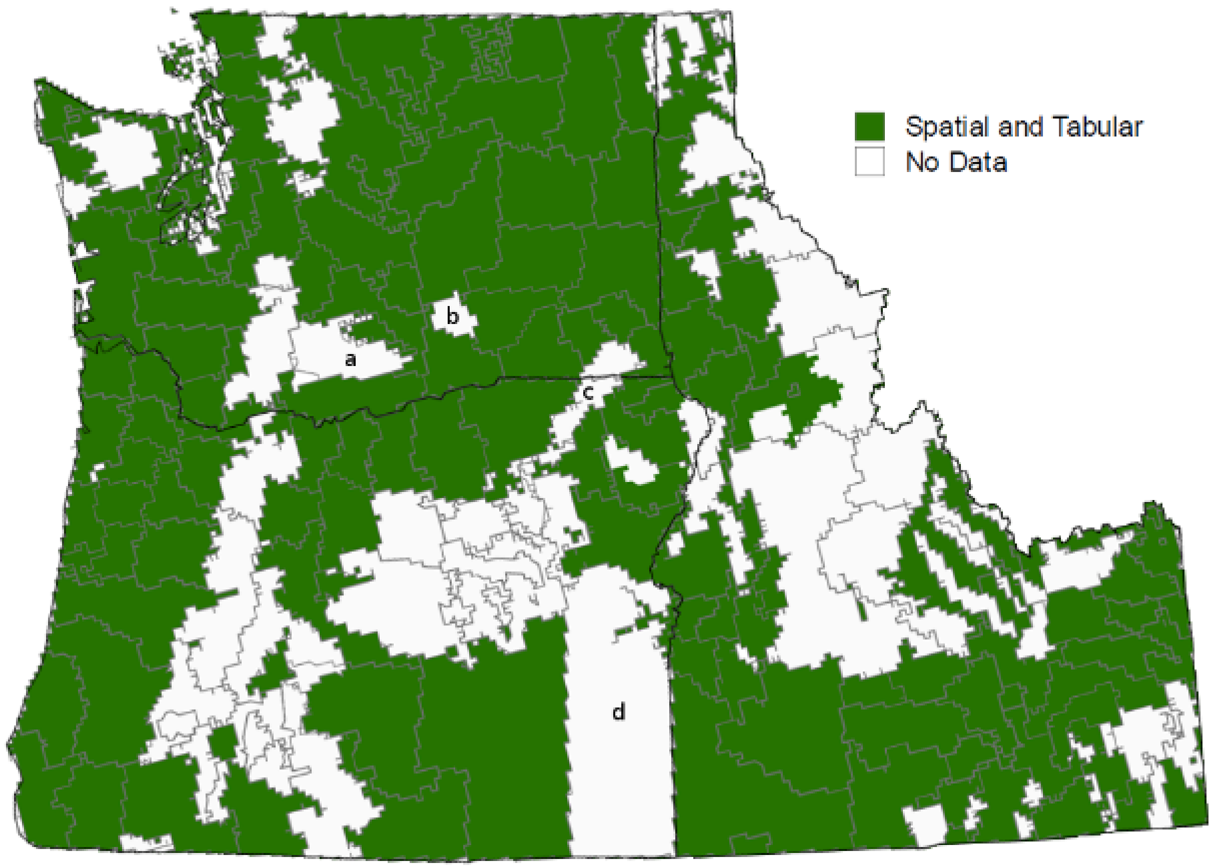


Figure 12: Available Soil Survey Geographic database, 1 July 2011. (a) Yakama Indian Reservation; (b) Hanford Nuclear Reservation; (c) Umatilla National Forest; (d) Malheur County. Modified from USDA-NRCS (2011a)

for trend surfaces which may be present over large geographic extents (Hartkamp et al., 1999).

PRISM monthly normals include surfaces of maximum and minimum temperatures (PRISM, 2011). Averaging these surfaces yields a monthly mean temperature. Subtracting a base temperature of 10ºC from these monthly mean temperature surfaces and multiplying by the number of days in the month gives monthly GDD. Heat accumulation was summed, by this method, for April through October (Figure 13).

The Western Regional Climate Center (WRCC) maintains a database of daily normals. Stations across Washington, northern and eastern Oregon and western Idaho containing data for at least eighty percent of this period of record (≥24 years) were included in this analysis (Figure

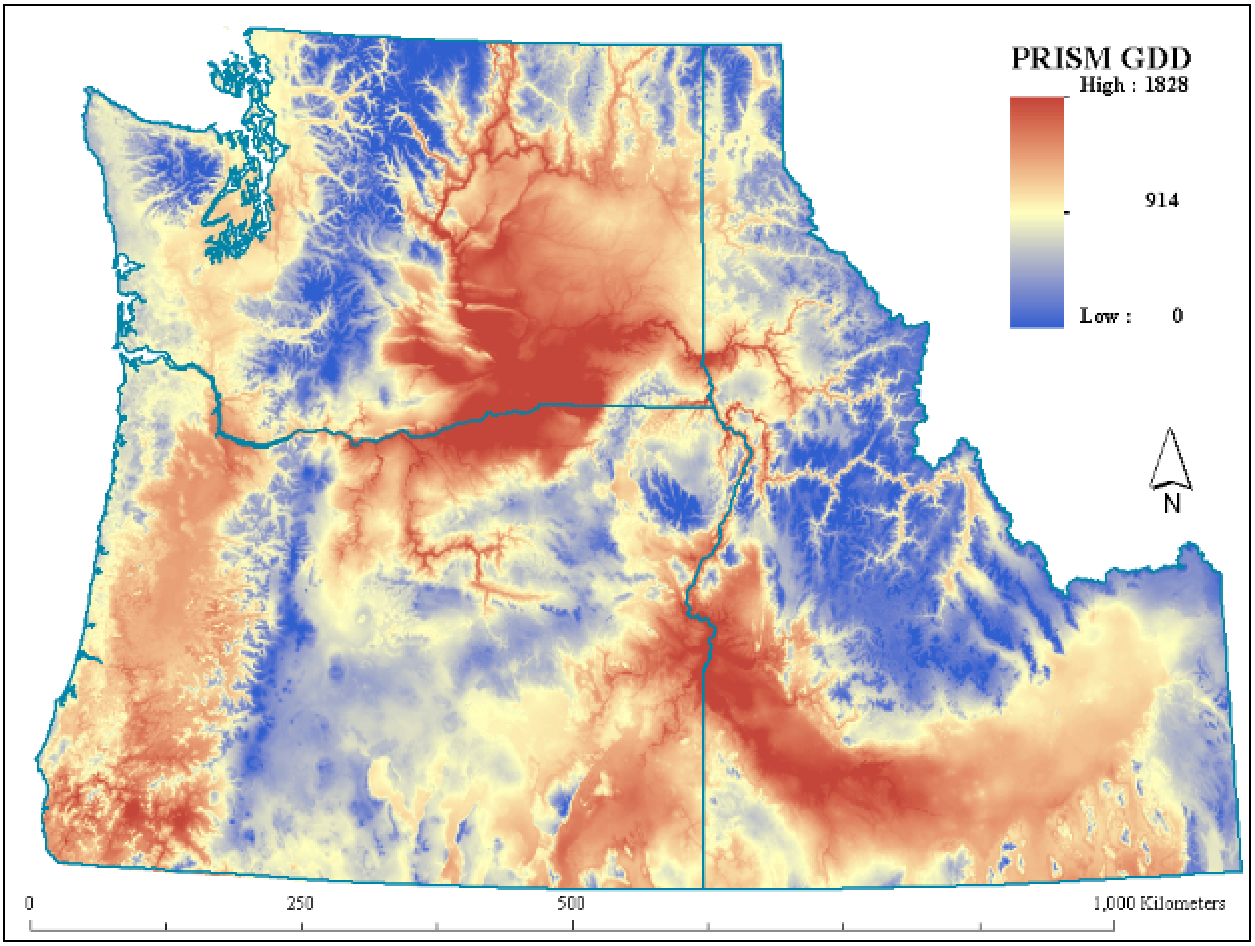


Figure 13: Growing degree-day surface calculated from Parameter-elevation Regressions on Independent Slopes Model monthly normals, 1971-2000.

14). The mean period of record for the 249 stations meeting this criteria was 28.7 years. Coordinates for the stations are given to 10^{-5} decimal degrees. Points were displayed as spatial data using the World Geodetic System (WGS), 1984 before projecting to UTM. Station elevations were extracted from the NED DEMs.

Since this weather station data is represented as point observations, it must be interpolated to produce a continuous surface of heat accumulation over the study area. We use methods similar to those described in Hall and Jones (2008). Daily maximum and minimum temperatures were averaged to daily mean temperatures. Elevation has a strong, predictable inverse relationship with temperature in well-mixed atmospheres characteristic of inland summer

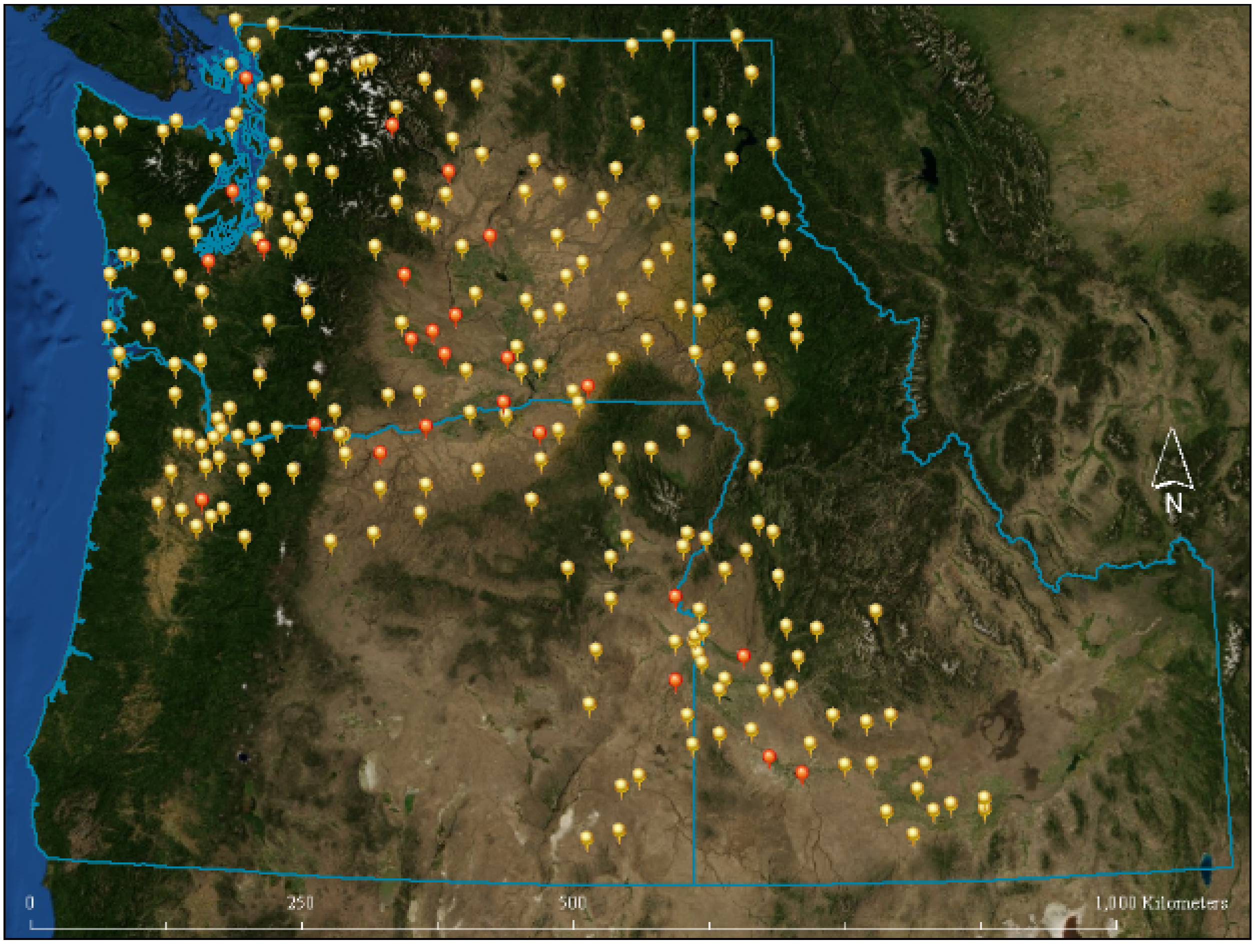


Figure 14: Location of Western Regional Climate Center weather stations with at least a 24-year period of record from 1971-2000. Red stations were used for validation of interpolations.

conditions (Daly et al., 2008). An environmental lapse rate of 6.49ºC/km vertical elevation change is widely accepted (IUPAC, 2010; Vicente-Serrano, 2003). This lapse rate was applied to each daily mean temperature so interpolations would occur over a network of stations hypothetically at sea level.

The geostatistical method of interpolation, kriging, requires normality, stationarity and isotropy (Hartkamp et al., 1999). Interpolations are performed for each day of the growing season and these conditions should be met for each interpolation. Figure 15 shows plots of mean daily temperature using WRCC data for the beginning, middle and end of the season with no strong indications of a violation of the assumption of normality. Trend surfaces are apparent in

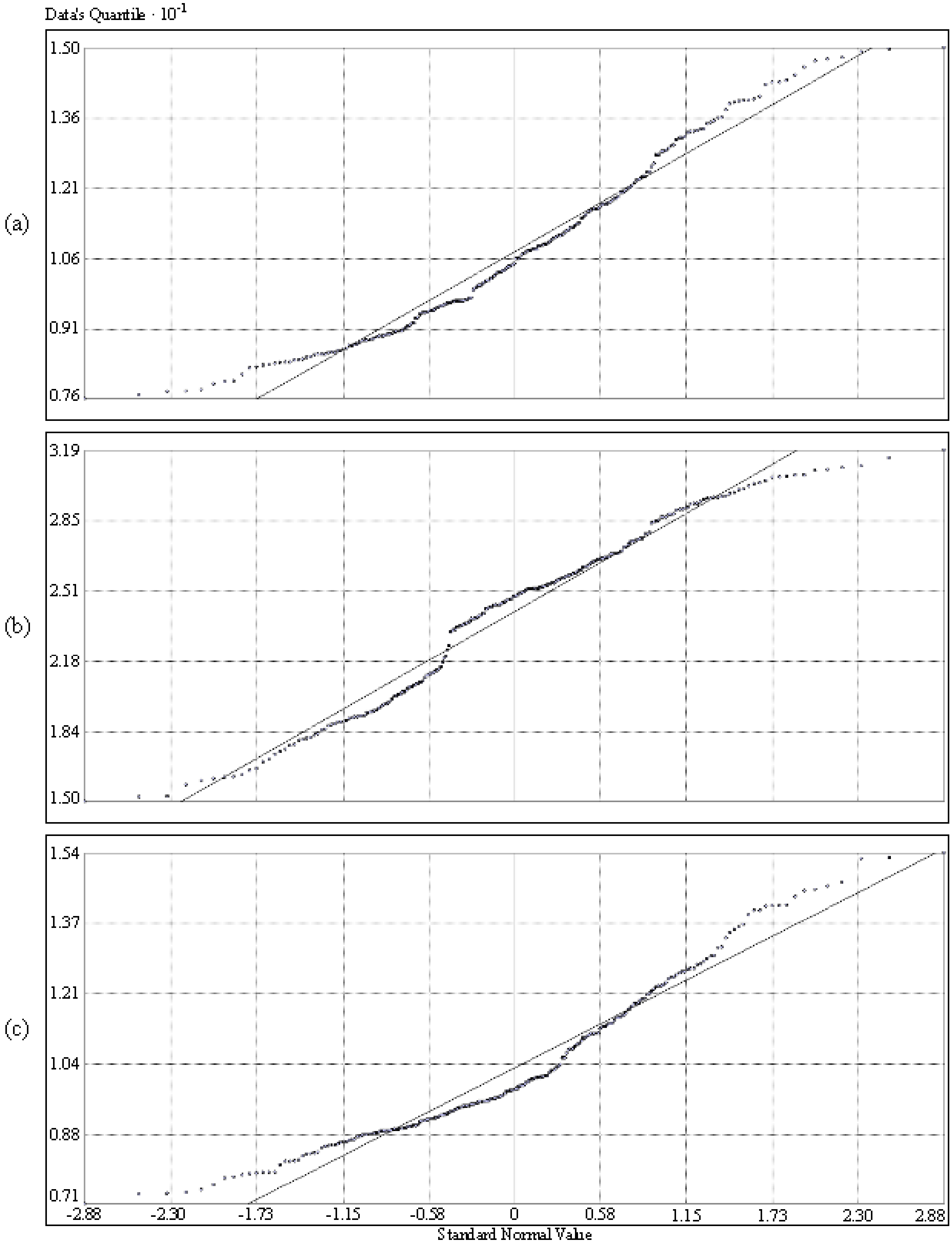


Figure 15: Western Regional Climate Center sea-level daily mean temperature normality plots for (a) 1 April; (b) 1 August; (c) 31 October. X-axis scales are consistent for all three plots.

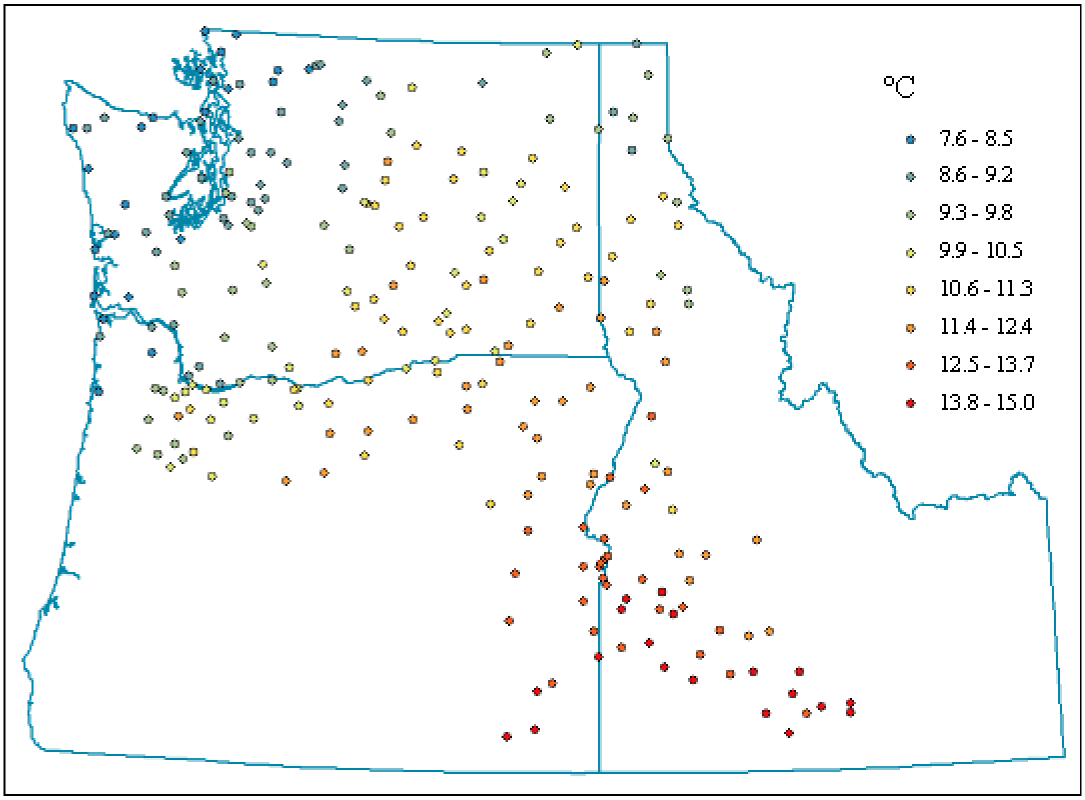
the data due primarily to maritime climates west of the Cascade Mountains, continentality on the eastern side and latitude. These trends change throughout the growing season (Figure 16). Latitude and day length tend to cause a north-south trend early and late in the growing season while a east-west or northwest-southeast trend is more apparent in the middle of the growing season.

The third condition, isotropy, requires semivariance to depend only on the lag distance and not direction. Figure 17 shows directional variograms for one day of WRCC sea-level daily mean temperatures. Variograms appear to vary with direction; range and sill appear similar between 0º and 45º and between 90º and 135º. Considering varying trend surfaces over time, it is reasonable to expect anisotropy to vary by direction through the growing season. Fitting variogram models is a complex process requiring considerable judgment and skill (Hartkamp et al., 1999).

Two interpolation methods were performed. Ordinary kriging (OK) assumes a constant, unknown mean. Figures 17 and 18 suggest a spherical model is appropriate for the semivariogram which agrees with work in interpolation of climatic variables (Hall and Jones, 2008; Hartkamp et al., 1999; Luo et al., 2008; Vicente-Serrano, 2003). Universal kriging (UK) accounts for the overriding trend surface by subtracting a modeled polynomial from observation points, modeling autocorrelation from the residuals for the interpolation then adding the polynomial back to the predicted surface (Esri, 2010). Universal kriging was performed with a linear semivariogram model with linear drift. Both kriging methods created surfaces with a resolution and lag size of 400 m and a variable search radius utilizing twelve points. Range, sill and nugget were calculated internally for each surface.

Figure 19 compares OK and UK interpolation surfaces of WRCC sea-level mean

(a)



(b)

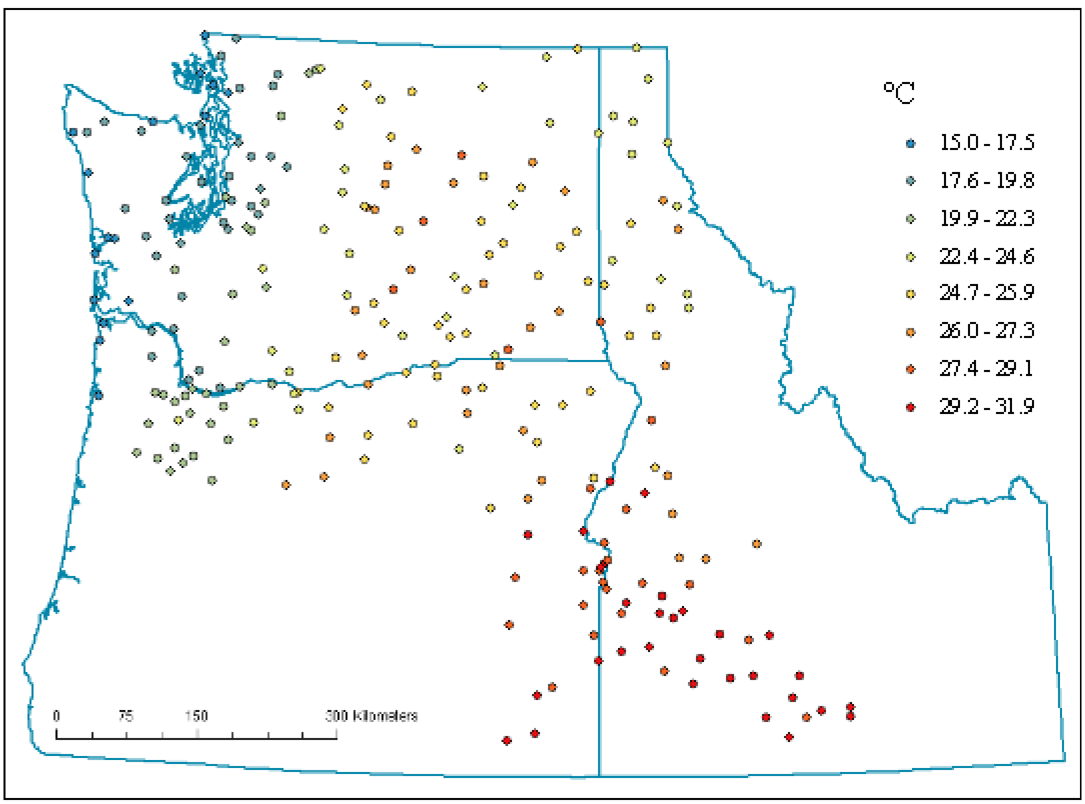


Figure 16: Examples of trends in Western Regional Climate Center sea-level daily mean temperatures for (a) 1 April; (b) 1 August. Trends surfaces vary throughout the season with (a) showing a north-south trend and (b) showing a east-west trend.

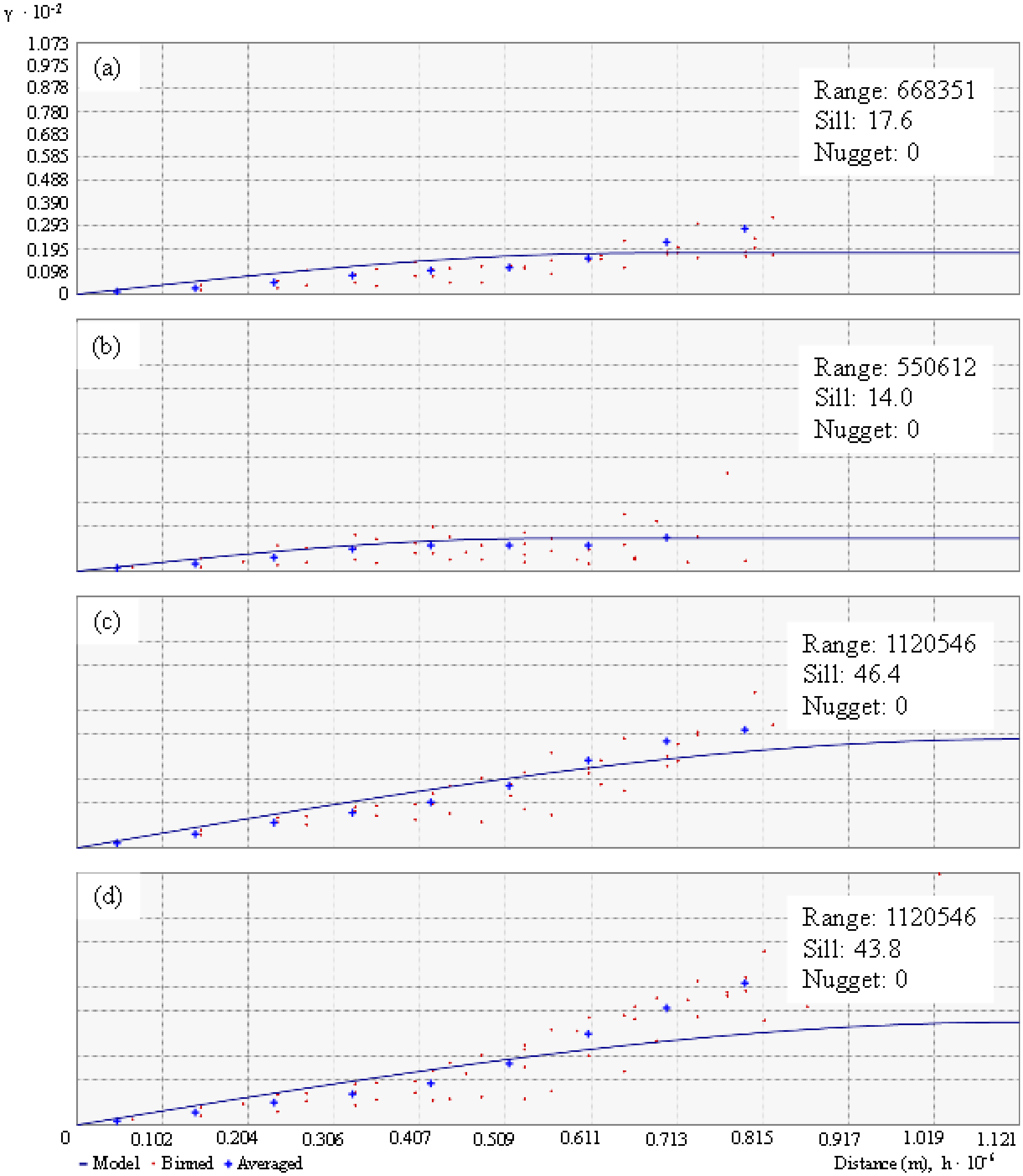


Figure 17: Directional variograms for Western Regional Climate Center sea-level daily mean temperatures for 1 August with 45° angle tolerance for (a) 0°; (b) 45°; (c) 90°; (d) 135°. Spherical model parameters were estimated visually, vary directionally and indicate anisotropy. Model fits are similar for (a) and (b) and (c) and (d). Axes scales are consistent for all four variograms.

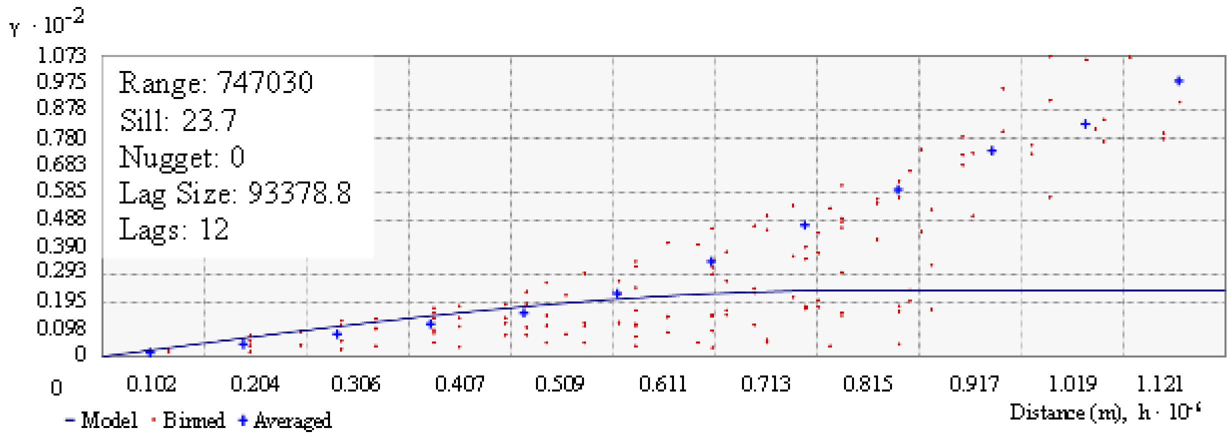


Figure 18: Variogram for Western Regional Climate Center sea-level daily mean temperature normal for 1 August, 1971-2000. Spherical model parameters were fitted using weighted least squares.

temperature on 1 April using variable radii of 6, 12 and 24 points. The interpolation creates a surface bound by a rectangle defined by the most extreme geographic locations of weather stations. The surfaces appear fractured with disparate values adjacent to one another where there are no weather stations, so decisions on parameters for the variable radius were made based on areas covered by actual observations. A twelve-point radius provides a more continuous, less fractured surface than six points and better differentiation than twenty-four points.

Interpolations of daily sea-level mean temperatures were then readjusted to actual elevations with NED DEMs using the same 6.49ºC/km lapse rate. A base temperature of 10ºC was subtracted from readjusted daily mean temperatures and the surfaces were summed to produce two GDD surfaces (Figure 20). Broad scale patterns are similar between PRISM, OK and UK GDD surfaces, but maximum heat accumulation was found to be greatest in the OK surface (1992 GDD), moderate in the PRISM surface (1828 GDD) and least in the UK surface (1772 GDD). The OK and UK interpolations both used exact techniques that assign actual observed values to their location (Hartkamp et al., 1999). Therefore, differences between these two surfaces lie in the spaces between weather stations. These interpolation methods also rely

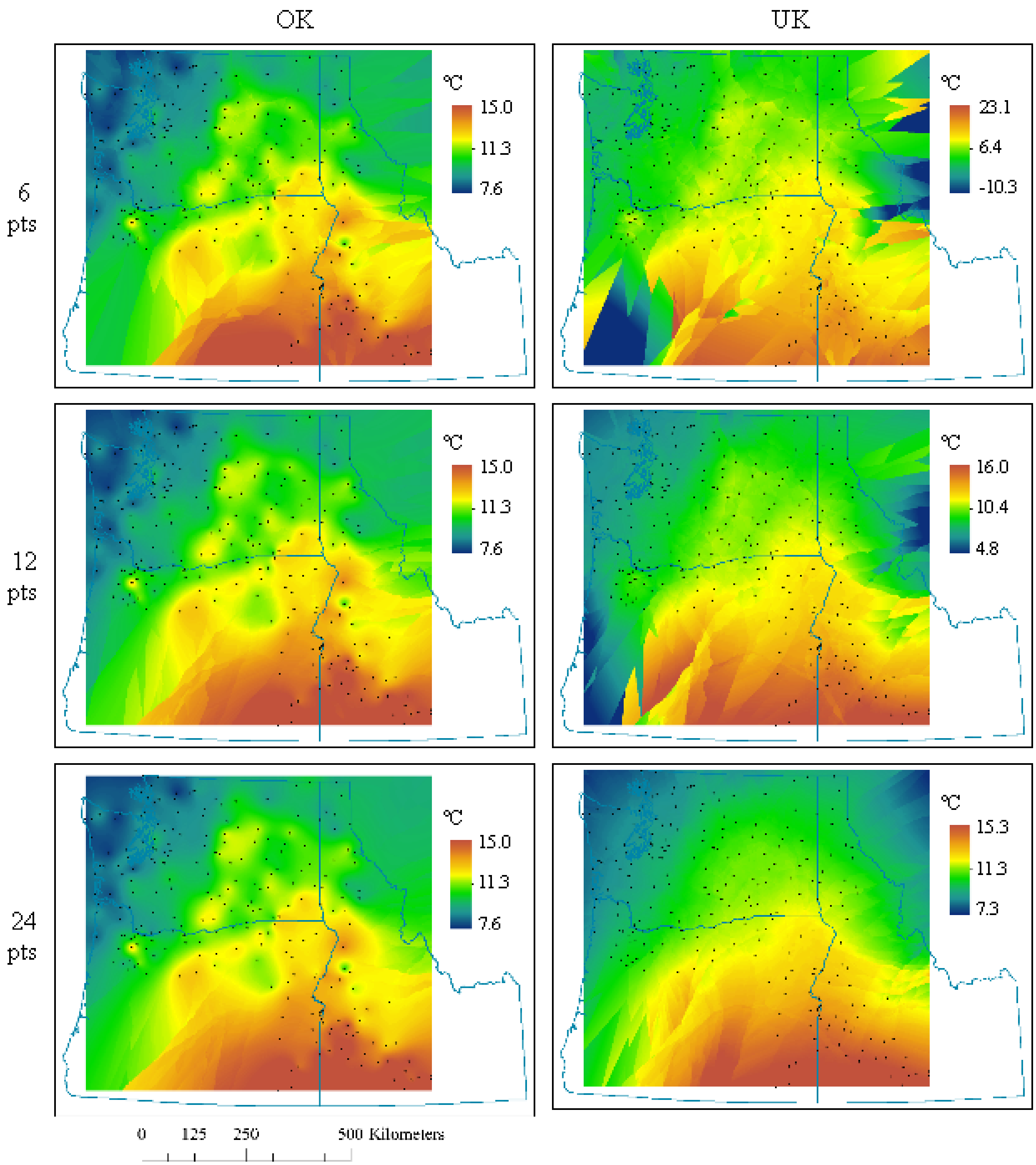


Figure 19: Variable radius interpolations using ordinary and universal kriging for Western Regional Climate Center sea-level mean temperature on 1 April. A 12-point variable radius was chosen for both interpolation methods for a balance of smooth surfaces and differentiation in temperature gradients. Both features are more notable in the universal kriging examples. Edges where stations are absent are erratic and not used in analysis.

(a)

(b)

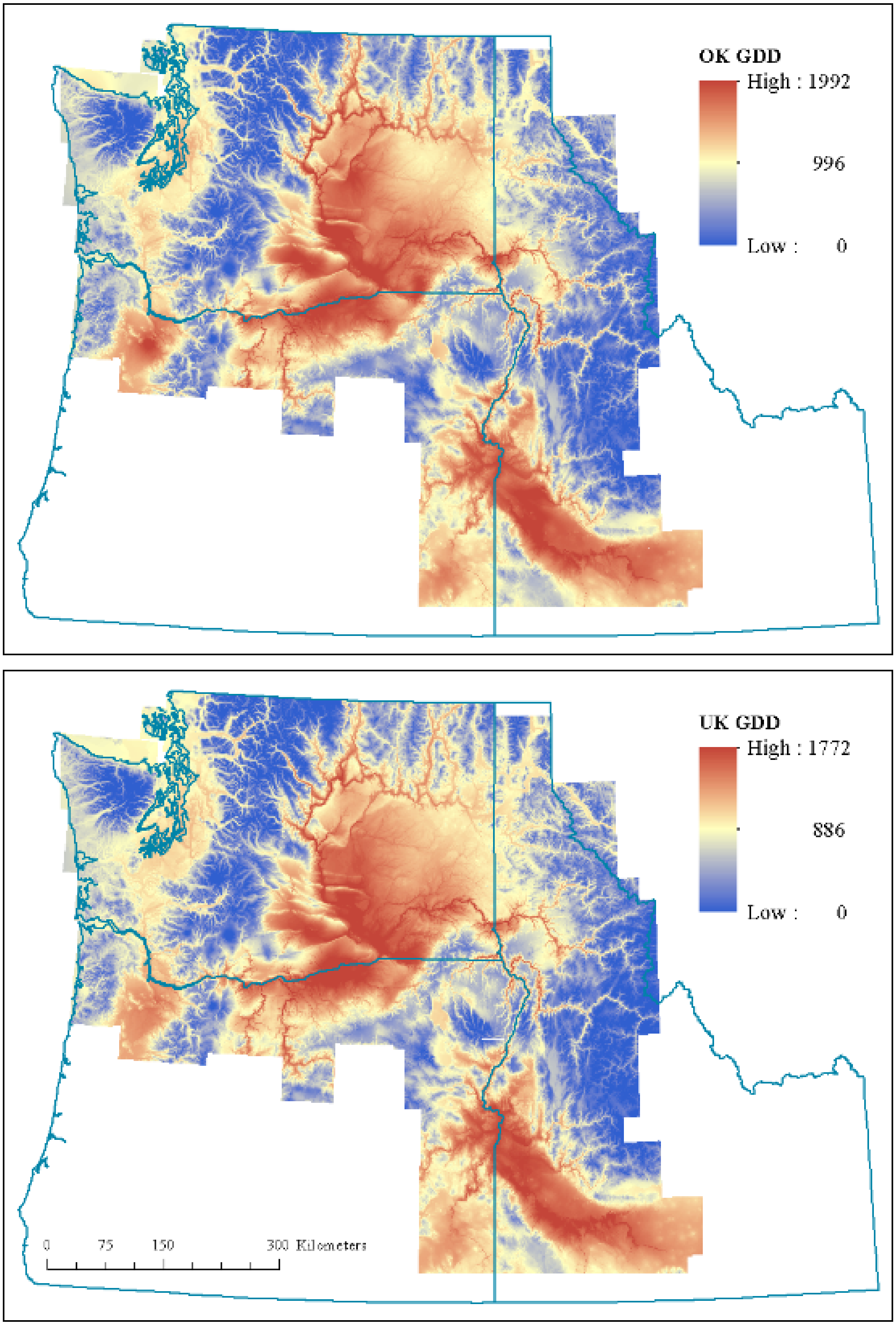


Figure 20: Growing degree-day surfaces interpolated from Western Regional Climate Center daily normals, 1971-2000, using (a) ordinary kriging and (b) universal kriging.

only on elevation to predict daily mean temperatures, unlike PRISM, which models using multiple physical factors. In a sense, we compromise physiographic robustness for temporal resolution.

Twenty-five weather stations, ten percent of the total used, were randomly selected to validate interpolated GDD surfaces with emphasis on stations in the vicinity of existing AVAs where available. Five stations were selected from both the Columbia Valley and Snake River Valley AVAs, four from the Puget Sound AVA, two from the Rattlesnake Hills AVA, one each from the Columbia Gorge, Lake Chelan, Red Mountain, Snipes Mountain, Wahluke Slope, Walla Walla and Yakima Valley AVAs and two from outside existing AVAs (Figure 14). Validation stations were removed individually, season-long interpolations and heat accumulation summations were performed and the resulting surfaces were compared to the removed station.

To calculate a latitude-temperature index (LTI) surface, a fishnet grid was created over the study area in a geographic coordinate system with an interval of 0.01 decimal degrees. North-south grid lines were removed. The line features were converted to points to which XY coordinates were added. The point features were joined to the line features and latitude values were assigned to the lines. A topo to raster interpolation was performed to create a raster surface from the latitude values with a cell size of 0.005 decimal degrees. This was projected to UTM with a cell size of approximately 800 m. The mean temperature of the warmest month (MTWM) was extracted from either July or August PRISM monthly normal maximum temperatures, the two warmest months in the region, and LTI was calculated as:

$$LTI = MTWM * (60 - \text{latitude}) \quad (1)$$

Heat accumulation and growing season length for *V. labruscana* were assessed by masking OK GDD and PRISM frost-free days (FFD) surfaces with Public Land Survey System

(PLSS) sections labeled as having a dominant crop of *V. labruscana* juice grapes in Washington State Department of Agriculture (WSDA) agricultural land use data. These two factors were rated in the context of one another. Longer growing seasons and greater heat accumulation receive the highest ratings.

Rating potential *U. necator* risk is best accomplished at the vineyard block or finer scale and research has focused on real-time risk assessment to facilitate preventative management practices and not long-term site risk rating (Gubler et al., 1999; Sall, 1980). Assuming a rough correlation between precipitation and relative humidity, PRISM monthly precipitation normals from 1971 to 2000 were masked with monthly maximum and minimum normals from April through August to produce precipitation surfaces during periods when *U. necator* is most infectious. When monthly normal maximum temperatures are less than 32ºC and minimums are greater than -2ºC, precipitation was summed, otherwise it was omitted.

2.1.1 Comparison to European wine region growing season length

A surface of median FFD from 1971 to 2000 was calculated by subtracting PRISM surfaces of median last spring frost date from median first frost date (Figure 21). Growing season lengths of wine grape growing regions in Europe were examined through weather station data from the European Climate Support Network's European Climate Assessment & Dataset (ECAD) and Zentralanstalt für Meteorologie und Geodynamik (Central Institute for Meteorology and Geodynamics [Austria], ZAMG) for comparison to the IPNW. Median growing season lengths were determined from ECAD data from 1971 to 2000 and ZAMG data from 1981 to 2000.

European median FFD are shown in Figure 22. The Krems weather station in the Wachau subregion of Lower Austria recorded a median of 184 FFD from 1981 to 2000. This is a region noted for light to full-bodied dry white wines, specifically Grüner Veltliner and Riesling (Clarke,

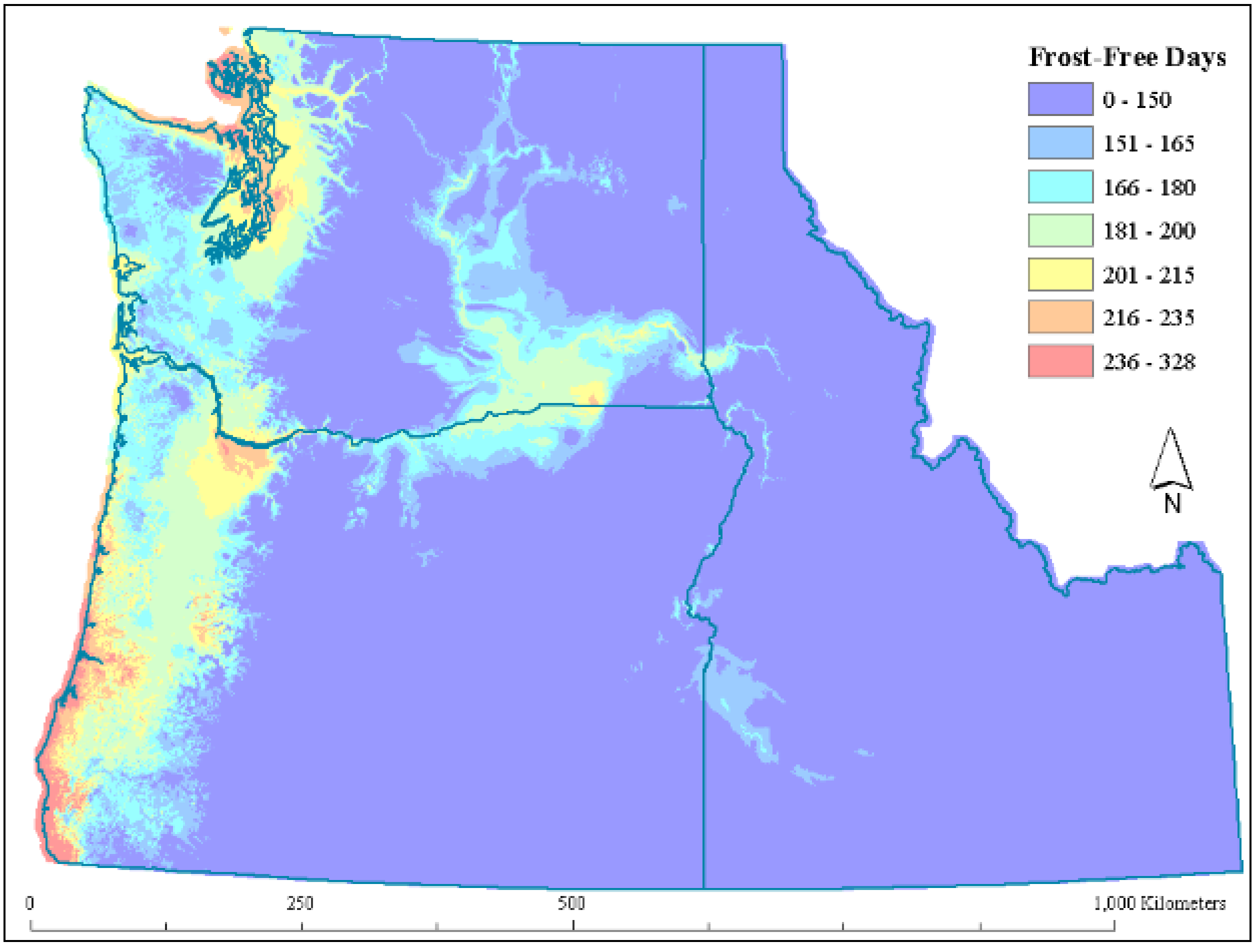


Figure 21: Median frost-free days from PRISM, 1971-2000. Much of the inland Pacific Northwest experiences a relatively short growing season in contrast to European growing regions (see Figure 23) although some comparable wine grape cultivars are grown. Climatic suitability must be examined with multiple variables, e.g. heat accumulation. Note the western portion of the region enjoys many frost-free days due to maritime climate, but most such areas lack necessary heat accumulation to ripen high-quality wine grapes.

1999; Johnson, 2003). Plantings on steep slopes along the Danube River maximize heat accumulation in a cool area (Gladstones, 1992).

The Strasbourg-Entzheim station in another cool region, Alsace in eastern France, recorded 190 FFD. Situated in the rain shadow of the Vosges Mountains, the region enjoys adiabatic warming, more cloud-free days and less relative humidity than elsewhere in the Rhine Valley (Gladstones, 1992). *Grand cru* wines are made from single varietals of Riesling, Gewürztraminer, Pinot Gris, Muscat and Sylvaner (Johnson, 2003). Long, sunny autumns allow

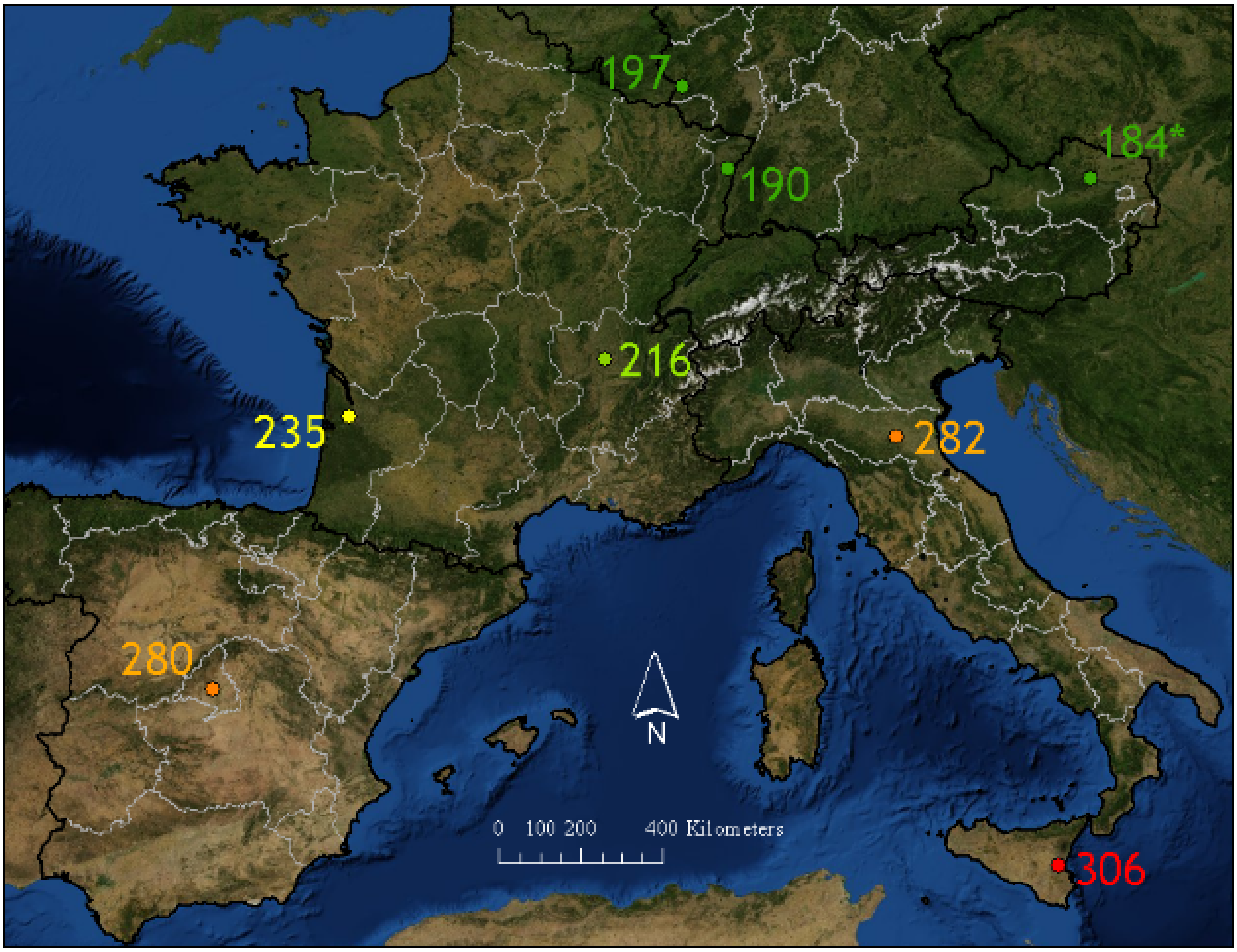


Figure 22: Median frost-free days from European Climate Assessment & Dataset and Central Institute for Meteorology and Geodynamics weather stations, 1971-2000. Krems, in the lower Wachau subregion of Austria (184 days), represents available records from 1981-2000. Strasbourg-Entzheim in Alsace recorded 190 frost-free days; Trier-Petrisberg in Mosel, 197; Bron Lyon, found between the Burgundy and Rhône, 216; Bordeaux-Merignac in Bordeaux, 235; Madrid-Retiro in Vinos de Madrid, 280; Bologna in Emilia-Romagna, 282; and Catania-Sigonella in Sicily, 306. Note these are point observations and do not capture variability within each region. The Bordeaux and Emilia-Romagna regions were examined with two stations apiece and median frost-free days were very similar between those stations.

for *Vendange Tardive* (late-harvested) wines displaying considerable residual sugar, intense fruity flavors and high alcohol levels. Conversely, *Crémant d'Alsace* (sparkling wines) are made from early harvested varieties like Pinot Blanc, Malbec and Riesling which display high acidity (Clarke, 1999). *Crémant rosé* is made exclusively with Pinot Noir, which struggles to ripen consistently in Alsace (Clarke, 1999; Johnson, 2003).

At the northerly limit of *V. vinifera* production and survivability (Gladstones, 1999), the Trier-Petrisberg station in the Mosel region of eastern France, Luxembourg and western Germany recorded 197 FFD. The winding Mosel, Saar and Ruwer Rivers cut through stony grey soils weathered from slate leaving south-facing slopes on heat-accumulating soils above moderating waterways upon which Müller-Thurgau, Elbling, Kerner and Riesling (the star) grow. Vintages are highly variable, as are microclimates within convoluted topography, but the region maintains a reputation of producing some of the best Riesling in the world. (Clarke, 1999; Johnson, 2003).

Lying between the Burgundy and Rhône regions in France, the Bron Lyon station recorded 216 FFD. Burgundy is most well-known for Pinot Noir and Chardonnay production with Gamay featuring prominently in Beaujolais (Johnson, 2003). Calcareous subsoils work in conjunction with Pinot Noir and Chardonnay's adaptation to high levels of soil calcium (Clarke, 1999; Gladstones, 1999). Gentle east and southeast facing slopes mean site selection as well as specific seasonal conditions are necessary for outstanding vintages (Gladstones, 1999; Johnson, 2003). The northern Rhône is dominated by Syrah with Mourvèdre, Grenache, Roussanne, Marsanne and Viognier playing roles in various appellations (Johnson, 2003).

The station at Bordeaux-Merignac, 60 km from the Bay of Biscay, recorded 235 FFD. This famed region is best known for its production of Cabernet Sauvignon, Cabernet Franc, Merlot, Petit Verdot, Malbec, Sauvignon Blanc and Sémillon (Johnson, 2003). Merlot, earlier flowering and ripening than the other reds, is often planted on cooler sites in an attempt to synchronize harvests (Gladstones, 1999). Some of the most highly regarded wines are grown from the best sites in Bordeaux, but it is also a diverse region with vineyards planted on gravel banks in the Médoc, limestone slopes of St-Émilion and heavy clays in the lowlands of Pomerol.

The least continental of all stations discussed thus far, moderate autumns struggle annually to ripen crops before storms roll in off the Bay of Biscay (Clarke, 1999).

Farther south, the Madrid-Retiro station recorded 280 FFD. Although the Vinos de Madrid *Denominación de Origen* experiences a more continental climate than Bordeaux, the lower latitude provides a substantially longer growing season (Johnson, 2003). Over the thirty-year period of record, the Madrid-Retiro station showed the most variability in FFD (standard deviation of 34.7), but not much greater than Bordeaux-Merignac (standard deviation of 33.0). Notable Spanish varieties in the region are Tempranillo, Grenache and Macabeo (Viura).

Situated in the epicurean hub of Emilia-Romagna, the station in Bologna recorded 282 FFD. While the Adriatic Sea lies close to the east, the region, and Italy in general, experience continental rather than Mediterranean climates with fewer sunshine hours than may be expected, which may contribute to the long growing season (Gladstones, 1992). Lambrusco is a notable volume production of Emilia while Albana is best known in Romagna (Johnson, 2003). On the east coast of Sicily, the station at Catania-Sigonella recorded a lengthy 306 FFD. Counterintuitively, this long, hot season harbors wine grape production dominated by indigenous white varieties such as Catarratto and Inzolia and some standout red varieties such as Nero d'Avola (Clarke, 1999; Johnson, 2003).

Comparison of Figures 21 and 22 show much of the IPNW record fewer median FFD than the Burgundy and Rhône regions of France. All but the northwestern portion of the Snake River Valley AVA recorded fewer than 150 median FFD, around the lower limit suggested for *V. labruscana* by Roper et al. (2006) and early-ripening *V. vinifera* by Bordelon (2009). Again, growing season length should not be examined alone, but in the context of heat accumulation and other climatic indices. European FFD data are also point measurements that do not capture the variability and complexity of the regions in which they are located.

2.1.2 Building composite suitability models

Component ratings for composite suitability models for *V. vinifera* and *V. labruscana* are summarized in Tables 2 and 3, respectively.

Slope rankings for *V. vinifera* suitability are very similar to work done by Jones et al. (2004, 2006) with slight differences at steeper slopes giving greater preference to air drainage over soil stability. Foss et al. (2010) allow for much steeper slopes, up to 45º or 100%, in their Boolean analysis presuming non-mechanized operation for much of this range. Vineyard Site Suitability Analysis (VSSA, 2011) and Wolf and Boyer (2003) do not account for modern, self-leveling equipment and recommend against site selection where slopes exceed 15%. Slope rankings for *V. labruscana* differ due to greater dormant cold hardiness and less reliance on cold air drainage (Roper et al., 2006) and disparate access to self-leveling machinery (Craig Bardwell, personal communication, 2011).

Aspect was divided symmetrically into two pairs of circular segments with equal area following similar guidelines given by VSSA (2011). East- and west-facing slopes are given moderate ranks, southern-facing slopes high ranks and northern-facing slopes and flat areas low ranks. Rankings differ from Jones et al. (2004) by giving greater ranks to east- and west-facing slopes because of potential benefits of early diurnal photosynthetic activity and canopy drying due to the former and additional heat accumulation for late-season cultivars on marginal sites due to the latter (Wolf and Boyer, 2003).

Soil drainage classes were ranked similarly to Jones et al. (2004, 2006), Jones and Duff (2007) and VSSA (2011). Soils that are wet at shallow depths for significant periods during the growing season and those in which internal free water is rare or excessively deep receive the

Table 2: Composite site suitability component ratings for *V. vinifera*. A rating of 'NoData' removes an area from consideration in a composite suitability model. Growing degree-days, growing season length and the latitude-temperature index (LTI) receive numeric codes forming classification groups (see Table 6). Abbreviations: ED (excessively drained), SED (somewhat excessively drained), WD (well drained), MWD (moderately well drained), SPD (somewhat poorly drained), PD (poorly drained), VPD (very poorly drained), AWC (available water-holding capacity), OK GDD (ordinary kriging growing degree-days), FFD (frost-free days).

	0	1	2	3	4	3	1	0	NoData
Topography									
Slope (%)	<1	1-5	6-15				16-25	26-30	>30
Insolation (Wh/ m^2)	<969,620	969,621-1,027,609	1,027,610-1,065,494	1,065,495-1,103,865	>1,103,865				
Aspect (°)	-1-67.5	67.6-112.5	112.6-247.5				247.6-292.5	292.6-360	
Soil									
Drainage	ED	SED	WD; MWD					SPD; PD; VPD	
AWC (cm/cm)	<0.075				0.075-0.15	0.16-0.2	0.21-0.25	>0.25	
Depth (cm)	0-50	51-100	>100						
pH	<6	6.1-6.5	6.6-7.5				7.6-8	>8	
Climate									
Precipitation (cm)	>50	36-50	15-35	<15					
OK GDD (°C)	*0*	*<I*	*I*	*II*	*III*	*IV*	*V*	*VI*	
	<900	900-1275	1276-1400	1401-1500	1501-1600	1601-1700	1701-1800	>1800	
FFD	*NoData*	*Ia*	*Ib*	*Ic*	*II*	*III*	*IV*	*VI*	
	<130	130-150	151-165	166-180	181-200	201-215	216-235	>235	
LTI	*<A*		*A1, A2*		*B*		*C*	*D*	
	<100		100-190		191-270		271-380	>380	

Table 3: Composite site suitability component ratings for *V. labruscana*. A rating of 'NoData' removes an area from consideration in the composite suitability model. Climatic variables receive numeric codes forming classification groups. Abbreviations: ED (excessively drained), SED (somewhat excessively drained), WD (well drained), MWD (moderately well drained), SPD (somewhat poorly drained), PD (poorly drained), VPD (very poorly drained), AWC (available water-holding capacity), OK GDD (ordinary kriging growing degree-days), FFD (frost-free days).

	0	1	2	3	4	1	0	NoData
Topography								
Slope (%)		0-3	4-15				16-30	>30
Insolation (Wh/m^2)	<969,620	969,621-1,027,609	1,027,610-1,065,494	1,065,495-1,103,865	>1,103,865			
Soil								
Drainage	ED	SED	WD; MWD				SPD; PD; VPD	
AWC (cm/cm)		<0.075		0.075-0.15	0.16-0.2	0.21-0.25	>0.25	
Depth (cm)	0-75	76-150	>150					
pH	<5.5	5.5-6	6.1-7			7.1-7.5	7.6-8.3	>8.3
$CaCO_3$ (%)	7.6-10	2.6-7.5	0-2.5					>10
Climate								

	<150 FFD	150-165	166-180	181-195	>195
<1200 OK GDD (°C)				0	100
1200-1375			0	100	200
1375-1550		0	100	200	300
1550-1725		100	200	300	400
>1725		200	300	400	500

lowest ranks (Soil Survey Division Staff, 1993). This is intended to balance vines' aversion to saturated soil conditions with the soil's ability to retain irrigation water for a reasonable duration.

Rankings for AWC for *V. vinifera* are similar to those of Jones et al. (2004) and weighted more towards higher AWC than proposed values in Wolf and Boyer (2003). Jones et al. (2004) performed site suitability analysis in the Rogue Valley, Oregon where irrigation is not obligatory and therefore a minimum threshold of 0.10 cm/cm is proposed to which we do not adhere. AWC rankings for *V. labruscana* are shifted from *V. vinifera* rankings to give greater consideration to greater AWC because restricting vegetative vigor is not a goal of *V. labruscana* management.

Depth to restrictive layer and soil pH follow ratings similar to those of Wolf and Boyer (2003) for *V. vinifera.* Similar minimum depths are recommended by VSSA (2011). Ratings for *V. labruscana* give greater weight to even deeper soils, again because managing vegetative growth is not a concern. *V. labruscana* pH ratings shift preferred ranges to more acidic soils in which vines can thrive (Meinert and Curtin, 2005) and pH values greater than 8.3 are removed from consideration due to greater intolerance of alkaline soils than *V. vinifera*. Calcium carbonate ratings are based on effervescence tests in sand (Table 4). Noneffervescent amounts of calcium carbonate receive the highest ratings while strongly effervescent amounts receive the lowest.

Heat accumulation groupings are a preliminary effort at distinguishing ripening groups. Classifications developed by Amerine and Winkler (1944) in California are often cited, but may not be appropriate for the IPNW. Since mean temperatures are calculated as a simple mean of daily or monthly maximum and minimum temperatures, diurnal temperature range can help inform actual heat accumulation.

The continentality, low relative humidity and extended day length during the growing season experienced in IPNW grape-growing regions result in often high temperatures during

Table 4: Effervescence reactions to hydrochloric acid with varying levels of $CaCO_3$ in Quincy fine sand.

$\%CaCO_3$	Reaction
0	Noneffervescent
1	Noneffervescent
2.5	Very slightly effervescent
5	Slightly effervescent
7.5	Strongly effervescent
10	Strongly effervescent

photosynthetically active hours and quickly cooling temperatures at night (Huggett, 2006; Meinert and Busacca, 2002). Figure 23 shows one example of different diurnal temperature ranges calculated from WRCC 1971-2000 normals for Prosser, WA and Napa, CA. The peak of this disparity occurs at the end of July and beginning of August with a difference of 3.8ºC. This suggests GDD requirements, as commonly calculated, may be lower for the same cultivars in the IPNW compared to other wine-producing regions. LTI groupings follow Jackson and Cherry (1988) and Jackson and Lombard (1993).

Minimum FFD in 2010 WSDA agricultural land use data *V. labruscana* dominated sections was 151 days, maximum was 198 and mean was 170. Minimum OK GDD in *V. labruscana* dominated sections was 1237, maximum was 1715 and mean was 1485.

Two composite suitability models were created for *V. vinifera*, one utilizing LTI, the other OK GDD, and one for *V. labruscana*. Each composite is organized as sub-composites of topographic, edaphic and climatic suitability. Component weightings are largely based on Jones et al. (2004) and Jones and Duff (2007). Individual component weights are summarized in Table 5. Because of ratings given to AWC, its weighting is one half of those assigned to other soil characteristics except for drainage to maintain an equal influence for the greatest possible AWC rating. Due to the coarseness of *U. necator* risk ratings, it was given relatively low weighting.

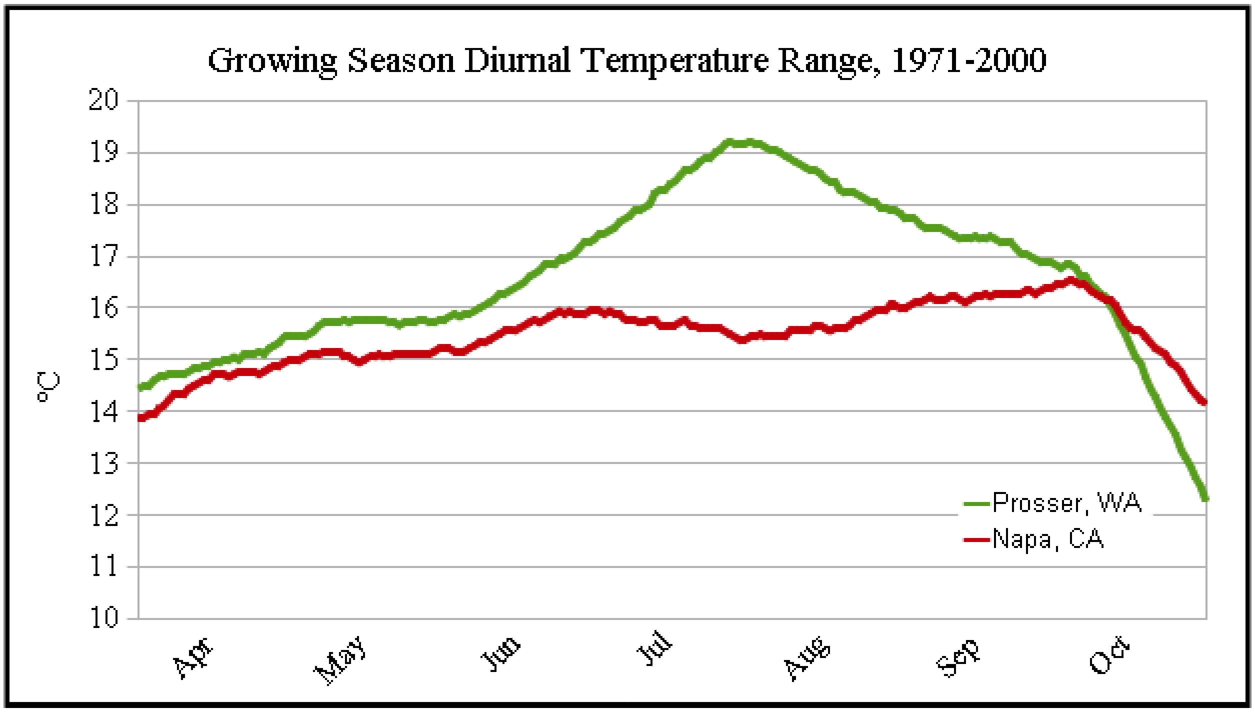


Figure 23: Example of diurnal temperature difference between inland Pacific Northwest and California wine regions from Western Regional Climate Center normals, 1971-2000. The station at Prosser (46°12'N, 119°45'W) exhibits a greater diurnal temperature range than Napa (38°17'N, 112°16'W) for the vast majority of the growing season, most notably in the hottest months of July and August. The lines cross on Ocrober 11, very late in the growing season, after which Prosser's diurnal temperature range is less than that of Napa.

Sub-composites are added together with equal weight.

Precipitation, topography and soil characteristics are represented in the ones and tens places of the composite numerical site suitability score after being multiplied by ten and converted to integers. Heat accumulation and growing season length inform cultivar selection in *V. vinifera* models and form the basis of ripening potential in the *V. labruscana* model. They comprise the hundreds and/or thousands places of suitability scores. Classification schemes and associated numerical codes for *V. vinifera* models are given in Table 6. Refer to Table 3 for *V. labruscana* model numerical codes.

For example, the composite suitability for a site with a slope of 10%, 1,050 kWh/m^2 of solar insolation, well drained soil, 0.22 cm/cm of AWC, 75 cm of depth to any restrictive layer, soil pH of 7.7, 10 cm of precipitation, 1,300 GDD and 185 FFD is calculated as:

$$\text{Int}\{10 * [(.7 * 2) + (.3 * 2)] + [(.4 * 2) + (.1 * 1) + (.2 * 1) + (.2 * 1)] + (.3 * 3)\} + 1000 + 300 = 1{,}342 \tag{2}$$

Suitability surfaces were built by county using ArcGIS ModelBuilder™. See Appendix A for details. Figures 24 through 26 are the resulting composite site suitability surfaces for the IPNW.

Table 5: Composite site suitability model component weightings. Each category, topography, soil and climate, are given equal weight when summed to calculate composite site suitability. Heat accumulation indices and growing season length are included in composites to form climatic classification groups. Abbreviations: LTI (latitude-temperature index), OK GDD (ordinary kriging growing degree-days), AWC (available water-holding capacity).

	LTI Model	**OK GDD Model**	***V. labruscana* Model**
Topography			
Slope	0.85	0.7	0.6
Insolation		0.3	0.4
Aspect	0.15		
Soil			
Drainage	0.4	0.4	0.4
AWC	0.1	0.1	0.075
Depth	0.2	0.2	0.15
pH	0.2	0.2	0.15
$CaCO_3$			0.15
Climate			
Precipitation	0.3	0.3	

Table 6: Heat accumulation and growing season length classification schemes for *V. vinifera* models. Abbreviations: LTI (latitude-temperature indes), GDD (growing degree-days), FFD (frost-free days).

LTI Model								
Group	<A	A1, A2	B	C	D			
LTI	<100	100-190	190-270	270-380	>380			
Code	0	100	200	300	400			
GDD Model								
Group	0	<I	I	II	III	IV	V	VI
GDD	<900	900-1275	1275-1400	1400-1500	1500-1600	1600-1700	1700-1800	>1800
Code	NoData	0	1000	2000	3000	4000	5000	6000
Group	0	Ia	Ib	Ic	II	III	IV	V
FFD	<130	130-150	150-165	165-180	180-200	200-215	215-235	>235
Code	NoData	0	100	200	300	400	500	600

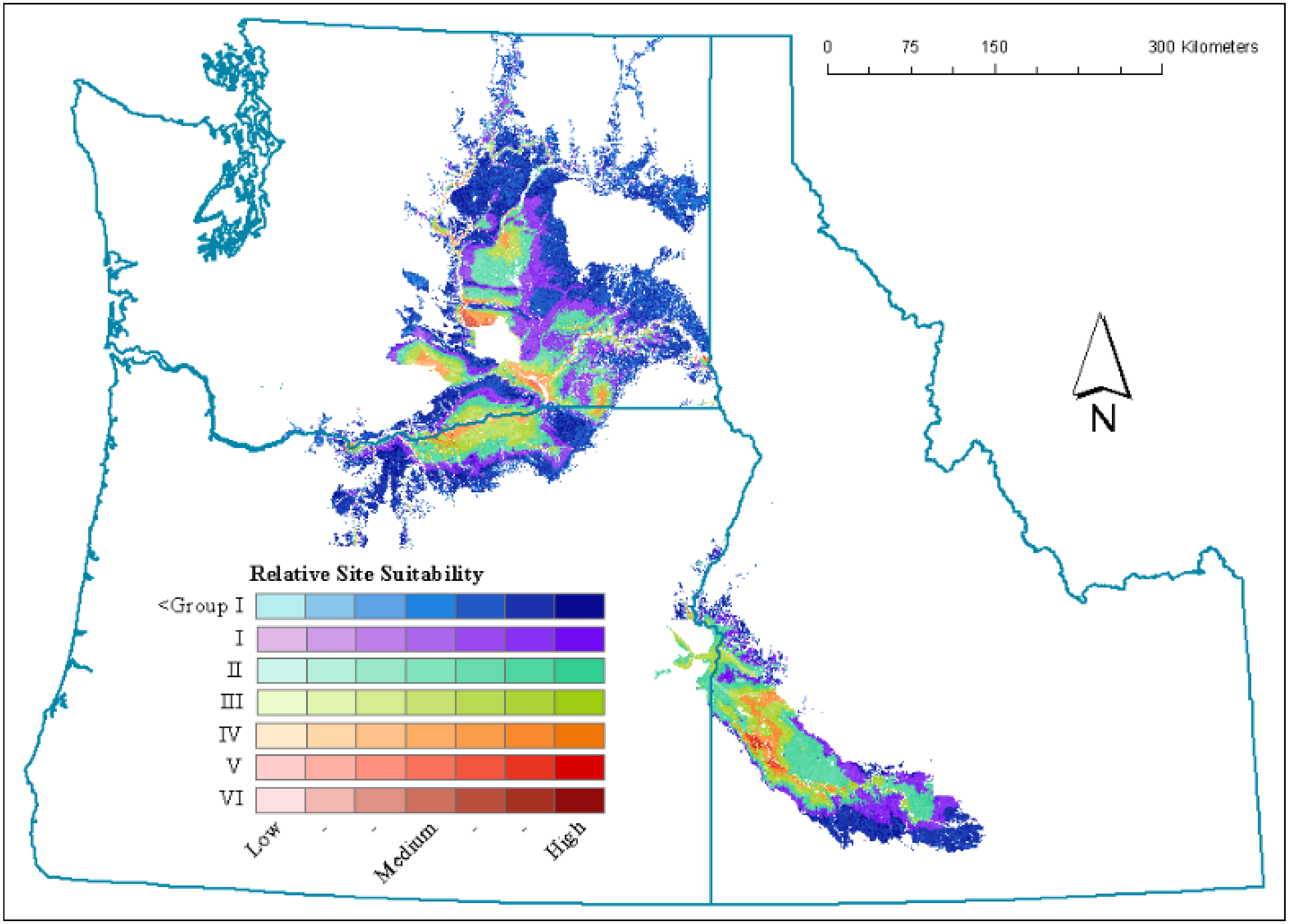


Figure 24: Inland Pacific Northwest *V. vinifera* site suitability model. Climatic groups are classifications of the ordinary kriging interpolation of degree-days surface (see Table 2). At this small scale, it is difficult to observe, but each pixel is shaded to indicate relative composite site suitability with darker pixels indicating greater site potential.

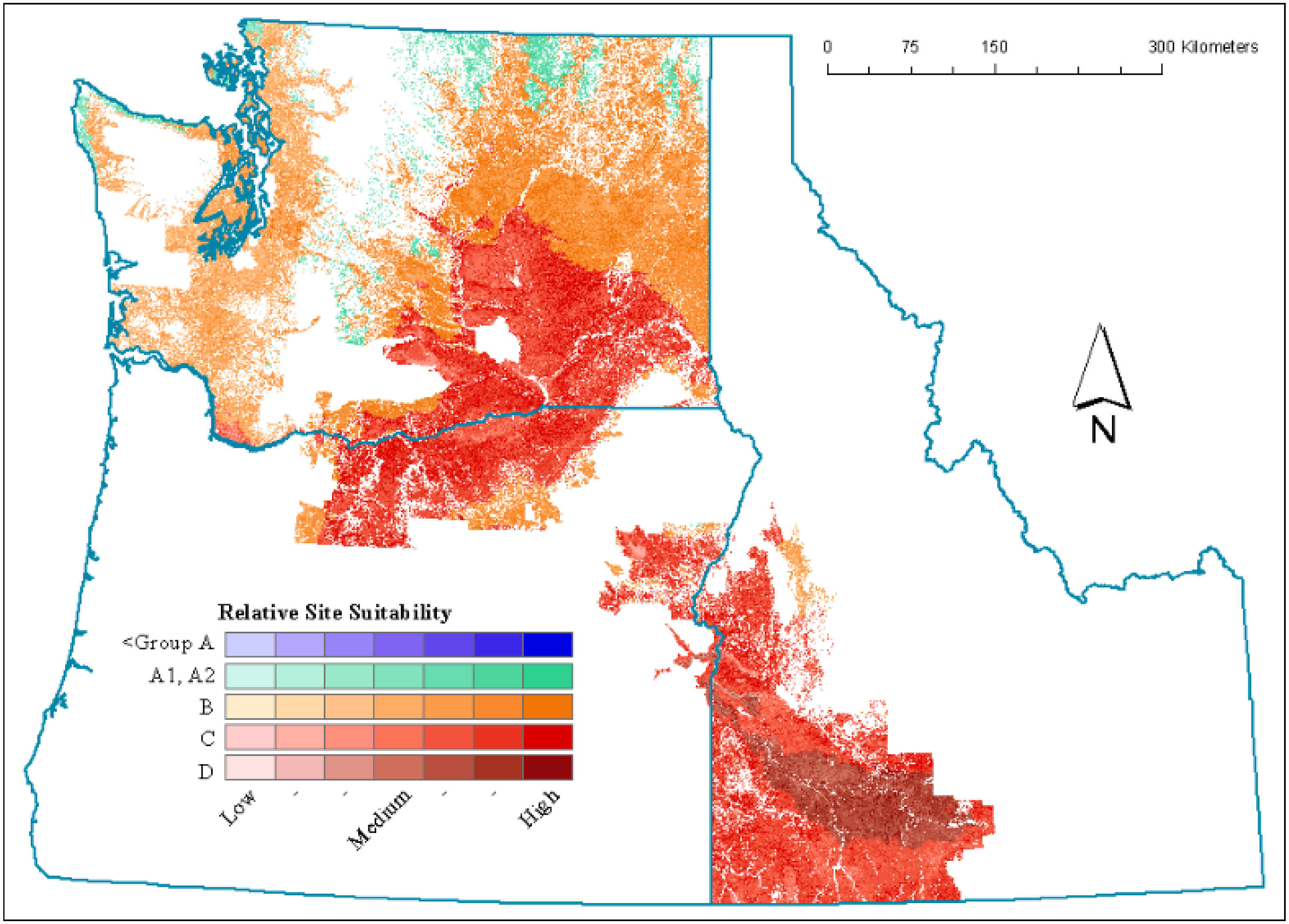


Figure 25: Inland Pacific Northwest *V. vinifera* site suitability model. Groups are based on latitude-temperature index classifications (see Table 2). At this small scale, it is difficult to observe, but each pixel is shaded to indicate relative composite site suitability with darker pixels indicating greater site potential.

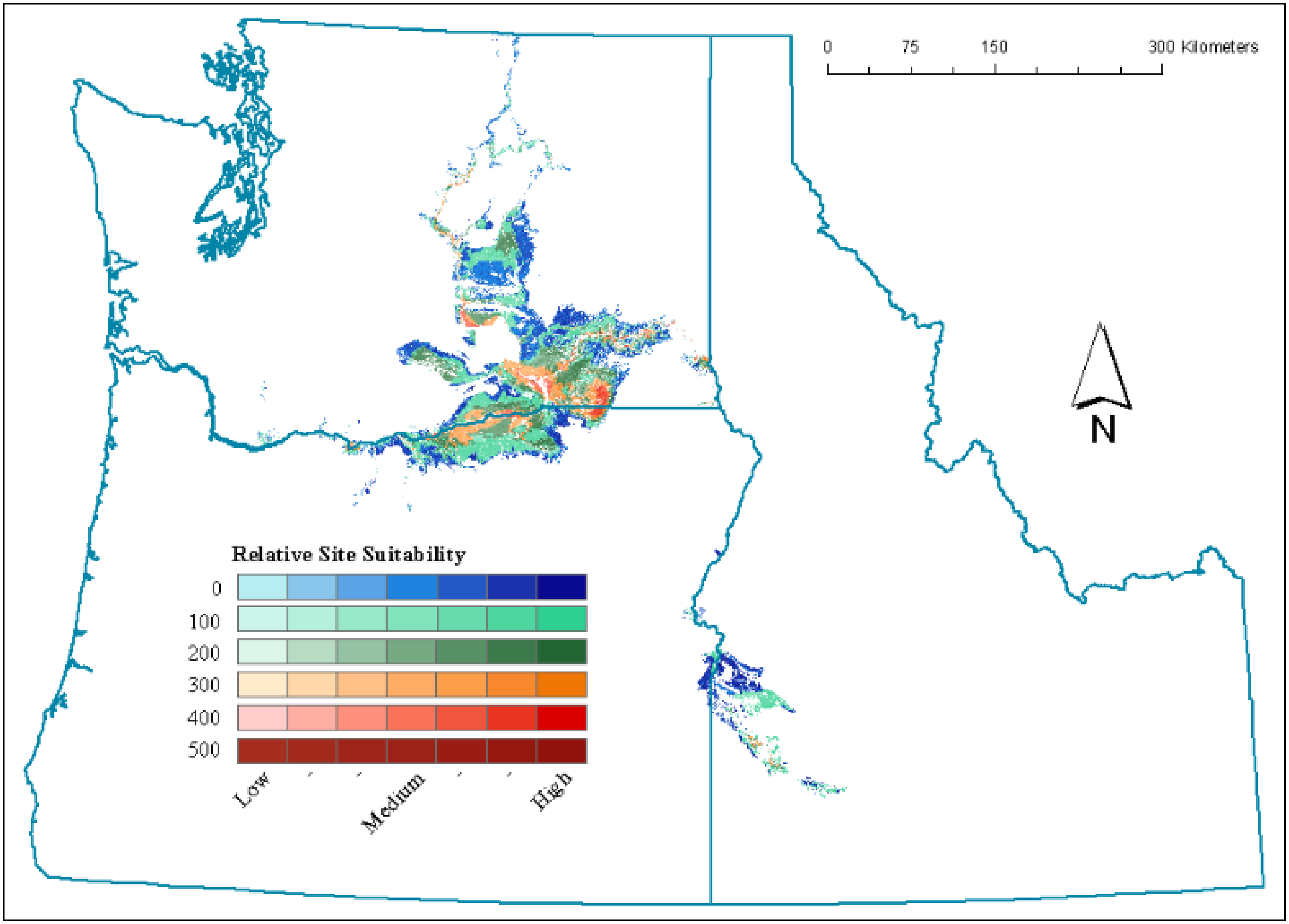


Figure 26: Inland Pacific Northwest *V. labruscana* site suitability model. Climatic groups are based on ordinary kriging interpolation of degree-days and frost-free day surfaces (see Table 3). At this small scale, it is difficult to observe, but each pixel is shaded to indicate relative composite site suitability with darker pixels indicating greater site potential.

CHAPTER THREE

ANALYSIS AND VALIDATION

3.1 Analysis and validation

Mapped site characteristics and composite topographic and edaphic suitabilities were masked for each American Viticultural Area (AVA) with water bodies from the National Hydrography Dataset (NHD) excluded. Summary statistics (minimum, maximum, mean, standard deviation and median for integer variables) were calculated for each except aspect, for which summary statistics mean little. Mean aspect for each AVA is included with analysis of solar insolation. Composite topographic and edaphic suitabilities were divided into five quantiles. These were compared to final rule or proposed rule descriptions of AVAs from the *Federal Register*. Composite topographic and edaphic suitability surfaces for *V. vinifera* were masked with areas of the 2010 Cropland Data Layer (CDL) designated as grapes as well as actual mapped vineyard blocks.

AVA boundaries were mapped following final rule or proposed rule descriptions in the *Federal Register*, the corresponding, georeferenced U.S. Geological Survey (USGS) topographic quadrangle maps and topographic lines extracted from the National Elevation Dataset (NED) digital elevation model (DEM). The proposed Ancient Lakes AVA boundary was provided courtesy Joan Davenport and the remainder except the Snake River Valley and proposed Naches Heights AVAs were provided courtesy Richard Rupp.

Some existing Washington vineyards were mapped by cultivar with a combination of global positioning system (GPS), aerial imagery, maps provided by growers and a commercially produced map of Red Mountain AVA by VinMaps™ (http://vinmaps.com/, 2007). Growers were interviewed regarding perceptions of vineyard performance, specifically issues relating to mapped environmental variables, and planting dates. Comparison of interview results and site suitability models represents a preliminary effort at ground truthing for the site selection model over a vast region and focused on the Wahluke Slope, Red Mountain, Yakima Valley, Horse Heaven Hills and proposed Ancient Lakes AVAs. In total, 1,100 ha were mapped.

Climatic variables (three growing degree-day (GDD) surfaces, latitude-temperature index (LTI), frost-free days (FFD) as well as ratios of GDD to FFD) were extracted from *V. vinifera* blocks mapped by cultivar. All blocks mapped as well as those confirmed to have been planted in 2003 or earlier (at least eight years old) were analyzed and compared to the literature on ripening requirement groups.

3.2 Comparison of mapped characteristics to AVA descriptions

Tables 7 through 9 summarize topographic characteristics by AVA and Tables 10 and 11 summarize composite topographic suitability for *V. vinifera* and *V. labruscana*, respectively. Tables 12 through 16 summarize soil characteristics and Tables 17 and 18 summarize composite soil suitability for *V. vinifera* and *V. labruscana*, respectively. Tables 19 through 24 summarize climatic characteristics. These summaries do not represent realistically plantable area within each appellation, but merely the entire area within boundaries excluding water features from the NHD. The availability of water for irrigation is often a greater limitation than other facets of site suitability (Busacca and Meinert, 2003; Norman et al., 2004). Discussion of AVAs proceeds in chronological order of establishment.

3.2.1 Yakima Valley AVA

The approximately 2,900 km^2 Yakima Valley AVA was the first appellation established in Washington state on 4 May 1983. A long history of viticulture exists in the Yakima River valley, an area bounded by four east-to-west basaltic uplifts, including both *V. labruscana* and *V. vinifera* production (ATF, 1983). According to 2010 CDL satellite imagery classifications, approximately 26,000 ha of grapes were planted in the Yakima Valley AVA.

Table 7: Summary statistics by American Viticultural Area of elevation, in meters, from National Elevation Dataset 10-meter digital elevation model and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	128	1096	331.02	156.03	268	6
Walla Walla Valley	122	697	314.74	118.20	292	4
Columbia Valley	23	1441	461.89	211.01	423	10
Red Mountain	167	428	227.08	40.70	213	1
Columbia Gorge	23	839	404.91	168.23	409	8
Horse Heaven Hills	77	670	322.68	123.11	320	5
Wahluke Slope	124	501	250.95	68.93	245	2
Rattlesnake Hills	258	920	433.49	133.72	397	9
Snake River Valley	514	1504	874.36	110.77	881	13
Snipes Mountain	220	398	279.13	33.31	272	3
Lake Chelan	289	1148	487.90	126.50	453	11
Naches Heights*	359	647	542.28	52.18	548	12
Ancient Lakes*	174	582	386.16	49.19	380	7

*Proposed AVA

Table 8: Summary statistics by American Viticultural Area of slope, in percent rise, calculated from National Elevation Dataset 10-meter digital elevation model and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	0	120	5.24	8.06	2	3
Walla Walla Valley	0	195	10.62	11.12	7	7
Columbia Valley	0	762	11.29	14.07	6	9
Red Mountain	0	69	7.67	8.72	5	5
Columbia Gorge	0	326	22.83	19.09	17	12
Horse Heaven Hills	0	134	6.58	8.44	4	4
Wahluke Slope	0	176	2.99	5.00	1	1
Rattlesnake Hills	0	92	11.51	10.19	8	10
Snake River Valley	0	839	10.75	15.30	4	8
Snipes Mountain	0	84	17.43	10.72	15	11
Lake Chelan	0	319	24.49	20.78	19	13
Naches Heights*	0	203	10.59	14.11	6	6
Ancient Lakes*	0	493	4.35	12.01	1	2

*Proposed AVA

Table 9: Summary statistics by American Viticultural Area of solar insolation, in kilowatt-hours per square meter, calculated over the growing season (April through October) from National Elevation Dataset 10-meter digital elevation model and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Mean Aspect	Rank
Yakima Valley	468.49	1179.07	1031.22	33.64	1031.97	171.4	10
Walla Walla Valley	265.58	1115.53	1007.19	47.77	1020.58	197.5	4
Columbia Valley	112.13	1234.53	1022.15	64.36	1034.76	181.9	6
Red Mountain	695.90	1094.09	1016.69	24.49	1022.96	207.3	5
Columbia Gorge	133.98	1155.36	983.50	93.97	1007.45	180.9	2
Horse Heaven Hills	452.97	1119.61	1031.74	36.41	1038.33	176.4	12
Wahluke Slope	551.52	1096.88	1027.91	17.69	1030.94	188.7	9
Rattlesnake Hills	568.57	1152.46	1031.58	39.18	1038.43	202.5	11
Snake River Valley	107.81	1263.39	1111.86	70.82	1128.24	177.4	13
Snipes Mountain	738.16	1095.47	994.42	45.65	1004.23	172.4	3
Lake Chelan	270.13	1152.14	951.64	89.38	979.68	174.0	1
Naches Heights*	300.54	1108.84	1026.22	63.06	1046.11	158.6	7
Ancient Lakes*	149.88	1092.35	1026.29	43.96	1039.39	148.7	8

*Proposed AVA

Table 10: Summary statistics by American Viticultural Area of topographic suitability for *V. vinifera* using slope and solar insolation. Proportional areas are divided between five quantiles. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	1Q	2Q	3Q	4Q	5Q	Max.	Mean	St. Dev.	Rank
Yakima Valley	0	6.00%	39.61%	26.40%	22.65%	5.34%	2.6	1.19	0.56	4
Walla Walla Valley	0	9.46%	34.18%	24.52%	30.90%	0.94%	2.6	1.22	0.52	5
Columbia Valley	0	13.88%	6.39%	55.83%	7.89%	16.01%	2.6	1.35	0.57	9
Red Mountain	0	10.35%	35.72%	14.64%	39.27%	0.02%	2.3	1.26	0.51	6
Columbia Gorge	0	8.23%	31.75%	15.34%	37.02%	7.66%	2.6	1.33	0.59	8
Horse Heaven Hills	0	3.25%	19.32%	41.99%	31.99%	3.45%	2.6	1.39	0.44	10
Wahluke Slope	0	13.81%	47.07%	22.22%	16.88%	0.03%	2.3	1.07	0.51	2
Rattlesnake Hills	0	2.68%	16.26%	29.13%	44.18%	7.75%	2.6	1.52	0.49	12
Snake River Valley	0	1.29%	3.86%	21.99%	47.06%	25.80%	2.6	1.83	0.53	13
Snipes Mountain	0	7.75%	33.25%	14.36%	44.59%	0.06%	2.3	1.27	0.54	7
Lake Chelan	0	11.31%	45.44%	15.77%	27.34%	0.14%	2.6	1.11	0.51	3
Naches Heights*	0	1.77%	20.86%	32.20%	41.63%	3.54%	2.3	1.42	0.49	11
Ancient Lakes*	0	1.49%	52.69%	34.37%	11.11%	0.34%	2.3	1.00	0.44	1

*Proposed AVA

Table 11: Summary statistics by American Viticultural Area of topographic suitability for *V. labruscana* using slope and solar insolation. Proportional areas are divided between five quantiles. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	1Q	2Q	3Q	4Q	5Q	Max.	Mean	St. Dev.	Rank
Yakima Valley	0	4.34%	13.77%	42.49%	31.41%	7.99%	2.8	1.50	0.49	9
Walla Walla Valley	0	19.51%	18.08%	44.83%	16.50%	1.07%	2.8	1.24	0.61	3
Columbia Valley	0	19.17%	18.69%	6.26%	39.25%	16.63%	2.8	1.48	0.64	8
Red Mountain	0	7.28%	27.95%	48.51%	16.24%	0.02%	2.4	1.37	0.47	5
Columbia Gorge	0	25.47%	13.18%	37.05%	14.60%	9.69%	2.8	1.24	0.75	4
Horse Heaven Hills	0	5.77%	10.55%	45.81%	31.96%	5.90%	2.8	1.56	0.51	12
Wahluke Slope	0	1.23%	40.01%	35.90%	22.83%	0.03%	2.4	1.38	0.41	6
Rattlesnake Hills	0	11.20%	8.30%	36.45%	35.30%	8.74%	2.8	1.56	0.61	11
Snake River Valley	0	2.76%	3.33%	10.20%	45.09%	38.62%	2.8	2.21	0.58	13
Snipes Mountain	0	33.86%	11.34%	43.17%	11.58%	0.06%	2.4	1.06	0.71	2
Lake Chelan	0	33.70%	16.80%	46.82%	2.53%	0.14%	2.8	0.96	0.63	1
Naches Heights*	0	9.86%	4.82%	47.08%	32.76%	5.48%	2.4	1.53	0.55	10
Ancient Lakes*	0	3.87%	3.27%	81.25%	11.20%	0.41%	2.4	1.42	0.34	7

*Proposed AVA

Table 12: Summary of drainage classes by American Viticultural Area from Soil Survey Geographic database and masked to exclude water features. Averages are calculated straight across American Viticultural Areas and not weighted by area. There is a predominance of soils classed as well drained. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Abbreviations: ED (excessively drained), SED (somewhat excessively drained), WD (well drained), MWD (moderately well drained), SPD (somewhat poorly drained), PD (poorly drained), VPD (very poorly drained).

	ED	SED	WD	MWD	SPD	PD	VPD
Yakima Valley	1.92%	5.60%	78.38%	0.65%	13.17%	0.28%	-
Walla Walla Valley	-	3.90%	86.84%	4.90%	4.18%	0.18%	-
Columbia Valley	6.56%	6.85%	82.98%	0.94%	2.04%	0.53%	0.10%
Red Mountain	0.60%	14.86%	84.54%	-	-	-	-
Columbia Gorge	-	0.16%	96.70%	-	2.86%	0.27%	-
Horse Heaven Hills	9.65%	9.45%	80.56%	-	0.25%	0.09%	-
Wahluke Slope	34.74%	33.72%	31.49%	-	0.05%	-	-
Rattlesnake Hills	-	0.03%	99.39%	-	0.58%	-	-
Snake River Valley	1.83%	4.59%	86.71%	0.84%	4.70%	1.21%	0.12%
Snipes Mountain	-	0.34%	99.21%	-	0.45%	-	-
Lake Chelan	-	0.91%	89.98%	9.11%	-	-	-
Naches Heights*	-	0.01%	98.29%	-	1.70%	-	-
Ancient Lakes*	4.98%	27.54%	67.22%	0.08%	-	0.18%	-
Average	8.61%	8.31%	83.25%	2.75%	3.00%	0.39%	0.11%

*Proposed AVA

Table 13: Summary statistics by American Viticultural Area of available water-holding capacity, in cm/cm, from 0-50 cm from Soil Survey Geographic database and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Rank
Yakima Valley	0.06	0.21	0.1693	0.0351	8
Walla Walla Valley	0.07	0.25	0.1864	0.0265	12
Columbia Valley	0.02	0.45	0.1633	0.0432	7
Red Mountain	0.08	0.19	0.1609	0.0369	5
Columbia Gorge	0.06	0.27	0.1632	0.0381	6
Horse Heaven Hills	0.04	0.21	0.1693	0.0411	9
Wahluke Slope	0.05	0.2	0.1204	0.0393	1
Rattlesnake Hills	0.09	0.21	0.1760	0.0322	11
Snake River Valley	0.03	0.45	0.1526	0.0389	4
Snipes Mountain	0.09	0.21	0.1895	0.0109	13
Lake Chelan	0.07	0.19	0.1429	0.0257	3
Naches Heights*	0.09	0.21	0.1694	0.0199	10
Ancient Lakes*	0.05	0.23	0.1427	0.1098	2

*Proposed AVA

Table 14: Summary statistics by American Viticultural Area of depth to any restrictive layer, in cm, from Soil Survey Geographic database and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Rank
Yakima Valley	25	201	164.70	63.11	7
Walla Walla Valley	0	201	190.10	36.65	13
Columbia Valley	10	203	140.94	68.25	3
Red Mountain	43	201	185.67	45.44	12
Columbia Gorge	23	201	158.28	58.63	6
Horse Heaven Hills	10	201	178.82	52.26	11
Wahluke Slope	18	201	174.41	54.81	10
Rattlesnake Hills	25	201	107.64	71.88	1
Snake River Valley	8	203	120.12	75.67	2
Snipes Mountain	40	201	165.67	61.75	8
Lake Chelan	28	201	170.17	56.60	9
Naches Heights*	38	201	142.08	31.77	4
Ancient Lakes*	13	201	156.56	69.75	5

*Proposed AVA

Table 15: Summary statistics by American Viticultural Area of soil pH from 0-50 cm from Soil Survey Geographic database and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Rank
Yakima Valley	6.7	9.1	7.62	0.45	10
Walla Walla Valley	6.5	9.3	7.36	0.53	4
Columbia Valley	5.6	10.1	7.28	0.48	3
Red Mountain	7.2	7.9	7.40	0.22	5
Columbia Gorge	5.6	7.5	6.48	0.48	1
Horse Heaven Hills	6.5	9.1	7.52	0.26	7
Wahluke Slope	6.9	8.7	7.73	0.37	13
Rattlesnake Hills	7	9.1	7.67	0.37	12
Snake River Valley	5.2	10.2	7.59	0.61	9
Snipes Mountain	7	8.6	7.63	0.30	11
Lake Chelan	6.5	8	7.43	0.36	6
Naches Heights*	7	9.1	7.10	0.26	2
Ancient Lakes*	6.7	8.7	7.55	0.34	8

*Proposed AVA

Table 16: Summary statistics by American Viticultural Area of calcium carbonate content, in percent, from 0-60 cm from Soil Survey Geographic database and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Rank
Yakima Valley	0	25	2.48	3.31	9
Walla Walla Valley	0	18	1.27	2.74	4
Columbia Valley	0	25	1.37	3.00	5
Red Mountain	0	10	3.28	2.06	12
Columbia Gorge	0	0	0.00	0.00	1
Horse Heaven Hills	0	20	2.22	2.74	8
Wahluke Slope	0	16	2.79	5.21	10
Rattlesnake Hills	0	20	3.01	3.24	11
Snake River Valley	0	28	5.45	6.54	13
Snipes Mountain	0	12	1.92	3.61	6
Lake Chelan	0	1	0.00	0.01	2
Naches Heights*	0	20	0.82	2.87	3
Ancient Lakes*	0	16	2.11	3.68	7

*Proposed AVA

Table 17: Summary statistics by American Viticultural Area of soil suitability for *V. vinifera* based on drainage class, available water-holding capacity, depth and pH. Proportional areas are divided between five quantiles. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	1Q	2Q	3Q	4Q	5Q	Max.	Mean	St. Dev.	Rank
Yakima Valley	0.5	-	6.29%	11.45%	22.66%	59.60%	2	1.55	0.40	4
Walla Walla Valley	0.5	-	2.86%	1.47%	14.30%	81.37%	2	1.65	0.26	8
Columbia Valley	0.1	0.01%	8.49%	32.75%	16.31%	42.44%	2	1.61	0.28	6
Red Mountain	1	-	-	0.59%	17.81%	81.60%	1.9	1.77	0.19	12
Columbia Gorge	0.5	-	0.96%	1.79%	20.01%	77.24%	2	1.70	0.22	10
Horse Heaven Hills	0.5	-	0.35%	9.78%	18.74%	71.13%	2	1.63	0.29	7
Wahluke Slope	0.5	-	0.04%	38.90%	25.85%	35.20%	2	1.31	0.29	1
Rattlesnake Hills	0.5	-	0.58%	25.27%	28.26%	45.89%	1.9	1.51	0.32	2
Snake River Valley	0.1	0.03%	3.78%	8.99%	38.79%	48.40%	2	1.52	0.32	3
Snipes Mountain	0.7	-	0.45%	19.45%	7.58%	72.52%	1.9	1.68	0.32	9
Lake Chelan	1.3	-	-	-	15.59%	84.41%	2	1.71	0.17	11
Naches Heights*	0.5	-	0.33%	1.37%	1.09%	97.21%	1.9	1.85	0.16	13
Ancient Lakes*	0.5	-	0.47%	4.04%	32.02%	63.47%	2	1.60	0.24	5

*Proposed AVA

Table 18: Summary statistics by American Viticultural Area of soil suitability for *V. labruscana* based on drainage class, available water-holding capacity, depth, pH and calcium carbonate content. Proportional areas are divided between five quantiles. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	1Q	2Q	3Q	4Q	5Q	Max.	Mean	St. Dev.	Rank
Yakima Valley	0.675	-	3.23%	13.28%	27.33%	56.16%	2	1.53	0.31	6
Walla Walla Valley	0.675	-	1.13%	0.83%	15.26%	82.78%	2	1.67	0.18	11
Columbia Valley	0.525	-	6.75%	52.14%	14.28%	26.83%	2	1.55	0.29	7
Red Mountain	0.825	-	-	15.46%	18.70%	65.85%	1.85	1.57	0.24	8
Columbia Gorge	0.675	-	0.95%	0.08%	1.98%	96.99%	2	1.81	0.20	13
Horse Heaven Hills	0.525	-	0.56%	21.60%	15.10%	62.75%	1.85	1.49	0.31	4
Wahluke Slope	0.825	-	-	41.93%	53.71%	4.36%	1.85	1.17	0.30	1
Rattlesnake Hills	1.025	-	-	26.49%	30.71%	42.79%	1.85	1.45	0.32	2
Snake River Valley	0.225	0.91%	3.28%	14.04%	43.56%	38.20%	2	1.48	0.32	3
Snipes Mountain	1.025	-	-	19.54%	3.09%	77.37%	1.85	1.65	0.32	9
Lake Chelan	1.225	-	-	-	17.60%	82.40%	2	1.67	0.17	10
Naches Heights*	0.825	-	-	1.49%	0.64%	97.87%	2	1.80	0.14	12
Ancient Lakes*	0.525	-	0.49%	3.63%	68.05%	27.82%	1.85	1.50	0.23	5

*Proposed AVA

Table 19: Summary statistics by American Viticultural Area of growing-degree days, in degrees Centigrade, interpolated from Western Regional Climate Center daily normals, 1971-2000, using ordinary kriging and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	634	1631	1396.7	197.79	1449	9
Walla Walla Valley	1056	1667	1454.4	102.31	1458	10
Columbia Valley	342	1947	1290.6	220.18	1320	4
Red Mountain	1298	1568	1493.0	44.76	1510	11
Columbia Gorge	520	1611	977.1	186.82	969	2
Horse Heaven Hills	952	1741	1367.2	144.61	1376	6
Wahluke Slope	1259	1943	1659.8	133.33	1667	13
Rattlesnake Hills	753	1523	1276.6	164.34	1311	3
Snake River Valley	612	1987	1386.1	169.25	1420	7
Snipes Mountain	1367	1559	1499.0	42.06	1511	12
Lake Chelan	710	1754	1337.5	171.21	1352	5
Naches Heights*	815	1167	951.8	70.92	946	1
Ancient Lakes*	1150	1657	1391.8	57.72	1395	8

*Proposed AVA

Table 20: Summary statistics by American Viticultural Area of frost-free days from Parameter-elevation Regressions on Independent Slopes Model normals, 1971-2000, and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	104	189	161.6	13.46	164	5
Walla Walla Valley	138	219	200.1	11.18	201	13
Columbia Valley	64	220	162.9	21.10	164	6
Red Mountain	170	180	176.1	2.08	176	12
Columbia Gorge	118	222	149.8	18.06	146	4
Horse Heaven Hills	128	207	173.6	15.09	177	11
Wahluke Slope	145	194	173.3	10.25	173	10
Rattlesnake Hills	119	167	148.2	10.41	150	3
Snake River Valley	83	188	139.3	13.90	141	2
Snipes Mountain	160	174	167.0	3.57	167	7
Lake Chelan	145	199	168.0	12.99	165	9
Naches Heights*	107	139	118.7	8.74	116	1
Ancient Lakes*	148	190	167.1	7.42	167	8

*Proposed AVA

Table 21: Summary statistics by American Viticultural Area of growing degree-days, in degrees Centigrade, from Parameter-elevation Regressions on Independent Slopes Model monthly normals, 1971-2000, and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	747	1630	1371.0	152.69	1414	7
Walla Walla Valley	922	1606	1487.3	109.23	1529	11
Columbia Valley	527	1764	1278.2	218.75	1312	5
Red Mountain	1465	1553	1501.2	19.59	1502	12
Columbia Gorge	698	1490	926.7	132.39	896	1
Horse Heaven Hills	1032	1645	1434.8	109.68	1464	9
Wahluke Slope	1117	1745	1511.8	132.18	1532	13
Rattlesnake Hills	924	1450	1213.7	131.25	1210	4
Snake River Valley	811	1828	1338.7	125.30	1357	6
Snipes Mountain	1372	1502	1447.3	30.53	1452	10
Lake Chelan	806	1391	1197.7	87.71	1215	3
Naches Heights*	925	1288	1061.1	87.33	1052	2
Ancient Lakes*	1130	1769	1379.7	69.86	1375	8

*Proposed AVA

Table 22: Summary statistics by American Viticultural Area of growing degree-days, in degrees Centigrade, interpolated from Western Regional Climate Center daily normals, 1971-2000, using universal kriging and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	602	1636	1384.8	186.72	1438	7
Walla Walla Valley	977	1695	1483.0	135.01	1509	10
Columbia Valley	325	1772	1268.5	241.04	1303	5
Red Mountain	1343	1626	1517.7	44.22	1526	13
Columbia Gorge	581	1581	1039.3	191.39	1027	2
Horse Heaven Hills	985	1768	1407.3	161.07	1401	8
Wahluke Slope	1229	1647	1487.3	79.12	1483	11
Rattlesnake Hills	744	1506	1260.5	158.48	1300	4
Snake River Valley	572	1736	1376.5	169.20	1413	6
Snipes Mountain	1355	1551	1488.0	41.68	1499	12
Lake Chelan	692	1509	1225.4	141.35	1258	3
Naches Heights*	903	1217	1017.7	64.71	1012	1
Ancient Lakes*	1148	1704	1415.3	64.05	1410	9

*Proposed AVA

Table 23: Summary statistics by American Viticultural Area of the latitude-temperature index calculated using Parameter-elevation Regressions on Independent Slopes Model monthly normals, 1971-2000, and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	252	319	300.3	11.24	303	7
Walla Walla Valley	282	327	318.3	7.45	321	12
Columbia Valley	214	336	291.1	25.31	296	6
Red Mountain	308	317	311.9	2.31	312	10
Columbia Gorge	246	301	269.9	10.15	269	3
Horse Heaven Hills	280	332	313.4	9.24	316	11
Wahluke Slope	285	318	304.4	7.12	305	8
Rattlesnake Hills	263	305	287.8	9.81	288	5
Snake River Valley	283	417	371.2	22.62	374	13
Snipes Mountain	300	309	304.7	2.67	305	9
Lake Chelan	233	272	258.3	7.41	259	1
Naches Heights*	254	283	265.7	6.76	264	2
Ancient Lakes*	269	309	286.7	5.63	286	4

*Proposed AVA

Table 24: Summary statistics by American Viticultural Area of potential *U. necator* risk, in centimeters of precipitation, from Parameter-elevation Regressions on Independent Slopes Model monthly normals, 1971-2000, and masked to exclude water features. Table sorted by chronological establishment or petitioning for American Viticultural Areas. Rankings by mean in ascending order.

	Min.	Max.	Mean	St. Dev.	Median	Rank
Yakima Valley	7	13	8.36	1.23	8	5
Walla Walla Valley	11	37	18.79	4.05	19	12
Columbia Valley	5	43	11.93	4.28	11	11
Red Mountain	8	9	8.08	0.27	8	4
Columbia Gorge	12	30	19.86	4.14	20	13
Horse Heaven Hills	7	12	9.22	0.86	9	7
Wahluke Slope	5	8	6.49	0.88	7	1
Rattlesnake Hills	8	11	8.80	0.76	9	6
Snake River Valley	7	29	11.86	4.03	11	10
Snipes Mountain	7	8	7.56	0.50	8	3
Lake Chelan	10	14	10.68	0.67	11	8
Naches Heights*	9	12	11.28	0.68	11	9
Ancient Lakes*	6	9	7.38	0.62	7	2

*Proposed AVA

The *Federal Register* describes the western portion of the AVA as a vast, flat expanse and the eastern portion as gently sloping north of the Yakima River (ATF, 1983). It is the second flattest of eleven inland Pacific Northwest (IPNW) appellations with a mean slope of 5.24% (Table 8). Spanning from 46º08'N to 46º31'N latitude, the area registers the fourth greatest solar exposure with a mean of 1,031 kWh/m^2 and a south-southeastern mean aspect of 171º (Table 9). Overall *V. vinifera* topographic suitability in the Yakima Valley is third lowest for IPNW AVAs, but fourth highest in overall *V. labruscana* topographic suitability reflecting relatively gentle slopes (Tables 10 and 11).

When the petition for establishment of the Yakima Valley AVA was filed, it was stated by the petitioner that most vineyards were planted on two soil associations, Warden-Shano and Scootenay-Starbuck silt loams with varying depths over basalt and/or gravel (ATF, 1983). The area is dominated by well-drained soils (78%) with a small component of somewhat poorly drained soils (13%) located primarily southwest of the Yakima River in the western portion of the AVA (Table 12). It has the seventh deepest soils with a mean of 165 cm (Table 14). Soil pH is relatively high with a mean of 7.62 and a maximum of 10.2 (Table 15) and calcium carbonate content can also be high with isolated areas reaching 25% (Table 16).

Climatic distinction for the Yakima Valley was established as warmer than mountains to the west and cooler than areas to the north and east (ATF, 1983). Heat accumulation does decline precipitously within 24 km to the west of the AVA boundary as elevations climb into the Cascade mountain range (data not shown) and the Walla Walla Valley, Red Mountain and Wahluke Slope AVAs, all lying north or east of Yakima Valley, record more GDD than the Yakima Valley according to ordinary kriging (OK) and universal kriging (UK) daily interpolations as well as Parameter-elevation Regressions on Independent Slopes Model (PRISM) monthly GDD (Tables

19, 21 and 22). Mean FFD were fourth lowest amongst IPNW AVAs at 162 (Table 20), potentially due to the flat terrain and associated cold air pooling.

3.2.2 Walla Walla Valley AVA

The Walla Walla Valley AVA, established 7 March 1984 (ATF, 1984a), originally consisted of approximately 1,050 km^2 and was expanded on 27 April 2001 to approximately 1,066 km^2 (ATF, 2001). The original appellation was bound by the confluence of the north and south forks of the Walla Walla River, the 610 m contour to its south and east, an approximation of the divide between the Walla Walla and Touchet River drainages to the north and the confluence of the Walla Walla and Columbia Rivers to the west. The expanded appellation includes area in the Touchet River drainage (ATF, 2001; Meinert and Busacca, 2000). CDL classifications from 2010 show only 150 ha planted to grapes, which appears to be a gross underestimation as other sources indicate approximately 650 ha (O'Hara, 2011).

Distinctive features listed in the *Federal Register* were limited both for the original and expanded appellation. According to the NED DEM, the range of elevations, 122 to 697 m, within the Walla Walla Valley AVA is greater than the stated 250 to 600 m (ATF, 2001). The loess derived soils were predominately classed as well drained (87%, Table 12). The AVA has the second greatest mean available water-holding capacity (AWC) at 0.186 cm/cm (Table 13) and the greatest mean depth to restrictive layer at 190 cm (Table 14).

Walla Walla Valley AVA also has the third lowest mean pH and third lowest mean content of calcium carbonate at 7.36 and 1.27%, respectively (Tables 15 and 16). These factors are related to the relatively high precipitation received, noted in both the original and expanded petitions (ATF, 1984a, 2001). The AVA has the second greatest potential *U. necator* risk (Table 24) and PRISM 1971-2000 normals show mean annual precipitation at 44.2 cm and a maximum of 96.1 cm within the AVA (data not shown). This is greater than the mean of 31.8 cm and maximum of 50.8 cm indicated in either final rule description from undisclosed sources (ATF, 1984a, 2001). The longest mean growing season is also found here at 200 days, which coincides with the description which states 190 to 220 FFD (ATF, 1984a). However, median FFD from PRSIM 1971-2000 normals also indicate a minimum growing season of 138 (Table 20).

3.2.3 Columbia Valley AVA

The immense Columbia Valley AVA, established 13 December 1984, encompasses approximately 46,000 km^2 (ATF, 1984b). It is a diverse region and many smaller appellations have been carved from within it since its establishment. The Yakima Valley AVA is included within the Columbia Valley AVA, as is the Walla Walla Valley AVA following a boundary adjustment (ATF, 2001). Since many smaller AVAs have been distinguished by more distinctive characteristics, this discussion will not explore the Columbia Valley AVA in depth.

3.2.4 Red Mountain AVA

Established 11 June 2001, the Red Mountain AVA covers approximately 1,650 ha and is contained entirely within the Yakima Valley AVA (TTB, 2001). The Saddle Mountains Formation of the Columbia River Basalt Group underlies the appellation upon which glacial flood sediments have been topped with loess and dune sands (Meinert and Busacca, 2002). The 2010 CDL appears once again to underestimate vineyard acres at approximately 120 ha, contrasting with nearly 290 ha reported by Meinert and Busacca in 2002, since when planted area has expanded.

Elevations within Red Mountain range from 167 to 428 m according to the NED DEM (Table 7), a greater range than the stated 183 to 305 m (TTB, 2001). Although blessed with southwest-facing slopes (mean aspect of 207°), the appellation records the fifth lowest mean solar insolation (1,017 kWh/m^2), although this is comparable to many other AVAs (Table 9). This may be partially due to relatively gentle slopes, fourth lowest amongst IPNW AVAs (mean of 7.67%, Table 8).

Soils of the Warden-Shano association dominate Red Mountain, including Warden silt loam, Hezel loamy fine sand, Scooteney silt loam and Kiona very stony silt loam (TTB, 2001). Again, this is an area dominated by well drained soils (85%) with a component of somewhat excessively drained soils (15%, Table 12). Soil depths are second only to Walla Walla Valley with a mean of 186 cm (Table 14). Red Mountain also records the second greatest calcium carbonate content, although the maximum is a moderate 10% (Table 16). Petrocalcic horizons accumulating on gravel lenses are localized features within Red Mountain serving as substantial calcium carbonate sources that may prove detrimental for vine growth and nutrient uptake, especially for *V. labruscana* (Meinert and Busacca, 2001). This feature leads Red Mountain's overall soil suitability to be the greatest for *V. vinifera* (Table 17), but only fifth greatest for *V. labruscana* (Table 18).

The petitioner stated heat accumulation on Red Mountain exceeds that of other areas in the Yakima Valley (TTB, 2001). This is confirmed by nearly all calculated surfaces of heat accumulation with Red Mountain recording a greater mean GDD and LTI than the Yakima Valley, Rattlesnake Hills and Snipes Mountain AVAs (Tables 21 through 23). Only OK GDD surfaces from Western Regional Climate Center (WRCC) 1971-2000 daily normals ranked Snipes Mountain slightly warmer than Red Mountain (Table 19). The growing season length in the appellation is second only to Walla Walla Valley with a mean of 176 FFD (Table 20). Elevation, southwest slopes, continental air mass movement through the gap between Red Mountain and Rattlesnake Ridge to the west and the Yakima River flowing to the west and around the northern boundary of the Red Mountain AVA all likely contribute to this long growing season (TTB, 2001).

3.2.5 Columbia Gorge AVA

The Columbia Gorge AVA, like the Columbia Valley and Walla Walla Valley AVAs, is the third to share area in both Washington and Oregon. Established 9 July 2004, this roughly 77,500 ha appellation straddles the Columbia River (TTB, 2004). The 2010 CDL shows 40 ha planted to grapes, but none of these lie on the Washington side of the Columbia River. The petitioner stated 115 ha of wine grapes were planted at the time of establishment (TTB, 2004).

Slopes are steep in this appellation with the second greatest mean of 22.83% (Table 8). Elevations range from 23 to 839 m (Table 7) with areas well above the 610 m contour defining a portion of the southern boundary (TTB, 2004). Despite a mean southerly aspect (181º), the Columbia Gorge AVA records the second lowest mean solar insolation (984 kWh/m^2) with the greatest standard deviation (Table 9). This is likely due to a greater proportion of north-facing slopes on the Oregon side of the AVA and hillshade effects due to steep slopes. These factors combine to give the Columbia Gorge AVA the fifth greatest topographic suitability for *V. vinifera* and fourth least for *V. labruscana* due to different weights given to slopes (Tables 10 and 11).

The Columbia Gorge is also dominated by well drained soils (97%, Table 12) and has the fifth least mean AWC (0.163 cm/cm, Table 13). This contrasts somewhat with final rule descriptions of slow to moderate permeability and high AWC, although the latter is given no quantitative context (TTB, 2004). The mean depth of 158 cm coincides well with descriptions from the petitioner (TTB, 2004). The appellation records the lowest mean pH (6.48) and is the only IPNW AVA with no trace of calcium carbonate in the Soil Survey Geographic (SSURGO) database (Tables 15 and 16). These factors combine to place the AVA at third in overall *V.*

vinifera soil suitability and number one in *V. labruscana* suitability (Tables 17 and 18).

The petitioner states that due to relatively cool conditions, *V. vinifera* grown in the AVA are generally early varietals like Pinot Noir and Gewürztraminer (TTB, 2004). Heat accumulation surfaces place the Columbia Gorge as the coolest IPNW AVA (Tables 19, 21 and 22) and it records the second lowest LTI (Table 23). Potential *U. necator* risk is greatest in this AVA (Table 24) and annual precipitation ranges over the strong precipitation gradient agree with the 46 cm on the eastern end and 76 cm on the western end (data not shown) stated by the petitioner (TTB, 2004).

3.2.6 Horse Heaven Hills AVA

Lying to the south of the Yakima Valley and Red Mountain AVAs and north of the Columbia River, the approximately 2,300 km^2 Horse Heaven Hills AVA was established on 1 August 2005 (TTB, 2005a). Bounded on the west by a 518 m contour and Pine Creek and by the ridge of the Horse Heaven Hills to the north, the 2010 CDL places approximately 7,100 ha of grapes in the appellation. A stark increase from the 2,444 ha planted as of 2002 (TTB, 2005a), although the accuracy of CDL classifications has been shown to be questionable.

As seen previously, elevation ranges from the NED DEM (77 to 670 m, TTB, 2005a) are greater than those stated in the final rule description (61 to 549 m, Table 7), but in this case, the minimum observed elevation in the DEM is greater than the stated minimum. Slopes are comparable to those in the Yakima Valley and Red Mountain AVAs (Table 8) face to the south with a mean aspect of 176º and solar insolation is second only to the Snake River Valley, which is at a much lower latitude (Table 9).

Like many IPNW viticultural areas, Horse Heaven Hills soils are composed of eolian sand and silt, glacial and slackwater sediments, gravel alluvium and Columbia River basalt colluvium, but the proportion and arrangement of these features distinguish appellations from one another (TTB, 2005a). The Horse Heaven Hills are dominated by soils classed as well drained (81%), but also have one of the greatest proportions of somewhat excessively (9%) and excessively drained (10%) soils (Table 12). The third deepest soils are also found here (mean of 179 cm, Table 14). Excessive drainage, relatively high AWC, pH and calcium carbonate content leave the Horse Heaven Hills in the middle of the pack in terms of *V. vinifera* soil suitability and fourth lowest in *V. labruscana* soil suitability (Tables 17 and 18).

Ten-year averages of heat accumulation provided in the petition list, from warmest to coolest, Red Mountain, Walla Walla Valley, Horse Heaven Hills and Yakima Valley (TTB, 2005a). This corresponds to rankings for PRISM and UK GDD (Tables 21 and 22), but not OK GDD, which lists the Yakima Valley as warmer than the Horse Heaven Hills (Table 19). This may be complicated by differing periods of record and the likelihood that the heat accumulations listed in the petition were from one or more weather stations rather than a spatially comprehensive analysis of each appellation.

3.2.7 Wahluke Slope AVA

Sitting atop a 24 km long mega alluvial fan deposited by the Missoula Floods, the approximately 33,000 ha Wahluke Slope AVA was established on 6 January 2006. (TTB, 2005b). CDL classifications place nearly 3,000 ha in grape production. Noted topographic features are gently south-facing slopes which decline to the east, south and west, providing for good air drainage, while the 451 m contour of the Saddle Mountains provide the northern boundary (TTB, 2005b). Wahluke Slope registers the lowest mean slope at 2.99% (Table 8), has a southerly mean aspect of 189º, fifth greatest mean solar insolation (Table 9) and the fourth longest growing season with 173 mean FFD (Table 20).

Deep eolian sands and silts have a mean depth of 174 cm, fourth deepest (Table 14), with relatively large areas of excessively and somewhat excessively drained soils. Drainage classes are split almost evenly between these two classes and well drained soils (Table 12). These soils also have the lowest AWC (mean of 0.120 cm/cm, Table 13), greatest pH (mean of 7.73, Table 15) and fourth greatest calcium carbonate content (mean of 2.79%, Table 16). Excessive drainage, low AWC and high pH contribute to its position at the bottom of both *V. vinifera* and *V. labruscana* soil suitabilities (Tables 17 and 18).

Based on the state of Washington's Public Agricultural Weather System (PAWS) data from 1994-2003, the petitioner states the Wahluke Slope is the driest in the region and recorded 1,674 GDD. It does have the lowest mean potential *U. necator* risk at 6.49 cm of precipitation (Table 24) and mean annual precipitation of 19 cm based on PRISM 1971-2000 normals (data not shown). OK and PRISM GDD surfaces rate it as the hottest of all IPNW AVAs (Tables 19 and 21), but UK GDD and LTI rate it as third and sixth hottest, respectively (Tables 22 and 23).

3.2.8 Rattlesnake Hills AVA

Fully within the Yakima Valley AVA, the nearly 28,000 ha Rattlesnake Hills AVA was established on 20 March 2006. Comprised of a portion of east-west hills between the Yakima and Moxee River Valleys and lying between the Hanford Reservation and Union Gap, 2010 CDL estimates indicate roughly 1,650 ha of grapes, substantially more than the 500 ha of commercial vines planted as of 2005 (TTB, 2006).

The petitioner states the appellation contains diverse topography along the southern face of the Rattlesnake Hills, much greater variability than the rest of the Yakima Valley and most vineyards have been located on southern ridges and terraces with good air drainage (TTB, 2006). The fourth steepest mean slope and third greatest mean solar insolation are found here with greater standard deviations than the Yakima Valley (Tables 8 and 9). This gives the Rattlesnake Hills the second greatest topographic suitability for *V. vinifera* and third greatest for *V. labruscana* (Tables 10 and 11). The slightly lower suitability for *V. labruscana* is likely due to steeper slopes that are deemed less suitable to growers with generally less access to self-leveling machinery capable of operating under such conditions.

Soils on the Rattlesnake Hills are dominated by those classed as well drained (99%, Table 12). They contrast with the more coarsely textured sandy soils of Red Mountain and Horse Heaven Hills and silty soils found elsewhere in the Yakima Valley and are shallow, especially above 335 m where soil formation was above the influence of the Missoula Floods (TTB, 2006). These finer soils have the third greatest AWC (mean of 0.176 cm/cm, Table 13), second highest pH (mean of 7.63, Table 15), third highest calcium carbonate content (mean of 3.01%, Table 16) and are the shallowest of all IPNW AVAs (mean of 108 cm, Table 14). These factors place the Rattlesnake Hills just ahead of the Wahluke Slope with the second lowest soil suitability for *V. vinifera* and *V. labruscana* (Tables 17 and 18).

The petitioner states that the Umptanum and Yakima Ridges to the northeast shield the Rattlesnake Hills AVA from arctic fronts, which are funneled toward the Red Mountain and Walla Walla Valley AVAs (TTB, 2006). This contradicts PRISM FFD data, which indicates the Rattlesnake Hills have the third shortest growing season at a mean of 148 FFD, 28 days shorter than the mean of Red Mountain and 52 shorter than that of Walla Walla Valley (Table 20). Heat accumulation claims are more accurate; the Rattlesnake Hills are substantially cooler than Red Mountain (Tables 19 and 21 through 23) and the area between the two AVAs is cooler than the Rattlesnake Hills AVA (data not shown).

3.2.9 Snake River Valley AVA

Straddling the border between Oregon and Idaho and situated in the rift basin that once contained ancient Lake Idaho, the approximately 21,400 km^2 Snake River Valley AVA was established on 9 April 2007 (TTB, 2007). CDL estimates of area planted to grapes in 2010 were 146 ha, all of which were within Idaho. This again appears to be an underestimate as petitioners claimed nearly 450 ha (TTB, 2007).

Although the boundary follows a 1,040 m contour for nearly its entirety and this is stated as its maximum elevation (TTB, 2007), the Snake River Valley contains over 47,000 ha exceeding this according to the NED DEM with a maximum of 1,504 m (Table 7), mostly located on hills and ridges between the 1,040 m contour and drainages in the western portion of the appellation. Although the central Snake River Plain where the majority of CDL grape classifications lie is relatively flat as stated in the petition (TTB, 2007), many steeper drainages in northern, western and southern portions of the appellation (data not shown) push mean slope up to 10.75% (Table 8). The Snake River Valley records the greatest solar insolation of IPNW AVAs (mean of 1,112 kWh/m^2) due to its lower latitude (42º29'N to 45ºN) and southerly mean aspect of 177º (Table 9). The substantially greater solar insolation ranks the Snake River Valley AVA as overall best topographic suitability for both *V. vinifera* and *V. labruscana* (Tables 10 and 11).

The large, edaphically diverse area is also dominated by well drained soils (87%) with small components of both somewhat excessively drained and somewhat poorly drained soils (5% each, Table 12). The final rule description provides little in terms of distinctive soil features, but shallow soils are noted and corroborated by SSURGO data with a mean depth of 120 cm, greater only than the Rattlesnake Hills AVA (Table 14). The Snake River Valley AVA also contains the greatest calcium carbonate content (mean of 5.45%, maximum of 28%, Table 16) and relatively high pH, fifth greatest (mean of 7.59, maximum of 10.2, Table 15).

Mean GDD over the AVA were at least 118ºC fewer than the average of four National Climatic Data Center weather station normals from 1971 to 2000, the same period of record used to compile GDD surfaces (TTB, 2007; Tables 19, 21 and 22). Over all three GDD surfaces, the Snake River Valley AVA recorded 68 to 149 fewer GDD than Walla Walla Valley with the greatest disparity appearing in the PRISM monthly GDD surface (Table 21). While showing less difference than stated by the petitioners assessing AVAs using point measurements, this does generally agree with their claims (TTB, 2007). The appellation also recorded the second fewest FFD (mean of 139), but exhibits a range second only to the massive Columbia Valley AVA and a maximum of 188 FFD (Table 20). Finding sites with an adequate growing season and heat accumulation are likely the greatest challenges to grape production within the Snake River Valley AVA.

3.2.10 Snipes Mountain AVA

A third sub-appellation located entirely within the Yakima Valley AVA, Snipes Mountain, was established on 20 February 2009. It is the smallest IPNW AVA at less than 1,700 ha. Lying north of the Yakima River, this appellation contains the landform of its namesake as well as 53 ha on Harrison Hill, east of Snipes Mountain, which is stated to have similar soils and contiguous topography with Snipes Mountain (TTB, 2009a). CDL classifications indicate approximately 460 ha of this area was planted to grapes as of 2010. This may be an overestimate compared to the 217 ha recently claimed by the petitioner (TTB, 2009a).

Although the Yakima Valley AVA encompasses a much greater elevation range and maximum elevation than Snipes Mountain, including the Rattlesnake Hills AVA to the north (Table 7), the Snipes Mountain AVA is substantially higher than its immediate vicinity, particularly to the south, as indicated by the petitioner. Additionally, steep slopes on the southern face of the landforms make Snipes Mountain the third steepest IPNW AVA with a mean slope of 17.43% (TTB, 2009a; Table 8). However, these steep slopes may lead to shading from adjacent hills. This in conjunction with a gently sloping north face give Snipes Mountain the third lowest solar insolation (mean of 994 kWh/m^2, Table 9). This places the appellation in the middle of the pack in overall *V. vinifera* suitability (Table 10), but slopes appear too steep for extensive *V. labruscana* cultivation (Table 11).

The appellation is comprised almost entirely of soils classed as well drained (Table 12). Although the petitioner states that nearly all soils, lacustrine or alluvial, are now generally dry, classified as Aridisols and contain more rock fragments than elsewhere in the Yakima Valley, Snipes Mountain has the greatest AWC of all IPNW AVAs (mean of 0.190 cm/cm). This would be expected to be lower than that of the Yakima Valley AVA, which the petitioner states is composed of 43% Mollisols (TTB, 2009a; Table 13).

Climatically, little is stated in the final rule establishing the Snipes Mountain AVA aside from steep southern slopes of Snipes Mountain and Harrison Hill draining cold air freely into the Yakima Valley below (TTB, 2009a). It recorded a mean of 6.4 greater FFD than the Yakima Valley AVA (Table 20). It is also relatively warm and dry during the growing season, recording the second greatest heat accumulation based on WRCC daily normal interpolations (Tables 19 and 22), the fourth greatest according to PRISM monthly normals (Table 21), the fifth greatest LTI (Table 23) and the second lowest potential *U. necator* risk (Table 24).

3.2.11 Lake Chelan AVA

The newest IPNW AVA is the farthest north sub-appellation (47º52'N) within the Columbia Valley AVA and flanks the southeastern 19 km of the 88-km-long Lake Chelan, the third deepest lake in the United States from which the appellation is named. Alpine glaciers descended from the Cascade Mountains during the last ice age, 14,000 to 18,000 y.b.p., carving the Lake Chelan Valley, including the lake. Lake Chelan AVA was established on 29 May 2009 and is roughly 9,700 ha (TTB, 2009b) planted with approximate 105 ha of grapes according to 2010 CDL classifications.

Lake Chelan AVA has the second greatest mean elevation of IPNW AVAs (488 m) and the NED DEM shows greater maximum elevation within the boundary (1,148 m, Table 7) than the 999 m unnamed peak in the northwest portion of the appellation mentioned by the petitioner (TTB, 2009b). It contains the steepest mean slope (24.49%, Table 8) with the steepest occurring at higher elevations along the western bank of Lake Chelan and along the northeastern portions of the appellation (data not shown). Along portions of the northern, southern and eastern banks of Lake Chelan, slopes are more gentle as stated by the petitioner (TTB, 2009b). High latitude and steep slopes at the foot of the Cascade Mountains give Lake Chelan AVA the least solar insolation (mean of 952 kWh/m^2, Table 9).

Distinctions in soil characteristics given by the petitioner focus on differences between the Lake Chelan Valley and the greater Columbia Plateau, primarily greater proportions of volcanic pumice and ash from the eruption of Glacier Peak approximately 12,000 y.b.p. and lower proportions of loess in the top 50 cm of soils. Most notably, soils with large proportions of volcanic ash, pumice or clays weathered from glass have unusually high AWC (TTB, 2009b). This is not corroborated by SSURGO data which ranks Lake Chelan with the second least mean AWC at 0.143 cm/cm and a maximum of only 0.19 cm/cm (Table 13). The appellation is dominated by well drained and moderately well drained soils (99% combined, Table 12), both of which receive greatest ratings in composite soil suitability. There is almost no trace of calcium carbonate (Table 16).

Lake Chelan's massive volume and moderating effect are emphasized by the petitioner as defining the appellation's distinctive climate (TTB, 2009b). Despite its high latitude and elevation, the AVA records the fifth greatest FFD (mean of 168, Table 20). Heat accumulation is also moderated by the lake and Lake Chelan is the second coolest IPNW AVA according to PRISM and UK GDD surfaces (Tables 21 and 22) and fourth coolest according to OK GDD (Table 19). The high latitude gives Lake Chelan the lowest mean LTI (Table 23). As stated by the petitioner, growing season length and heat accumulation drop precipitously as elevations increase to the north and west and, to a lesser extent, to the south and east across the Columbia River and away from the moderating influence of Lake Chelan (data not shown).

3.2.12 Naches Heights

The proposed Naches Heights AVA is completely contained by the Columbia Valley AVA and lies to the northwest of the Yakima Valley AVA. Bound by the Tieton River to the west, the Naches River to the north and east and Cowiche Creek and the Congdon (Schuler) Canal to the south, the appellation is defined by its elevated andesite plateau. The proposed boundary surrounds approximately 5,300 ha which the petitioner states is the home of 42 ha of grapes (TTB, 2011). Again, CDL classifications underestimate grape acreage, placing less than one hectare of grapes within Naches Heights. The comment period on this proposed AVA closed after 25 July 2011 (TTB, 2011).

The plateau is largely covered with moderate slopes, but the inclusion of cliffs along the northern, eastern and southern boundaries increases mean slope to 10.59% (Table 8). Approaching the Cascade foothills, mean elevation is second only to the Snake River Valley AVA at 542 m (Table 7). Excluding slopes over 30%, Naches Heights would have the third greatest overall *V. vinifera* topographic suitability and fourth greatest *V. labruscana* suitability if approved (Tables 10 and 11).

According to the petitioner, the appellation is dominated by Tieton loam and Ritzville silt loam, which are deep soils with adequate drainage (TTB, 2011). While 98% of the soils in the area are classed as well drained (Table 12), Naches Heights would have the fourth least mean depth at 142 cm (Table 14), which is not excessively shallow. AWC is fairly high with a mean of 0.169 cm/cm (Table 13). Soil pH and calcium carbonate content are low, second and third lowest, respectively (Tables 15 and 16). The appellation would have the greatest overall *V. vinifera* soil suitability and second greatest overall *V. labruscana* suitability (Tables 17 and 18).

Growing season length does decrease to the southwest, across the Tieton River, as claimed by the petitioner (TTB, 2011), but actually increases to the northeast, across the Naches River (data not shown). It is a very cool area with the shortest growing season amongst other IPNW AVAs (mean of 119 FFD, Table 20), least mean GDD according to OK and UK (Tables 19 and 22) and second least mean according to PRISM and LTI (Tables 21 and 23).

3.2.13 Ancient Lakes

As of 15 August 2011, the proposed rule to establish the Ancient Lakes viticultural area had not entered the *Federal Register*, but the petition had been written and submitted (J. Davenport, personal communication, 2011). The area climbs to the east of the Columbia River north of the Wahluke Slope AVA, is bound by the Beezely Hills to the north, the Frenchman Hills to the south and is completely contained within the Columbia Valley AVA. The proposed boundary encompasses approximately 66,000 ha on which CDL estimates place 280 ha of grapes in 2010. This is another underestimate of planted grape area; the petition states over 560 ha have been planted, but this includes area planted within the last three years.

The proposed Ancient Lakes AVA is characterized by gentle topography with a mean slope of 4.35% (Table 8) spanning from 174 m along the Columbia River to 582 m near its southern border (Table 7). It records nearly the same mean solar insolation as Naches Heights (1,026 kWh/m^2) placing both in the middle of the pack in IPNW AVAs. A wide range of aspects are found in the area and the most easterly of mean aspects (Table 9). The shallow slopes give Ancient Lakes the least mean overall *V. vinifera* topographic suitability (Table 10), but seventh greatest overall *V. labruscana* topographic suitability (Table 11).

Sandy soils are largely classed as well drained (67%) with a substantial component of somewhat excessively (28%) and excessively drained (5%) soils (Table 12). These soils also have the second least mean AWC at 0.143 cm/cm (Table 13). Soils are somewhat deeper than those of Naches Heights (mean of 157 cm, Table 14). Overall soil suitability is fifth least amongst IPNW AVAs for both *V. vinifera* and *V. labruscana* (Tables 17 and 18).

With cold air draining down to and carried away by the Columbia River, the Ancient Lakes recorded a mean of 167 FFD, sixth greatest amongst IPNW AVAs (Table 20). OK and PRISM GDD place it as the sixth warmest area (Tables 19 and 21) and UK GDD the fifth (Table 22), similar to the Yakima Valley AVA as claimed by the petitioner. However, the petitioner notes different accumulation rates, which can be important for cultivar selection and phenological development (Jackson and Lombard, 1993). Its relatively high latitude (46º58'N to 47º16'N) gives the Ancient Lakes the fourth least mean LTI (Table 23). It is a dry area during the growing season, as noted in the petition, recording the second least mean potential *U. necator* risk at 7.38 cm (Table 24).

3.3 Topographic and edaphic suitability for *V. vinifera* in CDL grapes

Comparisons of 2010 CDL grape classifications have been shown to be inconsistent when compared to *V. vinifera* grape acreage stated in final and proposed viticultural area rules in the *Federal Register*. Unfortunately, CDL classifications do not differentiate between *V. vinifera* and *V. labruscana*. Spatial classifications of *V. labruscana* area are provided by the Washington State Department of Agriculture (WSDA), but only by dominant crops within PLSS sections, roughly 2.6 km^2 squares that do not offer enough differentiation nor account for *V. labruscana* plantings too small to constitute a dominant crop within a section.

The 2010 CDL thematic mapper classifications used in this study utilize Landsat 5, Landsat 7 and Indian Remote Sensing Advanced Wide Field Sensor images to produce georeferenced land cover rasters with a 30 m ground resolution. Satellite images are provided USDA Farm Service Agency digitized field boundaries to train pixels for use in a classification and regression tree analysis (Craig, 2010). Luman and Tweddale (2008) performed an assessment of CDL accuracy in 2007 Illinois classifications. They found high user's accuracy, probability that a pixel from the classification actually matches the ground truth data, for predominant crops (e.g. 97.6% for corn, 96.7% for soybeans and 71.9% for winter wheat), but lower accuracy for crops representing less of agricultural land (e.g. 40.3% for rice and sorghum and 61.0% for miscellaneous fruits and vegetables). Grapes were not a crop assessed in Illinois.

Figure 27 shows four examples of comparisons of mapped vineyard blocks with 2010 Washington CDL surfaces. The Hilltop Vineyard in the Yakima Valley AVA is well represented by grape classifications; additional unmapped vineyards are in its immediate vicinity as are areas appearing to be apple orchards. The Mariposa Vineyard in the proposed Ancient Lakes AVA is also well represented. However, Ciel du Cheval and Klipsun Vineyards on the Red Mountain AVA are poorly covered by grape classifications. Grape pixels are spotty and the vineyards are largely classified as shrubland.

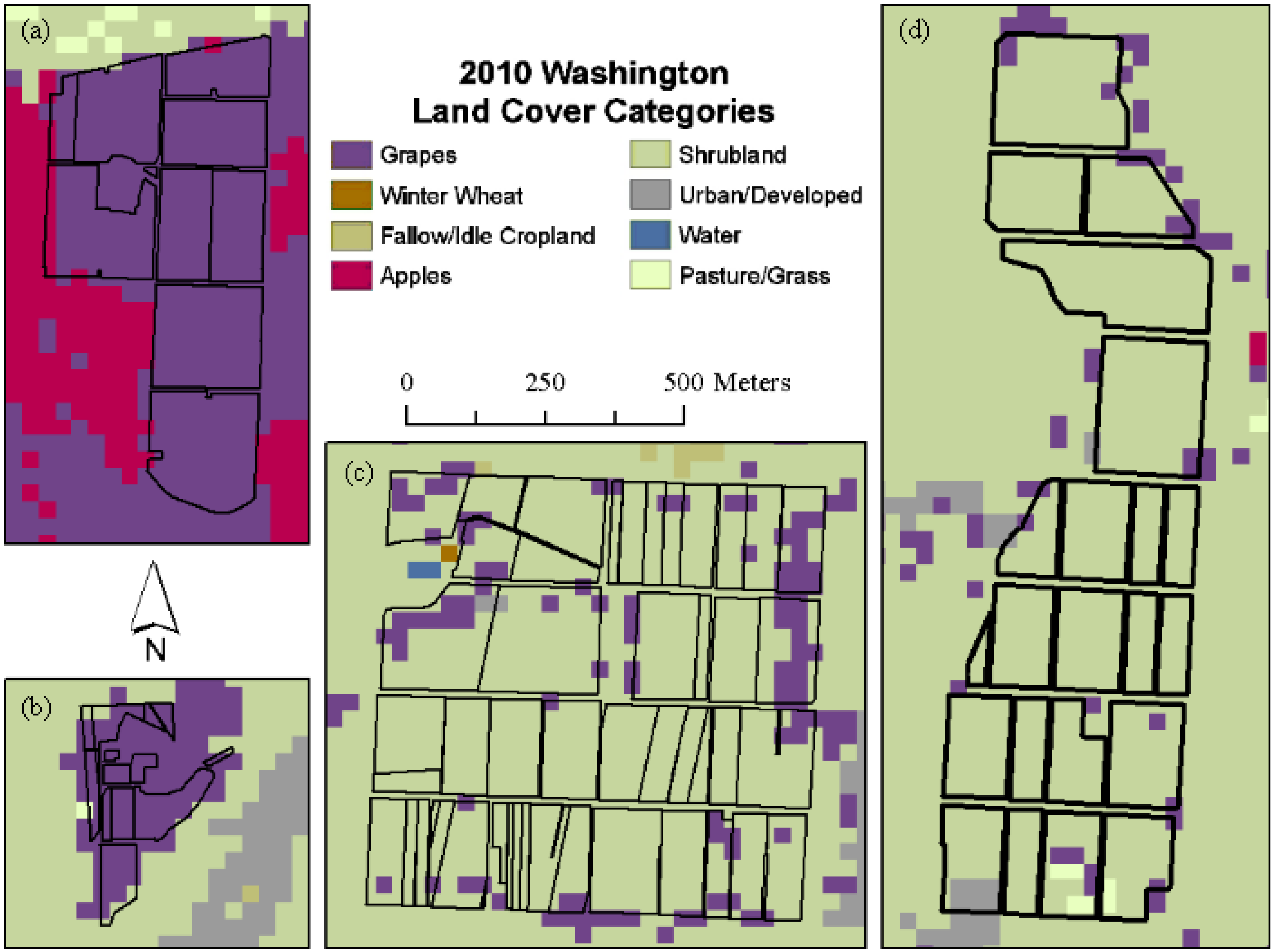


Figure 27: Example comparisons of Cropland Data Layer grape classifications to mapped vineyards. Accuracy is highly variable. (a) Hilltop Vineyard (46°18'N, 119°50'W) is represented well with grape classifications, unmapped vineyards are found in its vicinity; (b) Mariposa Vineyard (47°14'N, 120°W) is also well represented; adjacent (c) Ciel du Cheval and (d) Klipsun Vineyards (46°16'N, 119°26'W) are poorly represented and largely classified as shrubland.

In spite of this, CDL classifications are the best readily available inventory of the spatial distribution of grape area in the IPNW and were used to examine composite topographic and edaphic suitability for *V. vinifera* in areas presumably planted to grapes. Of the 42,010 ha classified in the CDL as grapes in Washington, Oregon and Idaho, 39,904 ha were within the study area. The remainder lay on the west side of the Cascade Mountains. There are many similarities between composite suitabilities for *V. vinifera* and *V. labruscana* (Tables 2, 3 and 5) and examination of *V. vinifera* was chosen because of the much greater value of the crop and sustained interest in expansion of *V. vinifera* area.

More assuredly *V. vinifera* acres, but far less spatially comprehensive are vineyard blocks mapped for ground truthing. Composite topographic and soil suitability surfaces for *V. vinifera* were also masked by these mapped blocks. A total of 1,100 ha were assessed as were 600 ha that were confirmed to have been planted in 2003 or earlier. These vineyard blocks eight years or older include all or portions of the Evergreen and Mariposa Vineyards in the proposed Ancient Lakes AVA, Clifton, Clifton Hill, Katherine Leone, North Ridge, Pheasant, Sundance, Talcott and Wahluke Slope Vineyards in the Wahluke Slope AVA, Hilltop and Sunnyside Vineyards in the Yakima Valley AVA and Ciel du Cheval and Klipsun Vineyards in the Red Mountain AVA.

Table 25 gives summary statistics for these extractions with areas divided into five quantiles. Topographic suitability is comparable over all three extractions; roughly one-third fall into the second quantile, forty percent in the third, one-fifth in the fourth and very little area in the lowest and highest quantiles. Soil suitability was more variable. The CDL extraction had nearly three-fifths of its area in the highest quantile while mapped vineyards were closer to two-fifths. Notably, grape areas in the lower two quantiles are nearly non-existent with only 3% in the second quantile in the CDL extraction. This was also reflected in appellation analysis which

Table 25: Summary statistics of topographic and soil suitability for *V. vinifera* area in the inland Pacific Northwest based on 2010 Cropland Data Layer classifications and all mapped vineyards as well as those planted for eight years or more. Proportional areas are divided between five quantiles.

	Min.	1Q	2Q	3Q	4Q	5Q	Max.	Mean	St. Dev.
CDL									
Topographic Suitability	0	4.65%	30.92%	42.73%	21.50%	0.19%	2.6	1.22	0.45
Soil Suitability	0.4	-	3.26%	10.06%	27.78%	58.90%	2	1.58	0.35
Mapped (all mapped *V. vinifera* area)									
Topographic Suitability	0	2.82%	33.27%	39.36%	24.47%	0.08%	2.3	1.26	0.40
Soil Suitability	0.8	-	-	12.82%	43.10%	44.08%	2	1.50	0.28
Mapped (planted 2003 or earlier)									
Topographic Suitability	0.3	4.12%	37.07%	37.72%	20.95%	0.13%	2.3	1.21	0.42
Soil Suitability	0.8	-	-	21.07%	38.76%	40.17%	2	1.45	0.30

resulted in very little representation in the lower two quantiles and even the third quantile for some AVAs for both *V. vinifera* and *V. labruscana* (Tables 17 and 18). This is due in part to very little area within AVAs classed as excessively, somewhat poorly, poorly and very poorly drained (Table 12), the drainage classes assigned a rating of zero.

3.4 Validation vineyards

Evaluating a site suitability model for *V. vinifera* is not as straightforward as for other agricultural species. For most other commodities, the primary goal is typically maximizing yield while maintaining quality above some minimum threshold and quantifiable with some objective metric. With premium wine grapes, discussions of yield typically revolve around restricting crop loads to ensure high quality. Perceptions of quality may be strongly influenced by marketing and the relationship growers establish and foster with wineries (Spayd, 1999).

Some research assesses crop quality through wine scores or awards (Bowen et al., 2005; Holland and Smit, 2010) or wine prices (Goldstein et al., 2008; Jones and Storchmann, 2001). Examining the final product introduces additional variables of the influence of the enologist and the procedures through which the wine is made on top of viticultural management. Others measure crop quality through total soluble solids, must pH, acid composition and/or anthocyanin content (Chorti et al., 2010; Nagel et al., 1972). Tesic et al. (2002a, 2002b) analyzed both wine scores and must characteristics. In either case, grapes must be tracked, ideally over several seasons, through fruit analysis and/or winemaking.

Nagel et al. (1972) note the difficulty of correlating any single must characteristic with sensory scores and varying optimums for different cultivars and/or desired wine styles. They use wine sensory analysis to determine grape quality, which, while informative, again adds an enological variable and is an inherently subjective process. Although lacking in thorough quantification of site quality, our approach to validation relies on interviews with growers and their perceptions of vineyard performance. Specifically, grower interviews focused on mapped environmental characteristics.

Rick Hamman of Hogue Ranches provided maps and tours of three vineyards he manages. Planted in 1991, the Hilltop Vineyard (46º18'N, 119º50'W) produces 6 ha of Chardonnay and 8 ha each of Cabernet Sauvignon and Merlot in the Yakima Valley AVA. Hilltop is unusual in its placement of wind machines at the highest points of the vineyard. Typically, they are placed at low spots where cold air is anticipated to accumulate to help break and mix atmospheric inversions, preventing damaging frosts. There is a valley to the north of Hilltop that fills with cold air and spills over to the top of the vineyard. It continues to slope down beyond the southernmost block, so cold air may linger near the top but drain well through the vineyard.

Past vineyard managers have observed the greatest cold damage occurring at the top of this vineyard. FFD data does indicate a very slightly shorter growing season at the northern end of Hilltop, 149 days compared to 151 at the southern end of the vineyard (Figure 28). This is an unusual circumstance, but a difference of two FFD over a relatively short distance is not inconsequential. Additionally, heat accumulation increases from north to south in all three GDD surfaces.

Hamman noted the entire vineyard is well drained and SSURGO data confirms this; the entire vineyard's soils are classed well drained. He also stated soils were shallower than the Sunnyside and Dead Canyon Vineyards. SSURGO data corroborates this with a mean depth to restrictive layer of 94.4 cm compared to 140.3 cm in Sunnyside and at least 201 cm in Dead Canyon. Referring to Table 14, SSURGO data depths appear to be capped at 201 or 203 cm in the study area.

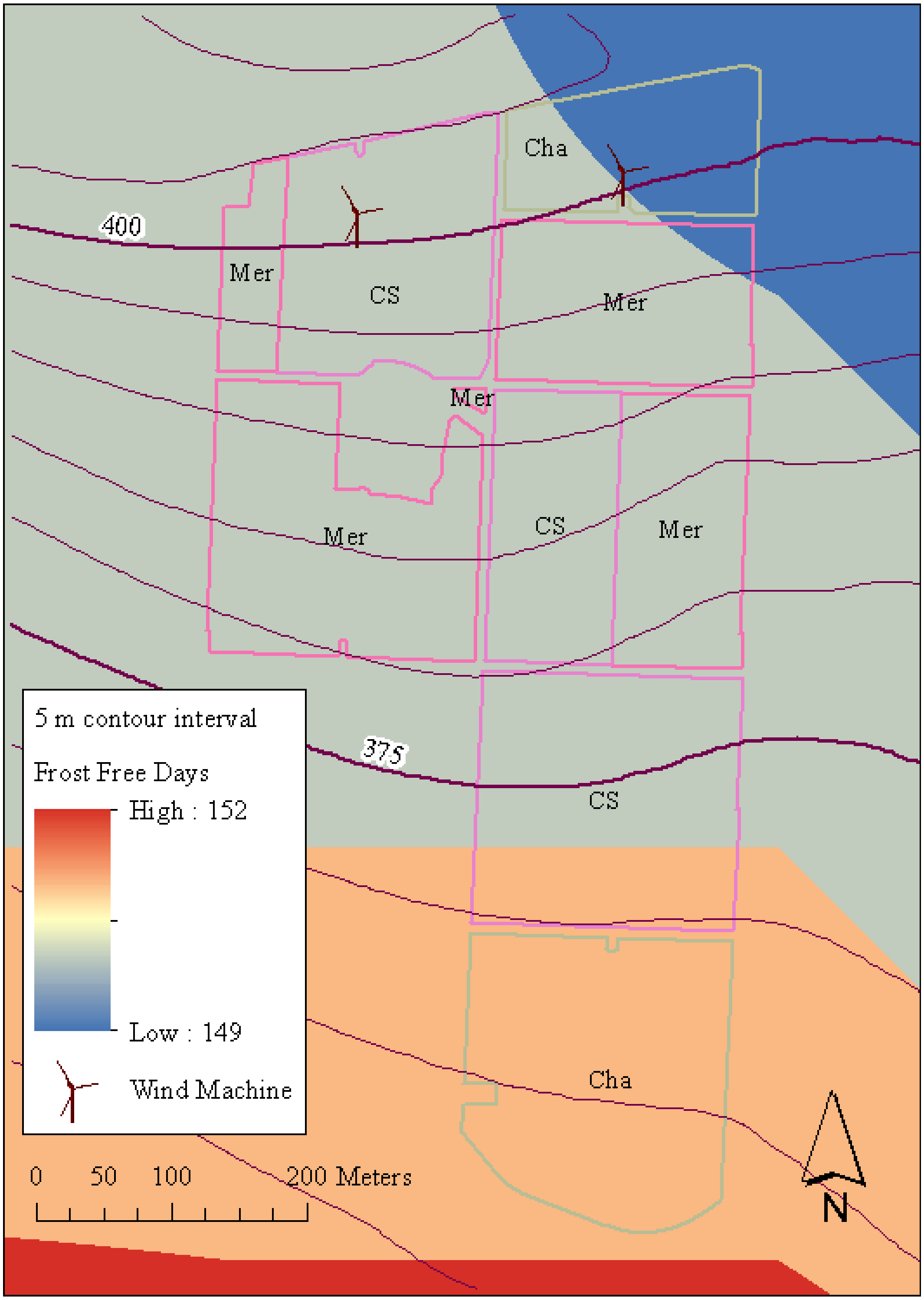


Figure 28: Hogue Ranches' Hilltop Vineyard (46°18'N, 119°50'W) is unusual in that wind machines used for frost protection are placed at the highest point in the vineyard. Elevation declines from north to south in the vineyard with a large bowl declining to the north. Growing season length data shows slightly fewer frost-free days at the top of the vineyard. Abbreviations: Cha (Chardonnay), CS (Cabernet Sauvignon), Mer (Merlot).

Without naming specific fruit qualities or assumptions of environmental causes, Hamman also noted two outstanding Cabernet Sauvignon blocks and one Chardonnay block of average quality. Composite site suitability, excluding heat accumulation and growing season length, are similarly high between all blocks in the vineyard, mean of 42.6 out of a possible maximum of 55, and the Chardonnay block actually rates the highest with a mean of 42.8.

Farther west up the Yakima Valley AVA, the Sunnyside Vineyard (46º22'N, 119º57'W) is planted to 20 ha of Chardonnay, 15 ha of Pinot Gris, 14 ha of Riesling, 5 ha of Sauvignon Blanc, 3 ha of Gewürztraminer and 2 ha of Sémillon. Most of the vineyard was planted in 1986; 11 ha of Pinot Gris were planted in 2006 and 2008.

Again, SSURGO data align well with Hamman's perceptions. He pointed out an unplanted piece southeast of the vineyard explaining soil tests revealed high salinity and pH prior to planting which SSURGO indicates has a pH of 8.6 (Figure 29). One Chardonnay block in Sunnyside goes into Hogue's reserve, indicating some winemaker preference, and the Riesling block goes into late harvest requiring at least 24º Brix.

The Chardonnay block registers the lowest composite suitability of the vineyard, a mean of 33.9 of a possible 55, compared to 37.5 for the Riesling and 41.3 for the remaining blocks. The Chardonnay block is relatively flat, has an AWC higher than what is rated as ideal, a high pH (8.1) and is shallow (64 cm). Again, Hamman had no insight on environmental factors that may contribute to the reserve block's perceived high quality. Sunnyside records around ten more FFD than Hilltop and mean heat accumulation (1,429 GDD) is 142.5ºC greater according to OK GDD. Both these factors may contribute to the Riesling's designation for late harvest.

Farther south in the Horse Heaven Hills AVA lies Dead Canyon Vineyard (46º55'N, 119º54'W), planted to 31 ha of Cabernet Sauvignon, 13 ha of Merlot and 2 ha of Syrah in 2006

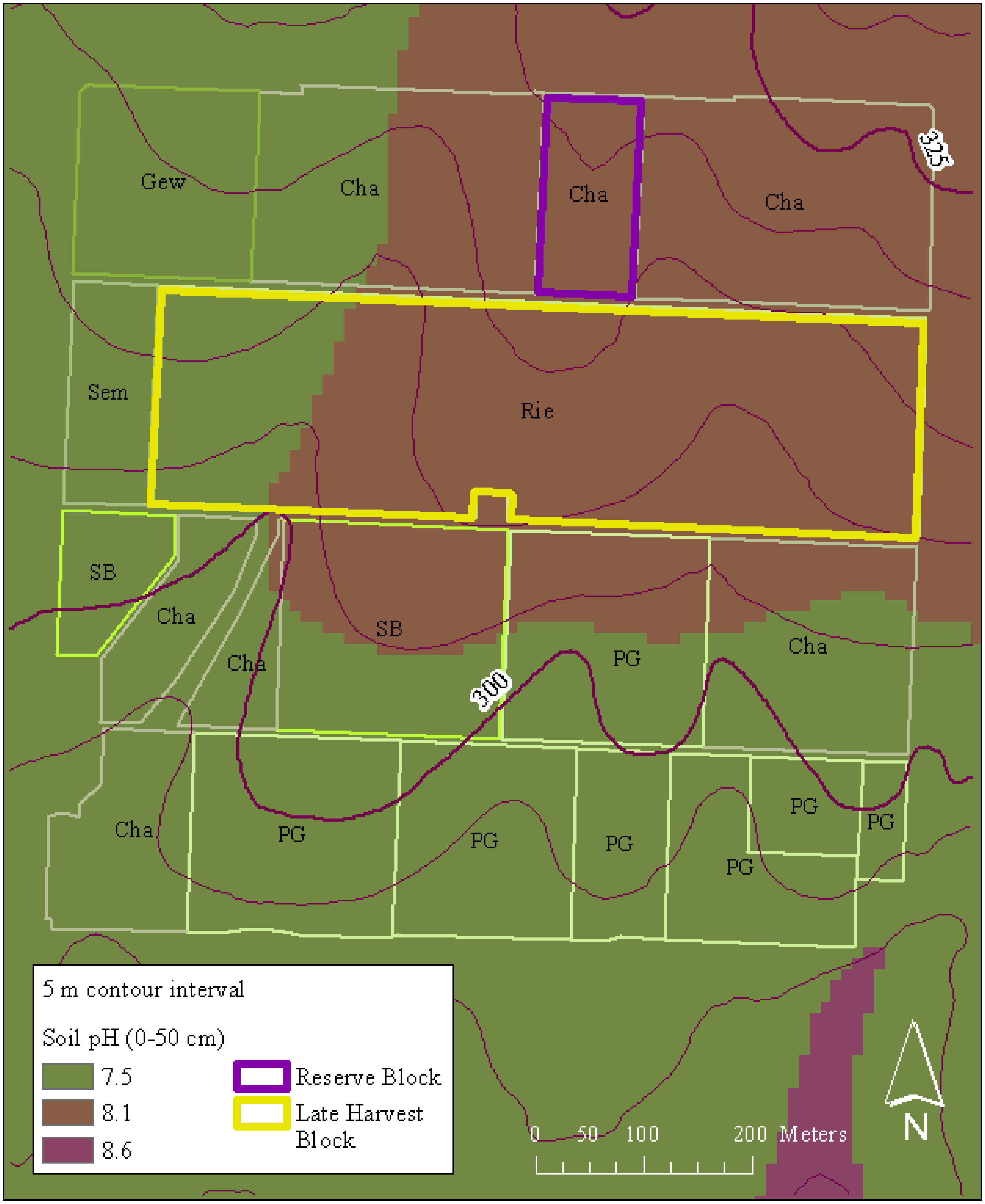


Figure 29: Hogue Ranches' Sunnyside Vineyard (46°22'N, 119°57'W) features reserve Chardonnay and late harvest Riesling blocks. Higher soil pH is found in these two blocks and the more alkaline portion noted in the southeast, unplanted corner was noted by grower Rick Hamman. Abbreviations: Cha (Chardonnay), Gew (Gewürztraminer), PG (Pinot Gris), Rie (Riesling), SB (Sauvignon Blanc), Sem (Semillon).

and 2007. Hamman noted the deep, uniform, sandy loams throughout the vineyard, greater AWC than Hilltop Vineyard and 100% primary bud loss following a November 2010 freeze that dropped temperatures as low as -23ºC. Soil depth was noted previously. Mean AWC is nearly the same between Dead Canyon and Hilltop, slightly higher in the former, but total available water is increased with greater depth.

Rating frost risk based on one year of damage is dangerous. Cold hardiness depends on cultivar and preceding temperatures, among other factors (Ferguson et al., 2011). Dead Canyon experiences a relatively long growing season, 172 FFD, which could potentially be detrimental in terms of cold damage if relatively high temperatures precede frost events when cold hardiness is low. However, Dead Canyon's relatively gentle slopes could exacerbate frost damage by allowing cold air to linger (Figure 30). Although equipped with wind machines, frost protection beyond a certain threshold can be extremely costly or impossible. Heat accumulation is greater here than Hilltop or Sunnyside with a mean of 1,529 GDD according to OK GDD. Composite site suitability for Dead Canyon is 38.6.

Hamman also noted that winemakers appear to believe the Yakima Valley is better suited to white cultivars than red due to insufficient heat accumulation. At current crop loads, he has found Yakima Valley vineyards cannot compete with Red Mountain in price and quality. Earlier in the day at an unmapped vineyard, Hamman was overseeing grafting of Chardonnay onto Merlot rootstock at the behest of the contracting winery.

To the northeast lie Ciel du Cheval and Klipsun Vineyards on Red Mountain AVA (46º16'N, 119º26'W). In a partnership with Quilceda Creek, Ciel du Cheval hosts a wide variety of cultivars on 54 ha: Barbera, Cabernet Franc and Sauvignon, Counoise, Grenache, Merlot, Mourvedre, Nebbiolo, Petit Verdot, Roussanne, Sangiovese, Syrah and Viognier planted between

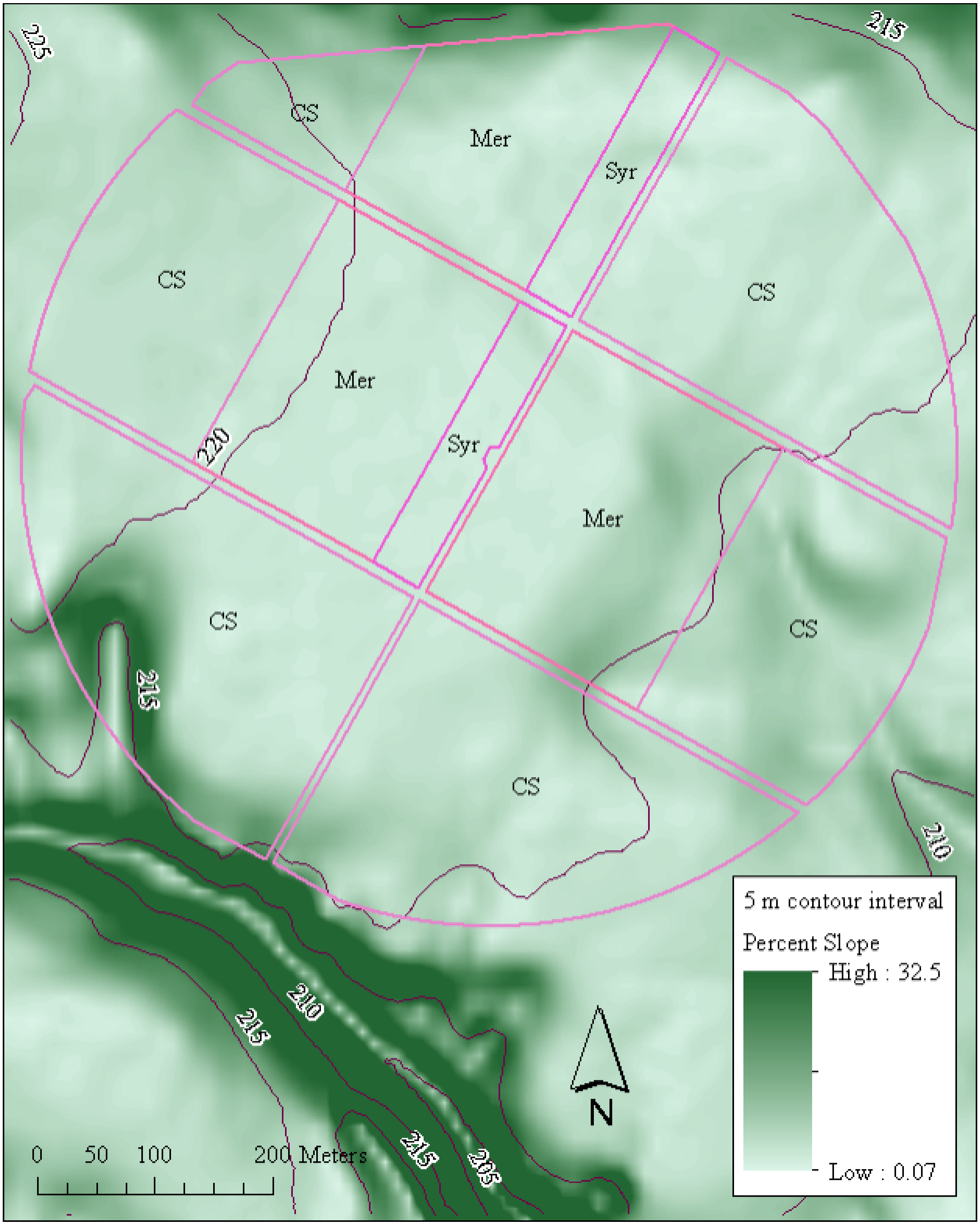


Figure 30: Hogue Ranches' Dead Canyon Vineyard (46°55'N, 119°54'W) suffered 100% primary bud loss in November 2010 when temperatures were as low as -23°C, which may have been due to relatively gentle slopes, especially continuing to the east and west, and cold air pooling. Abbreviations: CS (Cabernet Sauvignon), Mer (Merlot), Syr (Syrah).

1975 and 1998. Jim Holmes noted outstanding performance from the Roussanne and Mourvedre and poor vigor and ripening in one Cabernet Sauvignon block currently under consideration for removal, potentially due to excessive soil drainage.

Mean composite suitability is least within the Roussanne and Mourvedre (33.4), slightly higher in the poorly performing Cabernet Sauvignon block (34.6) and greatest in the remaining blocks (36.4), but all are quite similar. The relatively moderate overall ratings are due to shallow slopes (mean of 2.82%), excessively drained soils over half of the vineyard, including the problematic Cabernet Sauvignon block (Figure 31), and slightly high pH (mean of 7.6). Holmes also noted an area along the southwestern edge of the vineyard where cold air drainage is often problematic. A flat area extending to the west before declining briefly and flattening out again may not allow proper air drainage or it may be a feature too small for the 10 m DEM to capture.

Holmes mentioned conversion of several blocks to other cultivars. Chenin Blanc was replaced with Merlot and Grenache due to price, Chardonnay and Gewürztraminer performed well, but did not work out economically and Riesling was replanted with Syrah. Echoing Hamman's perceptions, Red Mountain appears to be moving away from white cultivars to red.

Just to the west of Ciel du Cheval lies Klipsun Vineyard, planted with 23 ha of Cabernet Sauvignon, 12 ha of Merlot, 6 ha of Sémillon, 4 ha of Syrah, 2 ha of Sauvignon Blanc and small areas of Malbec and Nebbiolo. Vineyard manager Julia Koch pointed out high vigor in southern blocks, a cold pocket in a southeastern portion of the vineyard and a portion of Cabernet Sauvignon suffering from low vigor and severe shatter, perceived to be related to excessive drainage and/or low AWC.

Although Klipsun is found on the western edge of Red Mountain which declines quickly, much of the central, eastern and northern portions of the vineyard are flat, which may contribute

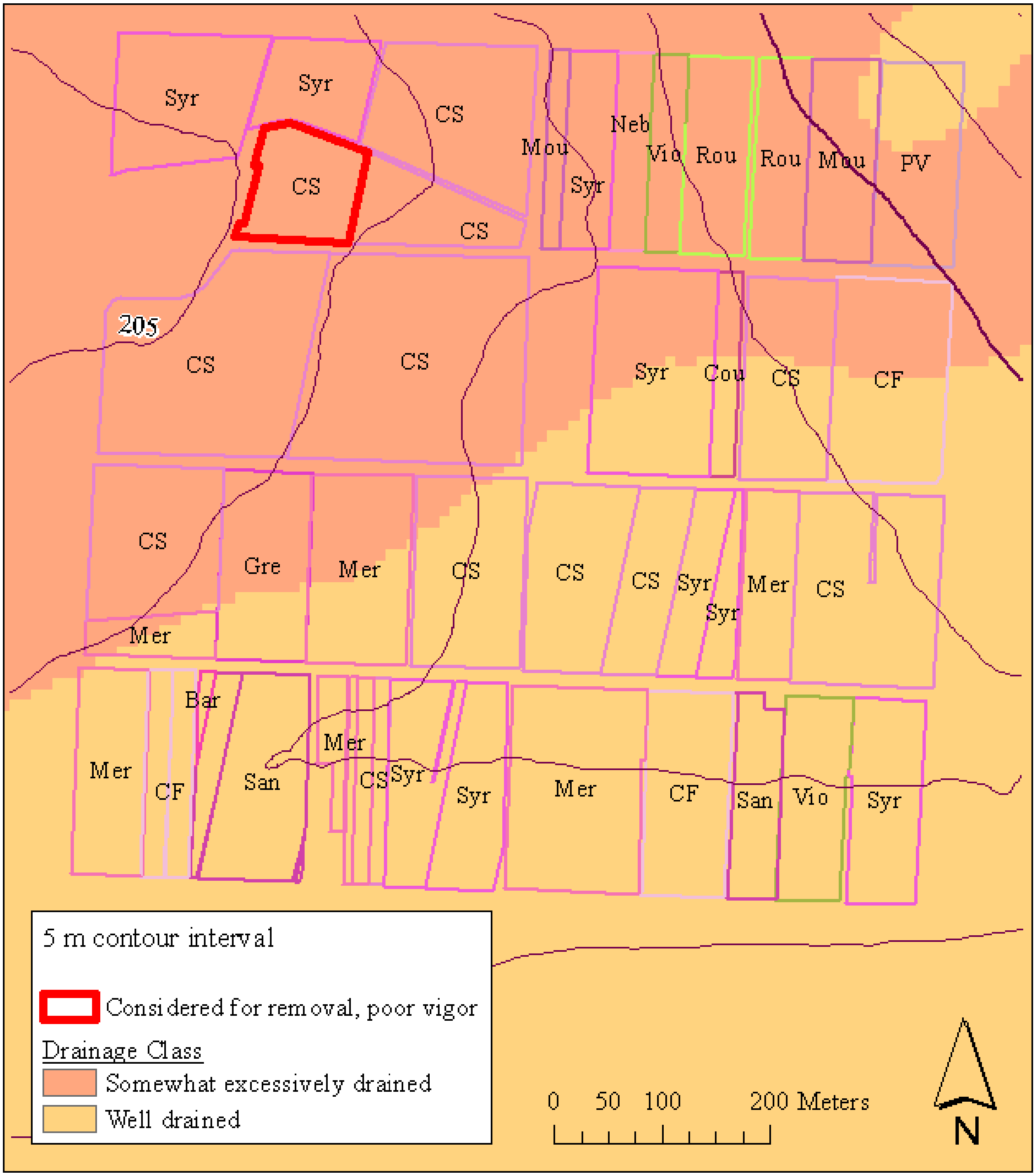


Figure 31: Ciel du Cheval Vineyard (46°16'N, 119°26'W) hosts a diversity of primarily red cultivars on Red Mountain. The Cabernet Sauvignon block highlighted in red is being considered for removal due to poor vigor potentially stemming from excessive soil drainage. Soil survey data does rate the block as somewhat excessively drained, but the same classification is given to nearly half the vineyard. Abbreviations: Bar (Barbera), CF (Cabernet Franc), Cou (Counoise), CS (Cabernet Sauvignon), Gre (Grenache), Mer (Merlot), Mou (Mourvedre), Neb (Nebbiolo), PV (Petit Verdot), Rou (Roussanne), San (Sangiovese), Syr (Syrah), Vio (Viognier).

to cold air pooling (Figure 32). In this case, SSURGO data does not reveal perceived vigor and shatter issues. AWC over the vast majority of the vineyard is 0.19 cm/cm, greater than what is rated as ideal, but not generally considered excessive. There is a small area classed as somewhat excessively drained and with AWC of 0.11 cm/cm, which actually falls into the most highly rated range, but it is approximately 300 m southeast of the area with shatter problems. Composite site suitability at Klipsun is 37.6.

Moving north to the Wahluke Slope AVA, Dustin Tobin of Milbrandt Vineyards' Wahluke Wine Company provided maps for nine vineyards with varying amounts of supplementary information. This discussion will focus on four for which Tobin went into greater detail.

Pheasant Vineyard (46º43'N, 119º51'W) was planted in 1999 to 10 ha of Riesling, 8 ha of Cabernet Sauvignon, 5 ha of Syrah, 3 ha of Merlot and 1 ha of Sangiovese. Tobin stated this vineyard was under consideration for removal due to persistent cold damage. During the November 2010 frost, Merlot, Cabernet Sauvignon and Syrah suffered 100% primary bud loss while Riesling was not severely damaged. Most telling in the spatial data is the exceptionally flat terrain, a mean slope of 0.54% and a maximum of only 1.67% with shallow slopes surrounding the vineyard, preventing sufficient cold air drainage (Figure 33). Composite site suitability at Pheasant is 30.9, tying for the lowest score among discussed vineyards.

To the northwest, North Ridge Vineyard (46º45'N, 119º52'W) was planted in 2003 to 14 ha of Cabernet Sauvignon, 5 ha of Syrah, 4 ha of Malbec and smaller areas of Barbera, Chardonnay, Dolcetto, Durif, Grenache, Merlot, Mourvedre and Petit Verdot. Tobin noted the shallow, ancient soils of the site, which lies above the depositional area of the Missoula Floods. SSURGO data shows a mean depth of 68 cm in the vineyard, far less than the 174 cm mean in the Wahluke Slope (Figure 34). He also noted that it is much warmer than Pheasant. Heat

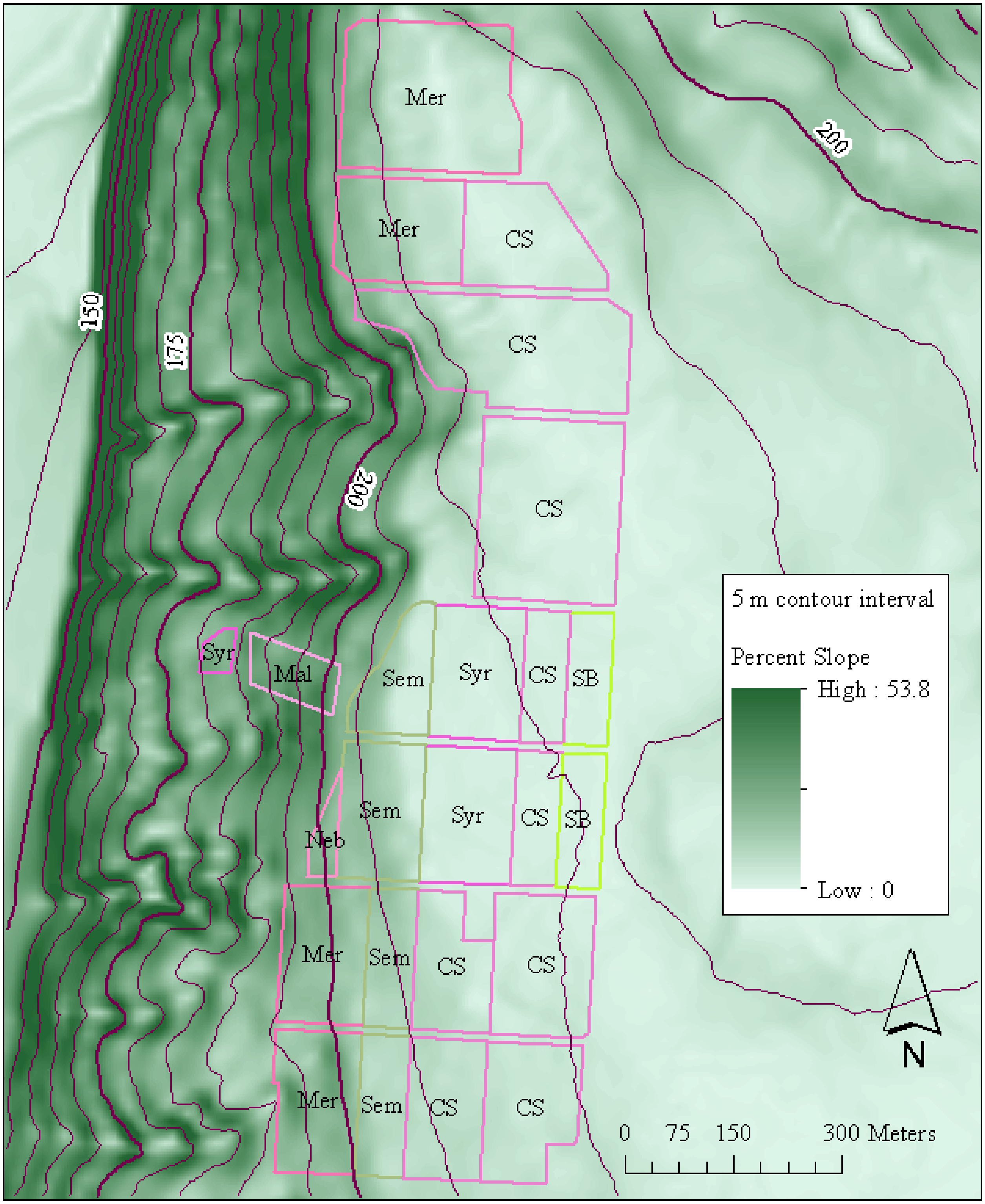


Figure 32: Klipsun Vineyard (46°16'N, 119°26'W) on Red Mountain faces frost damage problems, particularly along its eastern edge where slopes are gentle. New plantings of Malbec and Syrah are located on the western descent of Red Mountain. Abbreviations: CS (Cabernet Sauvignon), Mal (Malbec), Mer (Merlot), Neb (Nebbiolo), SB (Sauvignon Blanc), Sem (Sémillon), Syr (Syrah).

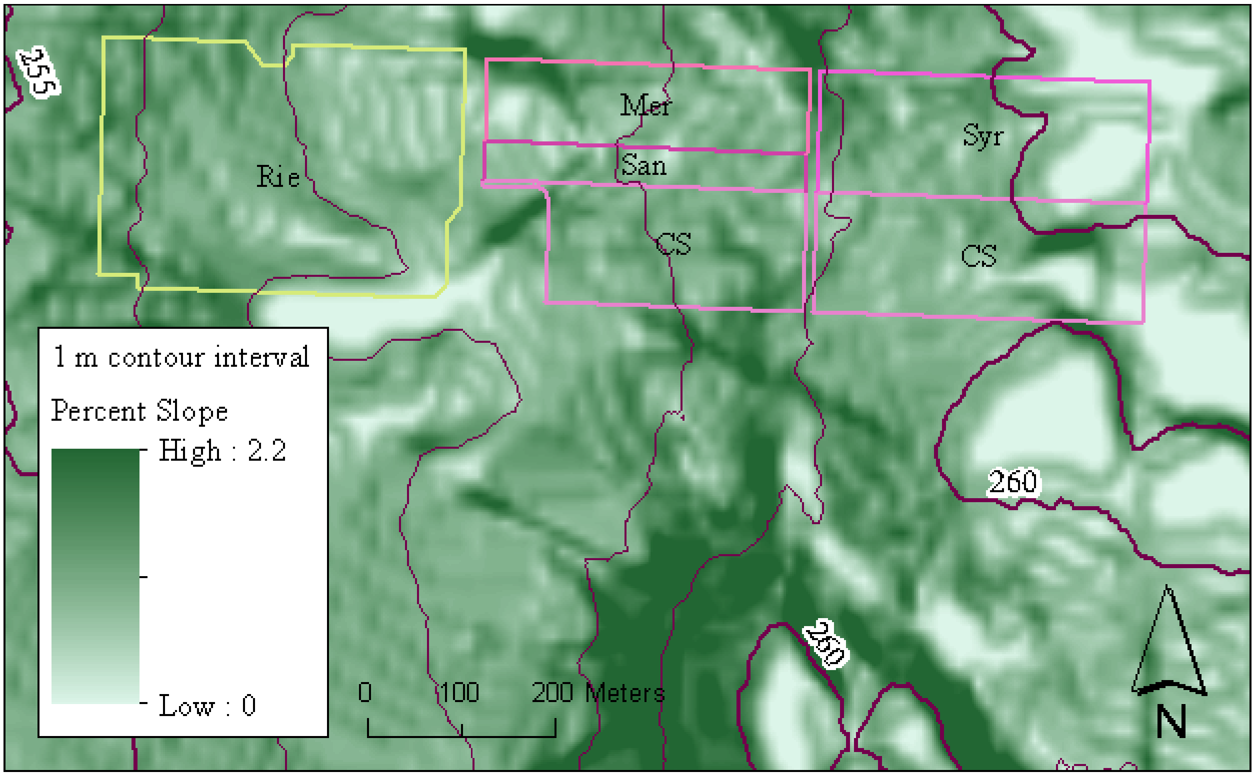


Figure 33: Milbrandt's Pheasant Vineyard (46°43'N, 119°51'W) is being considered for removal due to persistent frost damage. The vineyard and its vicinity are dominated by shallow slopes and inadequate cold air drainage. Abbreviations: CS (Cabernet Sauvignon), Mer (Merlot), Rie (Riesling), San (Sangiovese), Syr (Syrah).

accumulation data does not indicate this, but North Ridge does have predominately south-southwest facing slopes while Pheasant is both flat and variable in aspect. Composite site suitability at North Ridge is 33.3.

Moving west, Clifton Vineyard (46°45'N, 119°55'W) was mostly planted in 2000 to 14 ha of Cabernet Sauvignon, 12 ha of Merlot, 10 ha of Syrah and smaller areas of Cabernet Franc, Grenache, Malbec, Mourvedre, Nebbiolo, Viognier and Zinfandel. Tobin noted the site's low AWC in sandy soils, great depth to restrictive layer and high heat accumulation. AWC is relatively low, 0.09 cm/cm, but this actually falls into the ideal range according to our ratings (Figure 35). This is one of three vineyards undergoing trials of compost applications of 70% cattle feedlot manure and 30% pomace to promote AWC and soil fertility. Soils are deep with a

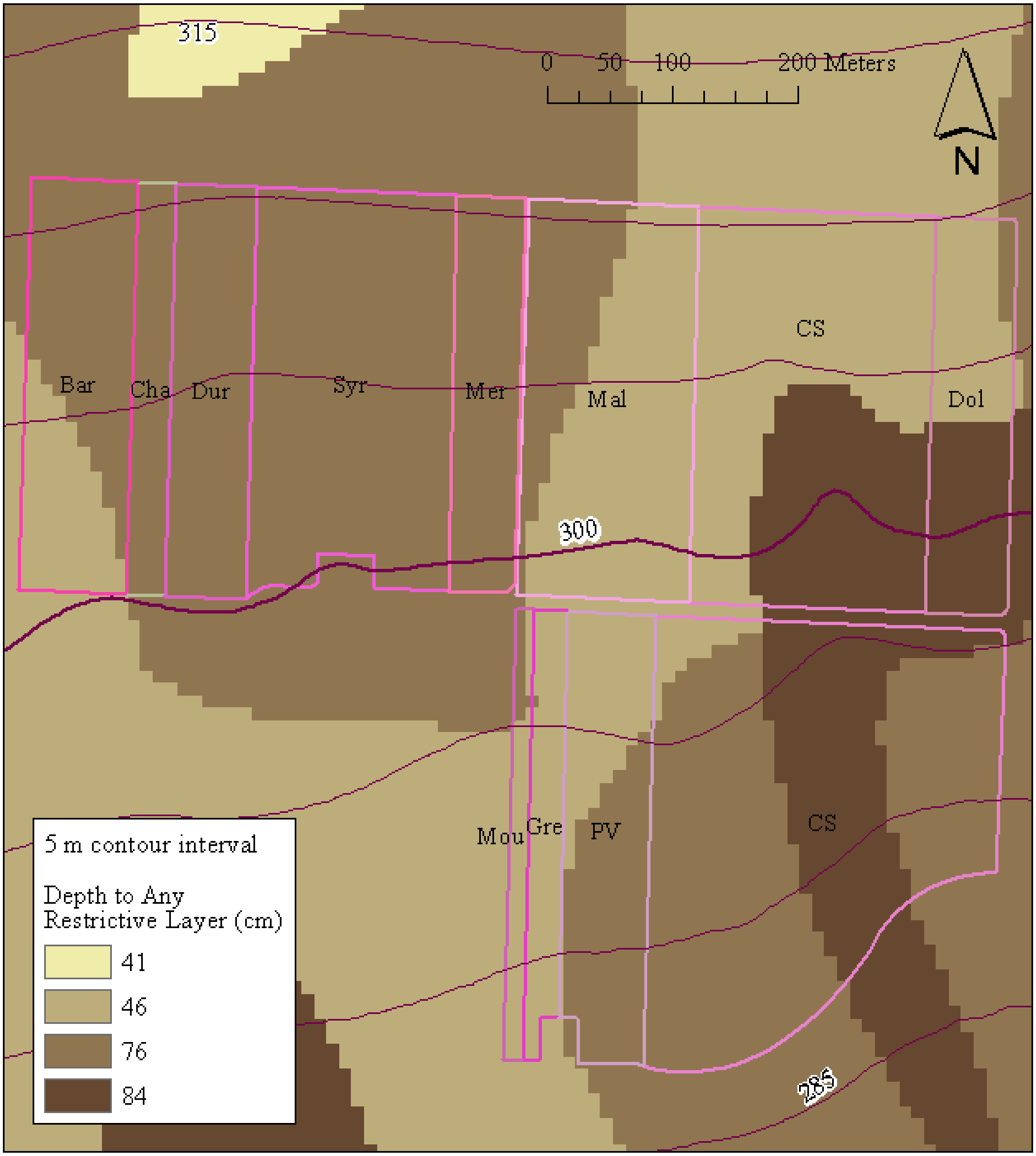


Figure 34: Milbrandt's North Ridge Vineyard (46°45'N, 119°52'W) contains shallow soils; much of the vineyard has soil less than 50 cm in depth according to soil survey data. Abbreviations: Bar (Barbera), Cha (Chardonnay), CS (Cabernet Sauvignon), Dol (Dolcetto), Dur (Durif), Gre (Grenache), Mal (Malbec), Mer (Merlot), Mou (Mourvedre), PV (Petit Verdot), Syr (Syrah).

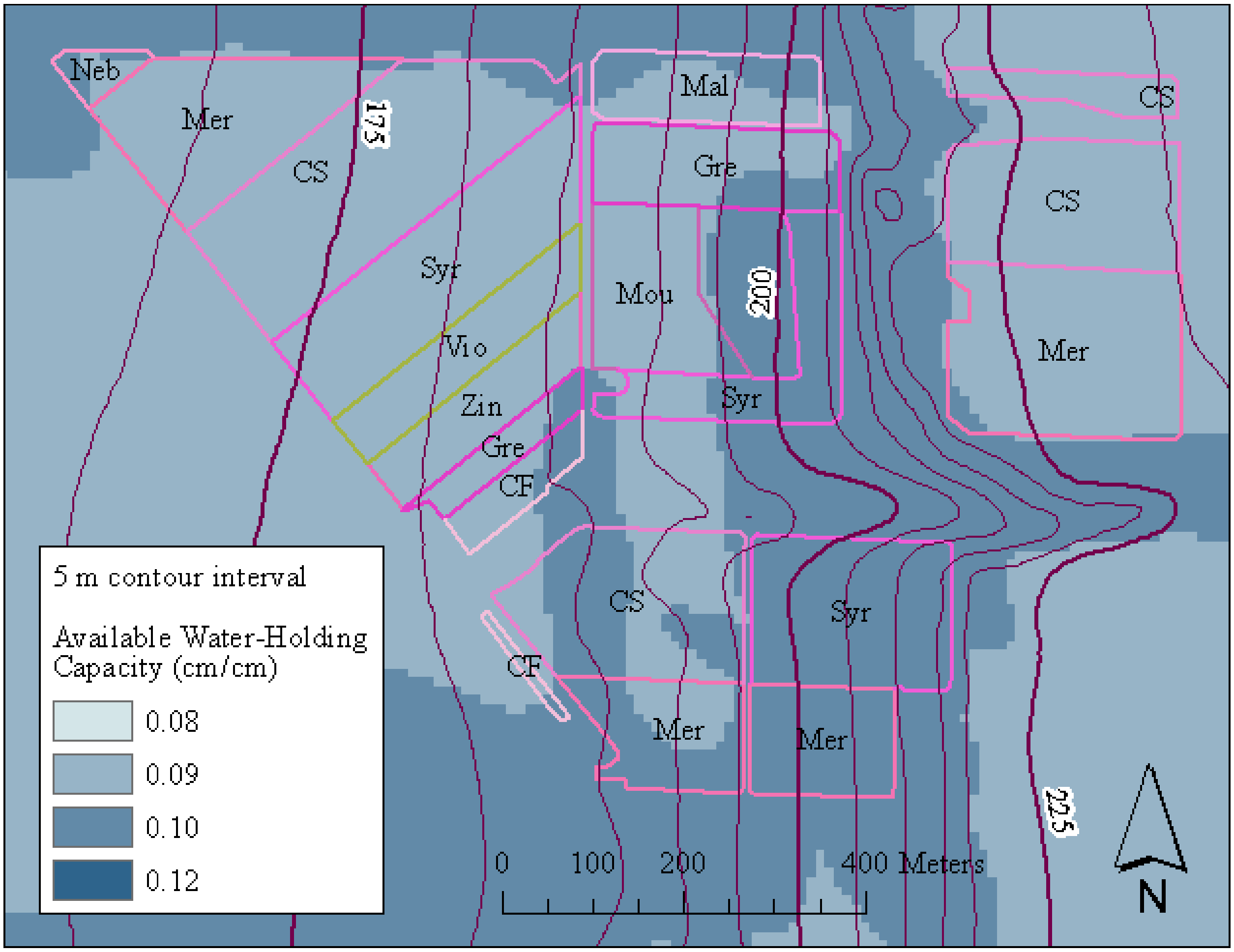


Figure 35: Milbrandt's Clifton Vineyard (46°45'N, 119°55'W) is one of several vineyards for which the grower noted low available water-holding capacity, but which soil survey data gives the greatest rankings. Abbreviations: CF (Cabernet Franc), CS (Cabernet Sauvignon), Gre (Grenache), Mal (Malbec), Mer (Merlot), Mou (Mourvedre), Neb (Nebbiolo), Syr (Syrah), Vio (Viognier), Zin (Zinfandel).

mean exceeding 200 cm. Clifton has the second greatest heat accumulation of the vineyards Tobin manages and is dominated by west and southwest-facing slopes. Composite site suitability at Clifton is 32.5

To the south, Katherine Leone Vineyard (46°43'N, 119°55'W) hosts 18 ha of Cabernet Sauvignon and 7 ha each of Merlot and Syrah, planted in 1999. Tobin stated this vineyard primarily goes towards bulk production and it has the second least mean composite suitability of the vineyards he manages (30.8). It was also noted to have high heat accumulation (Figure 36).

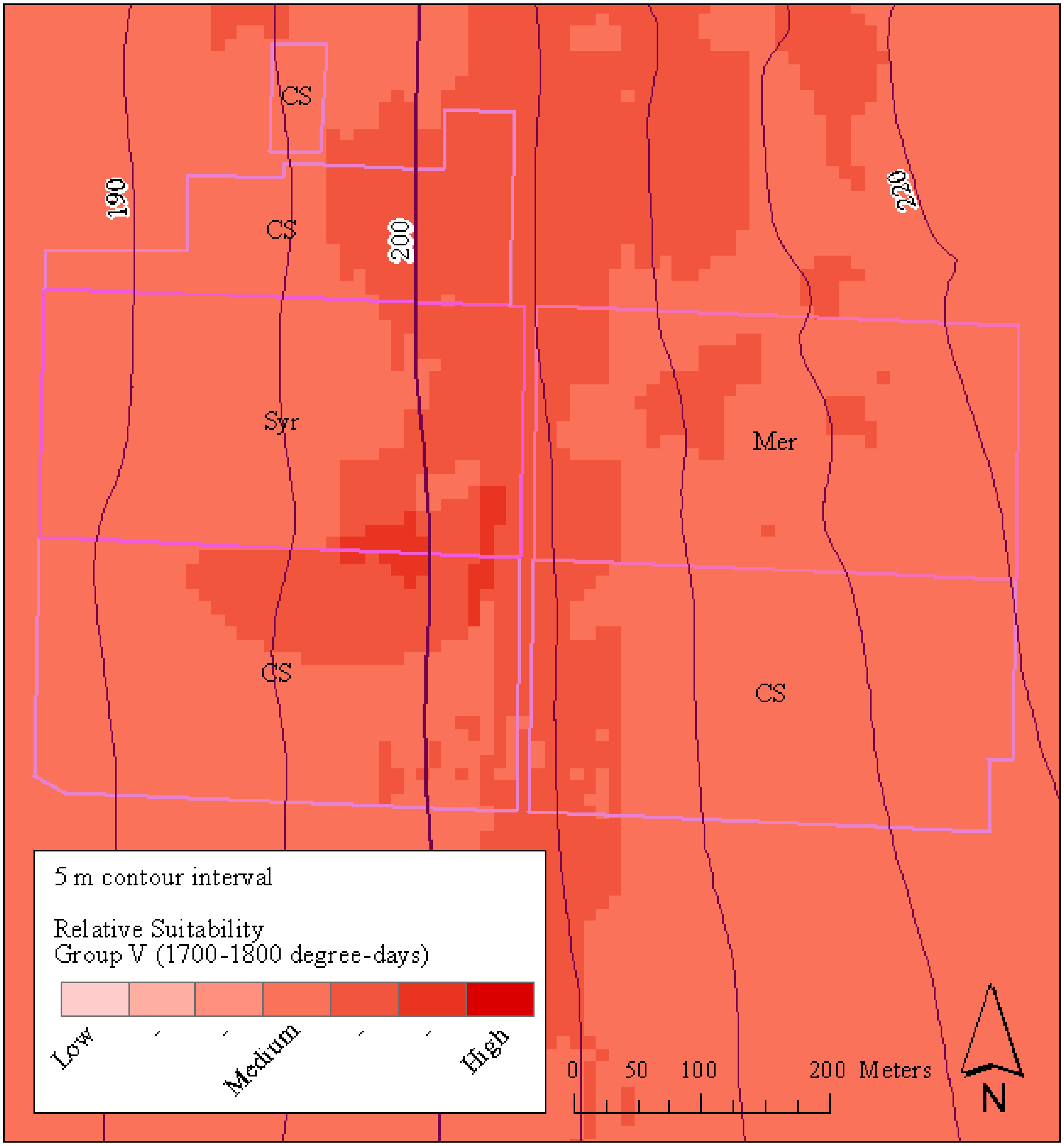


Figure 36: Milbrandt's Katherine Leone Vineyard (46°43'N, 119°55'W) produces fruit that largely goes into bulk production and has the second-lowest mean composite site suitability score of the vineyards managed by grower Dustin Tobin. Katherine Leone's low scores stem from excessively drained soils, relatively shallow slopes and western facing slopes garnering low solar insolation. Abbreviations: CS (Cabernet Sauvignon), Mer (Merlot), Syr (Syrah).

OK GDD confirms this as the hottest vineyard Tobin manages with a mean of 1,751 GDD. Once again, perceptions of deep soils match SSURGO data which show greater than 200 cm of depth across the vineyard. Katherine Leone ties Pheasant with the lowest composite site suitability score of discussed vineyards at 30.9.

Farther north along the western edge of Grant County is the cooler, proposed Ancient Lakes appellation. Cameron Fries of Mariposa Vineyard (47º14'N, 120ºW) offered his insights on the 4 ha planted from 1991 to 2003. This includes 2 ha of Roussanne and smaller areas of Cabernet Sauvignon and Franc, Malbec, Merlot, Pinot Noir and Syrah. Water demand in the vines is persistent challenge for Fries. SSURGO data classes most of the vineyard as somewhat excessively drained and mean AWC over the vineyard is 0.11 cm/cm, which again falls in our ideal range.

Fries claimed the site is warmer than its immediate vicinity. Mean OK GDD in the vineyard is 1,493ºC and this decreases approximately 100ºC within 0.5 km to the northwest and southeast (Figure 37). Roussanne, Syrah and Cabernet Franc were noted as the best performers and the easiest to grow while the Merlot had proved more challenging. Cabernet Franc and Syrah blocks receive the second and third-highest composite scores, means of 42.3 and 40.6, respectively. Merlot scores the lowest with a mean of 38.0. Roussanne scores second-lowest, but comparable to Syrah (mean of 40.0).

Farther south, Ryan Flanagan of Milbrandt Vineyards provided maps of five vineyards. Four of these were planted in 2007 or later, so perceptions of performance and fruit quality have not yet fully developed. Discussion will focus on the 182 ha Evergreen Vineyard (47º7'N, 119º57'W, Figure 38), planted from 1999 to 2002 with 39 ha of Riesling and 4 ha of Sauvignon Blanc blocks planted in 2005 and 2010. Other cultivars are 49 ha of Chardonnay, 26 ha of

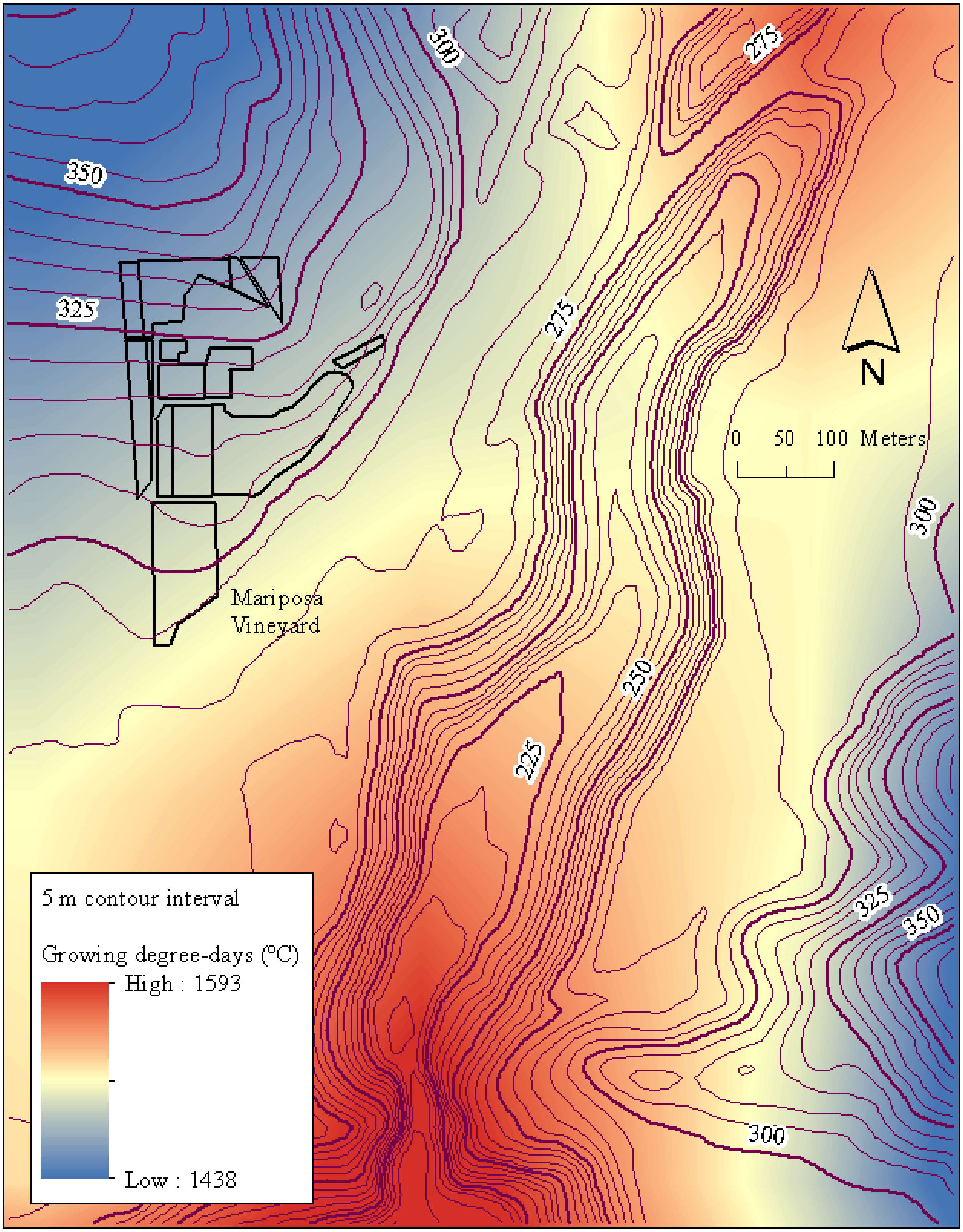


Figure 37: Mariposa Vineyard (47°14'N, 120°W) lies on the western bank of Lynch Coulee on a relatively warm site benefiting from southern exposures. Heat accumulation decreases rapidly to the northwest and southeast as elevations increase.

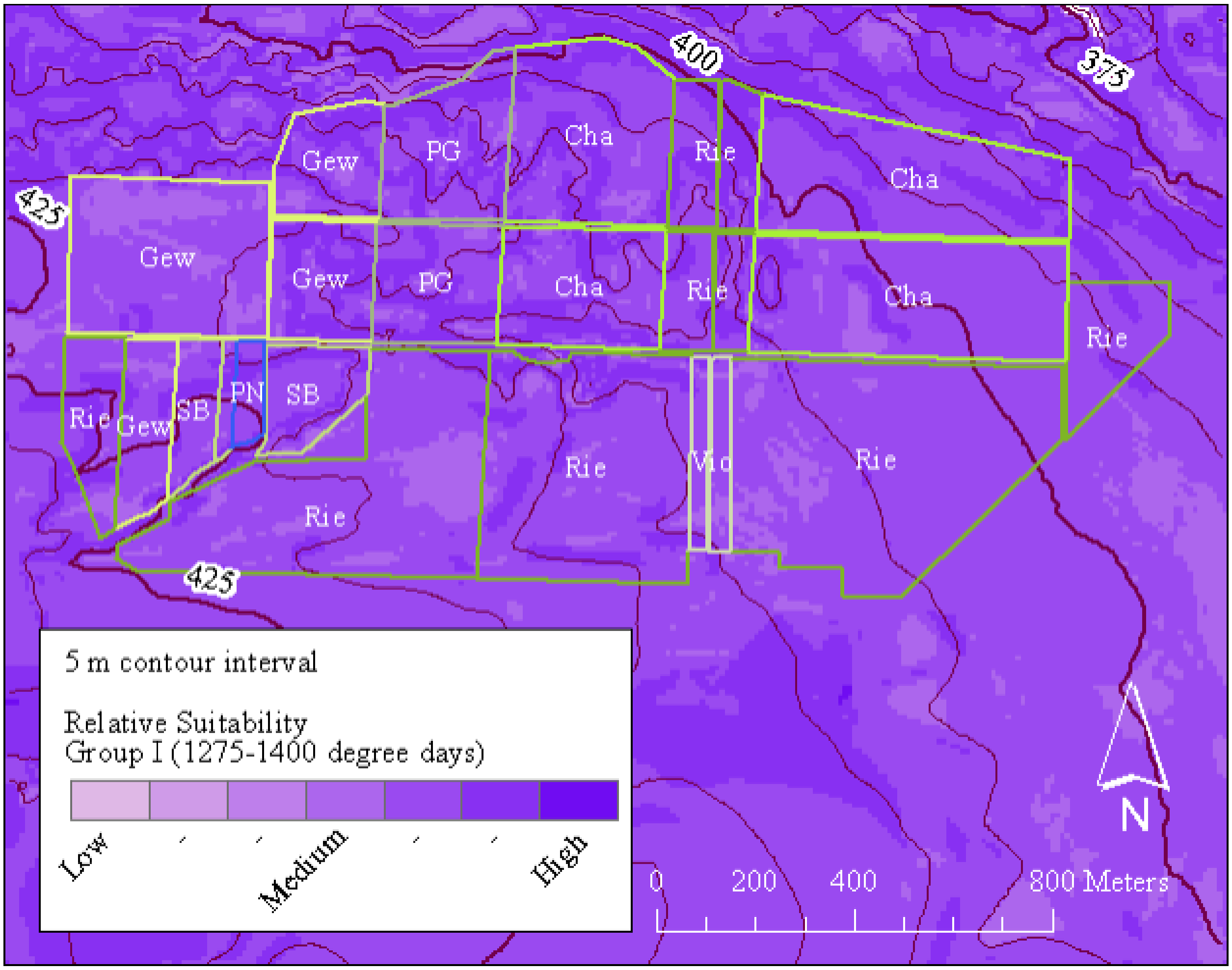


Figure 38: Milbrandt's Evergreen Vineyard (47°7'N, 119°57'W) illustrates the heterogeneity possible over a vineyard. Varying slopes, shallow, alkaline soils and many aspects contribute to the variety. Abbreviations: Cha (Chardonnay), Gew (Gewürztraminer), PG (Pinot Gris), PN (Pinot Noir), Rie (Riesling), SB (Sauvignon Blanc), Vio (Viognier).

Gewürztraminer, 14 ha of Pinot Gris, 3 ha of Viognier, 1 ha of Pinot Noir and 43 ha of older Riesling and 3 ha of older Sauvignon Blanc.

Flanagan pointed out the shallow soils featuring fractured caliché on Evergreen Ridge upon which the vineyard is situated. Soils are indeed quite shallow; SSURGO data shows a mean of 55 cm and a minimum of 18 cm. Calcium carbonate is present, but in relatively low quantities (mean of 0.83%, maximum of 4%). Greater concentrations may be found below 60 cm, which is the depth to which calcium carbonate was mapped. Shallow soils are found on topographically high points where AWC was also noted to be low. SSURGO data shows a mean of 0.15 cm/cm and a minimum of 0.13 cm/cm, both at the upper end of the ideal range. Similar to the Milbrandt Vineyards in the Wahluke Slope, 100% feedlot manure is being used to amend areas with low AWC. Composite site suitability at Evergreen is 37.3.

Milbrandt finds the area too cool to economically ripen red cultivars and of the 387 ha planted between the five vineyards, only 1 ha of Pinot Noir is planted as the token red cultivar. The five vineyards recorded a mean of 175 FFD and OK GDD records a mean of 1,330ºC. This is 62ºC less than the proposed Ancient Lakes AVA mean (Table 19) over a fairly long growing season, 8 days longer than the appellation mean (Table 20).

3.5 Climatic requirements of cultivars

Validation of heat accumulation surfaces shows mean daily errors of -0.13ºC for OK and -0.15º for UK compared to actual observed GDD over the 25 validation stations. This means, on average, both interpolation methods underestimated heat accumulation at the validation stations. Mean absolute daily errors were 0.66ºC for OK and 0.50ºC for UK. These values are comparable to cross-validation results for PRISM monthly minimum and maximum temperatures for western states (Daly et al., 2008).

These differences may seem relatively low, but can add up over the 214-day growing season. The greatest difference in the OK surface was found at the Walla Walla Regional Airport station which interpolated 368 fewer GDD than the actual observation. For the UK surface, the greatest difference was at the Priest Rapids Dam station, interpolated at 357 fewer GDD than the actual observation. Errors tend to be greatest at stations in isolation, those without other nearby stations (Hall and Jones, 2008). One weakness of this type of jackknife validation is it ultimately provides error measurements over only a very small area, where weather stations are available

(Daly et al., 2008).

Determining which heat accumulation surface best represents actual conditions based on what each says about different cultivars is not a straightforward matter. Many *V. vinifera* cultivars can ripen fruit over a relatively wide range of climatic conditions (Schultz and Jones, 2010; Figure 8). Heat requirements also differ depending on desired wine style (Gladstones, 1992; Jackson and Cherry, 1988; Jackson and Schuster, 2001). Table 26 lists cultivars in groups based

Table 26: Wine grape maturity groups and corresponding biologically effective degree-days (BEDD) to ripeness for making dry or semi-sweet table wines. Cultivars included in mapped validation vineyards are underlined. Modified from Gladstones (1992)

	Red wines	White or rosé wines
Group 1 1050 BEDD	-	Madeleine, Madeleine-Sylvaner
Group 2 1100	Blue Portuguese	Chasselas, Müller-Thurgau, Siegerrebe, Bacchus, <u>Pinot Gris</u>, Muscat Ottonel, Red Veltliner, <u>Pinot Noir</u>, Meunier
Group 3 1150	<u>Pinot Noir</u>, Meunier, Gamay, <u>Dolcetto</u>, Bastardo, Tinta Carvalha, Tinta Amarella	<u>Gewürztraminer</u>, Sylvaner, Scheurebe, Elbling, Morio-Muskat, Kerner, Green Veltliner, <u>Chardonnay</u>, Aligoté, Melon, <u>Sauvignon Blanc</u>, Frontignac, Pedro Ximenes, Verdelho, Sultana
Group 4 1200	<u>Malbec</u>, <u>Durif</u>, <u>Zinfandel</u>, Trollinger, <u>Tempranillo</u>, Tinta Madeira, Pinotage	<u>Sémillon</u>, Muscadelle, <u>Riesling</u>, Welschriesling, Furmint, Leanyka, Harslevelü, Sercial, Malvasia Bianca, <u>Cabernet Franc</u>
Group 5 1250	<u>Merlot</u>, <u>Cabernet Franc</u>, <u>Syrah</u>, Cinsaut, <u>Barbera</u>, <u>Sangiovese</u>, Touriga	<u>Chenin Blanc</u>, Folle Blanche, Crouchen, <u>Roussanne</u>, Marsanne, <u>Viognier</u>, Taminga, <u>Cabernet Sauvignon</u>
Group 6 1300	<u>Cabernet Sauvignon</u>, Ruby Cabernet, Mondeuse, <u>Tannat</u>, Kadarka, Corvina, <u>Nebbiolo</u>, Ramisco, Alvarelhao, Mourisco Tinto, Valdiguié	Colombard, Palomino, Dona Branca, Rabigato, <u>Grenache</u>
Group 7 1350	Aramon, <u>Petit Verdot</u>, Mataro, Carignan, <u>Grenache</u>, Freisa, Negrara, Grignolino, Souzao, Graciano, <u>Mourvedre</u>	Muscat Gordo Blanco, Trebbiano, Montils
Group 8 1400	Tarrango, Terret Noir	Clairette, Grenache Blanc, Doradillo, Biancone

on BEDD requirements. Several red varieties appear twice in the table, requiring less heat to produce fruit suitable for rosé production. Table 27 lists major cultivars in groups based on LTI. Again, several varieties are listed in multiple groups. Pinot Noir and Chardonnay listed in Group IA are more suitable for sparking wine production (Jackson and Schuster, 2001).

Table 28 lists means of climatic variables extracted from mapped vineyards planted in 2003 or earlier by cultivar. Table 29 lists the same for all mapped vineyards, which includes four additional cultivars, but discussion will focus on those vineyards eight years old or older. By comparing cultivars in ascending order by each climatic variable and comparing the lists to recommendations of required heat, we can get a sense of how each climatic variable surface performs. It is important to note the very small area which has been mapped and to remember this work represents preliminary validation efforts. Refer to Tables 26 and 27 for relative heat requirement recommendations.

Sorted by OK GDD, Gewürztraminer area registers the least heat accumulation, which is

Table 27: Grape varieties grouped according to ripening ability in different climates and the latitude-temperature index (LTI). Cultivars in Groups IC and II are sometimes grown in cooler regions, but seldom achieve comparable quality. Cultivars included in mapped validation vineyards are underlined. Modified from Jackson and Cherry (1988) and Jackson and Schuster (2001)

Group and LTI		Grapes Grown
Group IA LTI < 190	1. very cool	Siegerrebe, Ortega, Optima, Madelaine x angevine 7672, Reichensteiner, Müller Thurgau, Seyval blanc, Huxelrebe, Bacchus, Perle, Schonburger, Triomphe d'Alsace
	2. cool	Pinot Gris, Pinot Blanc, Pinot Noir, Pinot Meunier, Chasselas, Gewürztraminer, Sylvaner, Chardonnay, Faberrebe, Kerner, Scheurebe, Auxerrois, Aligoté
Group IB LTI 190-270	cool-warm	Riesling, Pinot Noir, Chardonnay; the latter two varieties can produce heavier, fuller bodied wines than those produced in regions classified under Group IA
Group IC LTI 270-380	warm	Cabernet Sauvignon, Cabernet Franc, Merlot, Malbec, Sauvignon Blanc, Sémillon
Group II LTI > 380	warm-hot	Carignane, Grenache, Syrah, Thompson's Seedless (Sultana), Cinsault, Zinfandel

Table 28: Means of climatic variables for mapped vineyards planted for eight years or more. Table sorted alphabetically by cultivar; white varieties in green, red varieties in red. Each climatic variable is divided into five quantiles and color-coded: first quantile (black), second quantile (blue), third quantile (green), fourth quantile (orange), fifth quantile (red).

		GDD (°C)					Ratios		
Cultivar	Area (ha)	OK	PRISM	UK	FFD	LTI	OK:FFD	PRISM:FFD	UK:FFD
Barbera	2.9	1589.5	1411.6	1425.5	167.9	297.3	9.44	8.41	8.47
Cabernet Franc	7.1	1537.7	1481.9	1522.9	173.6	307.5	8.85	8.53	8.78
Cabernet Sauvignon	147.5	1578.4	1480.9	1492.2	171.9	305.6	9.17	8.61	8.69
Chardonnay	82.5	1397.0	1411.1	1418.8	170.8	293.6	8.20	8.27	8.33
Counoise	0.4	1500.0	1481.0	1515.0	173.0	311.6	8.72	8.56	8.81
Dolcetto	2.1	1594.1	1413.0	1426.6	168.0	297.0	9.45	8.41	8.46
Durif	2.1	1593.0	1409.2	1425.2	167.8	297.0	9.47	8.40	8.47
Gewürztraminer	29.1	1333.0	1394.4	1393.9	174.0	288.1	7.67	8.02	8.02
Grenache	5.6	1661.1	1545.8	1543.7	177.3	309.2	9.35	8.71	8.71
Malbec	8.1	1607.6	1449.5	1475.3	169.9	300.6	9.42	8.52	8.65
Merlot	107.6	1597.2	1497.1	1479.0	171.4	304.9	9.31	8.73	8.64
Mourvedre	4.5	1642.5	1541.2	1543.1	177.1	308.7	9.27	8.70	8.72
Nebbiolo	2.2	1546.1	1470.1	1521.4	171.5	307.6	8.99	8.56	8.86
Petit Verdot	7.5	1539.8	1424.0	1475.8	167.0	300.6	9.18	8.53	8.82
Pinot Gris	17.1	1354.3	1404.6	1407.2	173.2	289.9	7.84	8.12	8.14
Pinot Noir	1.4	1340.3	1405.1	1409.2	176.2	287.3	7.62	7.97	8.01
Riesling	71.2	1419.0	1416.5	1427.2	172.0	293.4	8.25	8.24	8.29
Roussanne	3.9	1494.1	1487.6	1525.5	175.4	303.0	8.60	8.48	8.78
Sangiovese	7.2	1595.0	1496.0	1489.6	172.6	305.7	9.24	8.66	8.63
Sauvignon Blanc	10.6	1421.3	1405.6	1440.2	168.8	298.7	8.43	8.33	8.54
Sémillon	7.8	1501.2	1481.8	1513.0	173.6	312.7	8.64	8.54	8.71
Syrah	56.4	1651.1	1537.4	1504.1	176.0	307.6	9.39	8.73	8.55
Tempranillo	2.1	1518.1	1412.0	1496.6	164.5	299.0	9.23	8.58	9.10
Viognier	8.5	1543.4	1497.6	1487.5	177.0	301.3	8.72	8.46	8.41
Zinfandel	3.6	1738.6	1582.8	1529.5	178.0	307.5	9.77	8.89	8.60

Table 29: Means of climatic variables for all mapped vineyards by cultivar. Table sorted alphabetically by cultivar; white varieties in green, red varieties in red. Each climatic variable is divided into five quantiles and color-coded: first quantile (black), second quantile (blue), third quantile (green), fourth quantile (orange), fifth quantile (red).

		GDD (°C)					Ratios		
Cultivar	Area (ha)	OK	PRISM	UK	FFD	LTI	OK:FFD	PRISM:FFD	UK:FFD
Albarino	0.3	1317.2	1365.3	1392.3	175.0	287.0	7.54	7.80	7.98
Barbera	2.9	1591.2	1409.8	1423.4	167.9	297.0	9.46	8.41	8.47
Cab. Franc	12.6	1514.8	1484.8	1515.4	174.5	308.9	8.70	8.51	8.71
Cab. Sauvignon	247.5	1556.8	1488.1	1509.3	173.1	308.8	9.01	8.59	8.74
Chardonnay	188.1	1389.3	1404.3	1422.9	172.6	293.0	8.05	8.14	8.24
Chenin blanc	2.0	1516.6	1508.0	1532.6	177.0	312.0	8.57	8.52	8.66
Counoise	0.4	1500.0	1481.0	1515.0	173.0	311.6	8.72	8.56	8.81
Dolcetto	2.5	1600.9	1432.8	1436.9	168.9	298.1	9.47	8.48	8.50
Durif	2.1	1593.0	1409.2	1425.2	167.8	297.0	9.47	8.40	8.47
Gewürztraminer	31.1	1337.0	1400.3	1396.5	174.2	289.6	7.69	8.04	8.03
Grenache	5.6	1663.8	1546.7	1543.9	177.3	309.1	9.37	8.71	8.71
Lemberger	6.0	1517.0	1505.1	1534.3	176.5	312.0	8.61	8.53	8.71
Malbec	12.0	1616.3	1470.7	1480.7	171.1	301.6	9.45	8.62	8.65
Merlot	172.6	1579.3	1502.1	1498.8	172.9	307.5	9.15	8.69	8.69
Mourvedre	4.5	1652.9	1546.3	1544.2	177.1	308.6	9.31	8.70	8.71
Nebbiolo	2.8	1547.2	1483.4	1532.7	173.0	309.7	8.96	8.57	8.88
Petit Verdot	11.2	1566.6	1457.7	1485.7	169.0	302.5	9.24	8.62	8.77
Pinot gris	46.7	1371.3	1381.0	1416.2	170.7	292.1	8.04	8.10	8.30
Pinot noir	1.4	1340.3	1405.1	1409.2	176.2	287.3	7.62	7.97	8.01
Riesling	217.1	1357.4	1385.7	1408.8	174.0	289.4	7.81	7.97	8.10
Roussanne	4.0	1493.1	1488.1	1524.7	175.6	303.0	8.58	8.47	8.76
Sangiovese	9.4	1565.7	1493.9	1491.9	173.5	307.0	9.03	8.61	8.60
Sauvignon blanc	15.4	1407.4	1411.3	1439.2	171.2	297.0	8.22	8.25	8.40
Sémillon	10.8	1507.0	1486.5	1520.6	174.6	312.9	8.62	8.51	8.70
Syrah	74.9	1610.8	1529.7	1507.3	176.3	309.1	9.16	8.68	8.57
Tannat	0.8	1548.0	1527.9	1567.0	178.8	317.0	8.65	8.55	8.77
Tempranillo	2.1	1518.1	1412.0	1496.6	164.5	299.0	9.23	8.58	9.10
Viognier	8.6	1542.4	1497.5	1487.4	177.0	301.4	8.71	8.46	8.40
Zinfandel	4.1	1701.5	1571.0	1521.0	177.8	307.7	9.58	8.84	8.57

listed as a warmer cultivar than Pinot Gris (Gladstones, 1992). Petit Verdot ranks in the middle of the pack despite being listed in the warmest group from which represented cultivars are listed. Dolcetto, placed in the same group as Gewürztraminer is the eighth warmest. Recommendations for heat units to ripen Zinfandel are inconsitent. Gladstones (1992) lists it as a cool-warm variety and Jackson and Schuster (2001) list it was a warm-hot variety. Zinfandel area recorded the greatest heat accumulation according to the OK GDD surface. Sorted by PRISM GDD, Gewürztraminer, Petit Verdot and Zinfandel rank similarly as they did with OK GDD. Dolcetto adheres more closely to its cooler recommended rank.

Gewürztraminer again finds itself at the bottom of the list when sorted by UK GDD. Barbera, a recommended warmer cultivar, ranks slightly cooler than Dolcetto, Sauvignon Blanc and Riesling. Petit Verdot again finds itself in the middle of the list and Zinfandel moved down two spots to third warmest, behind Grenache and Mourvedre.

Sorted by LTI, Pinot Noir edges out Gewürztraminer for the coolest spot. Again, Petit Verdot appears out of place near the middle. Mourvedre and Grenache, warm cultivars, are supplanted by Sémillon, which ranks as the warmest cultivar according to LTI. It should be noted that although cultivars from Group IA to Group II are represented in mapped vineyards, the range of LTI fall entirely within a relatively narrow range of at the lower end of Group IC. The classifications were developed with a global wine perspective (Jackson and Cherry, 1988) and appear to be unsuitable for the IPNW.

Rankings for the three ratios of GDD surfaces to FFD create a muddled picture of cultivar rankings compared to the literature. Pinot Noir, Gewürztraminer and Pinot Gris consistently rank as the coolest cultivars according to these three metrics. Mourvedre and Grenache rank near the warmest for the PRISM GDD-to-FFD ratio, but are supplanted from the top spots by cooler cultivars like Dolcetto, Durif and Malbec. Petit Verdot finally finds its way to the third warmest according to the UK GDD-to-FFD ratio.

3.6 Conclusions

Spatial representation of environmental characteristics important for the successful production of grapes provides a holistic, efficient means for initial site evaluation. This type of database development and analysis has not previously been performed in the IPNW and should prove useful in assisting both neophyte and struggling growers with site and cultivar selection and in spatially representative exploration of current and future viticultural areas. Although preliminary validation efforts indicate reasonable reliability in predictions of site suitability, this type of analysis will never replace actual site visits. It can, however, focus prospectors' attention to potentially the most problematic areas on a site.

Sites that are ideal in every facet are rare and successful grape production is an exercise in compromising site characteristics and adapting management practices to suit the setting. Extractions of topographic and edaphic suitabilities from CDL and mapped grape areas show very little area falling into the lowest of five quantiles, which indicates some degree of validity in the site selection model. Although perfect sites are uncommon, poor sites seldom sustain long-lived vineyards.

Soil characteristics and topographically-driven climatic features generally corresponded to grower perceptions. However, a lack of distinction in soil survey data made some perceived problem areas less evident than others. One common discrepancy between grower interviews and soil characteristic rankings was AWC. Areas growers found to have lower than ideal AWC tended to fall into our ideal range suggesting AWC ratings may need to shift to give greater weight to higher AWC.

Also notable is the lack of areas rating zero in composite soil suitability. Although areas exist receiving the lowest consideration for every soil characteristic mapped, they appear to rarely, if ever, coincide. Largely this is due to predominately favorable drainage classes in the study area, but may indicate that more stringent soil characteristic rankings could help additionally differentiate favorable sites.

Modeled climatic data offers spatial insight typically unavailable through examination of weather station data, but an understanding of uncertainty associated with modeling processes is critical. The scale at which climatic data sets are modeled do not reflect microclimatic conditions most directly influencing vine development and performance, but coupled with topographic data, a synthesis of climatic features important to growers is possible.

Despite providing greater temporal resolution, GDD surfaces interpolated from daily mean temperatures appear to be questionable in their accuracy. Climate normals from 1981-2010 should be available in the near future from PRISM and the WRCC providing both normals from more recent observations coinciding with the existence of more vineyards and a greater density of stations meeting the minimum requirement for period of record which will improve interpolation accuracy. Comparison of 1971-2000 and 1981-2010 normals will also reveal how the region's climate is changing. Expanded availability of high-resolution DEMs and soil survey data will also improve representation of site features. Continued validation efforts will further increase understanding of the potential and limitations of grape production in the IPNW.

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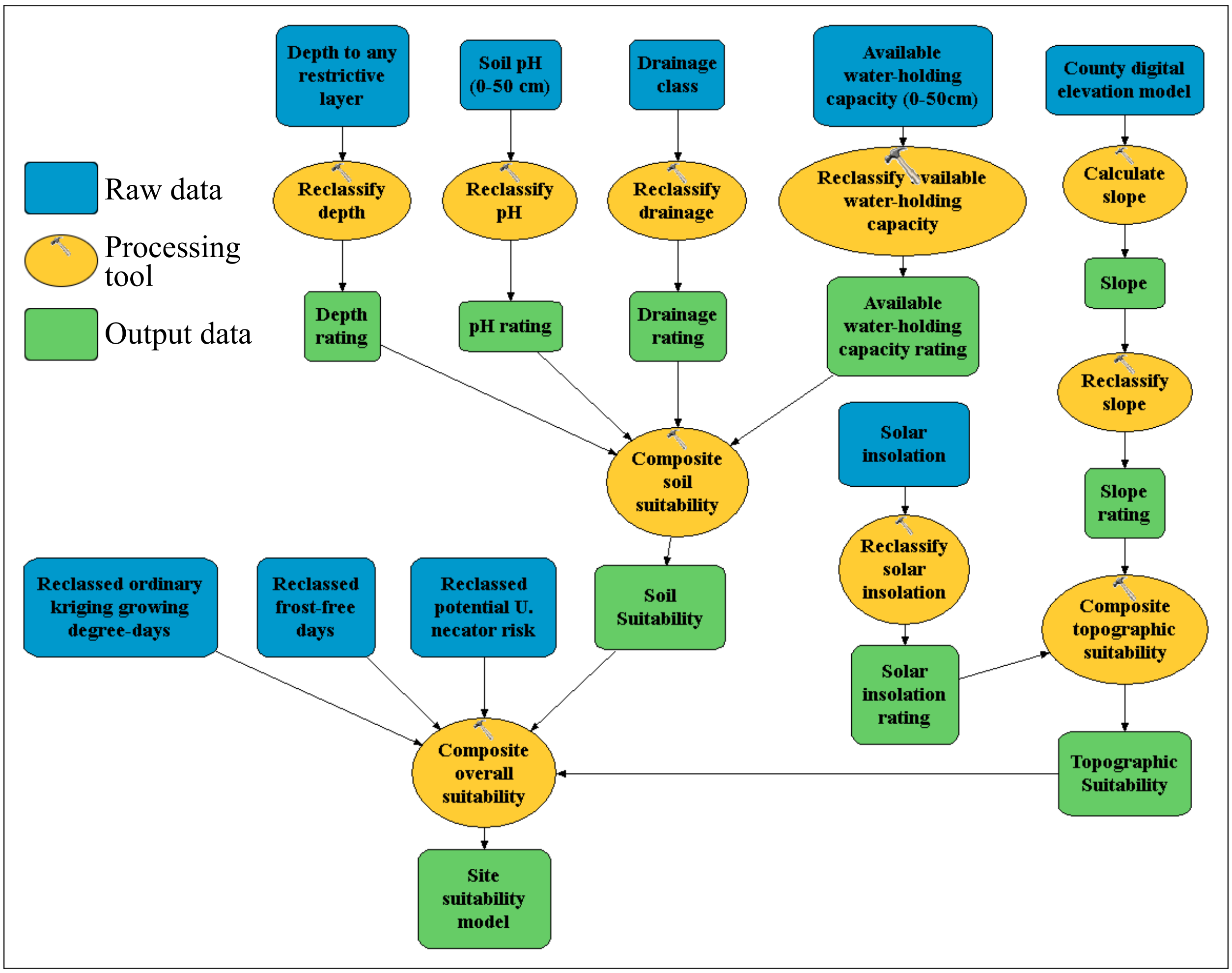
APPENDIX A

COMPOSITE MODEL PROCESSING

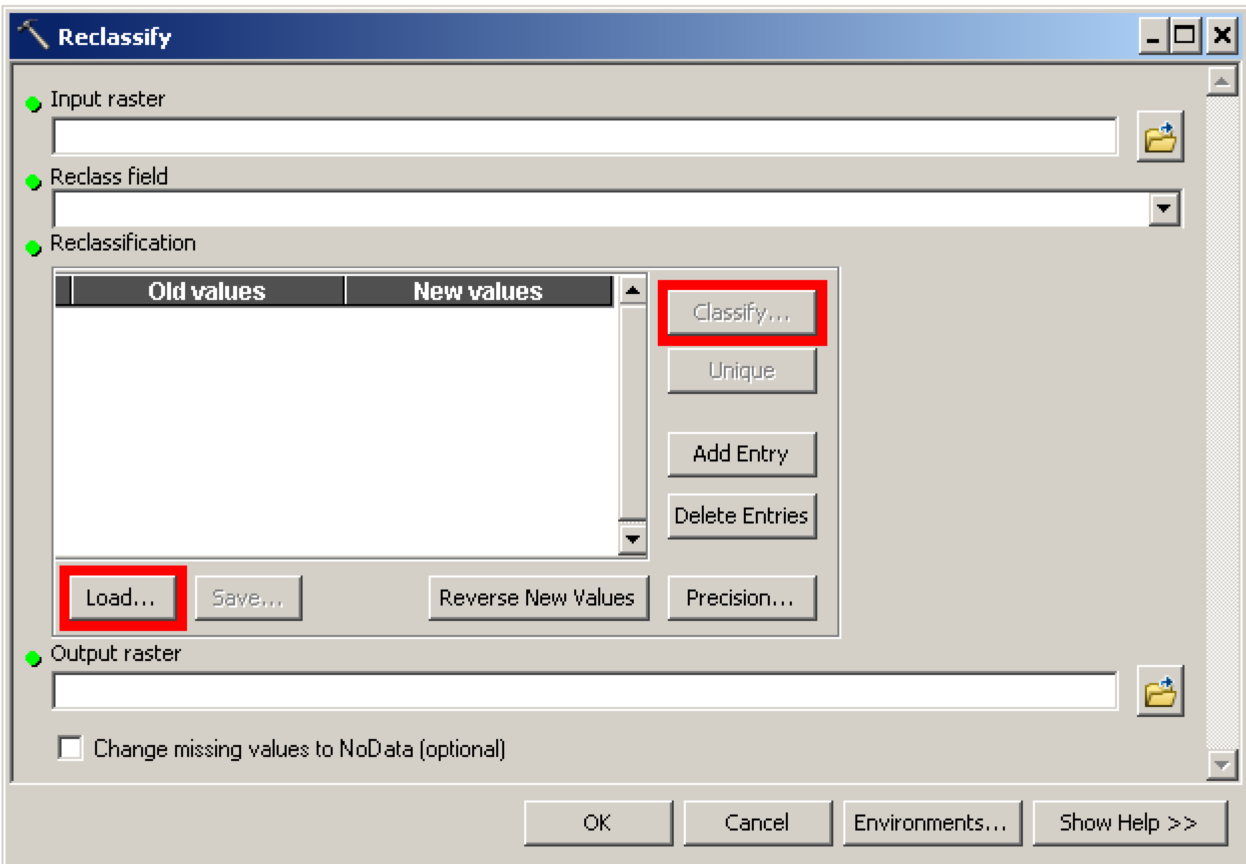
Esri's ModelBuilder™ expedites geographic information system processing through easily edited, compiled work flow. Within this appendix, the term 'model' refers to a product of ModelBuilder.

Site suitability surfaces were processed by county for organizational purposes and to maintain operably sized datasets. One model was created for each county for each suitability surface. An example of one model for *V. vinifera* suitability using growing degree-days interpolated using ordinary kriging is presented below:



Raw or previously reclassed data is processed with several tools, predominately Reclassify (in the Reclass toolset) and Raster Calculator (in the Map Algebra toolset) in the

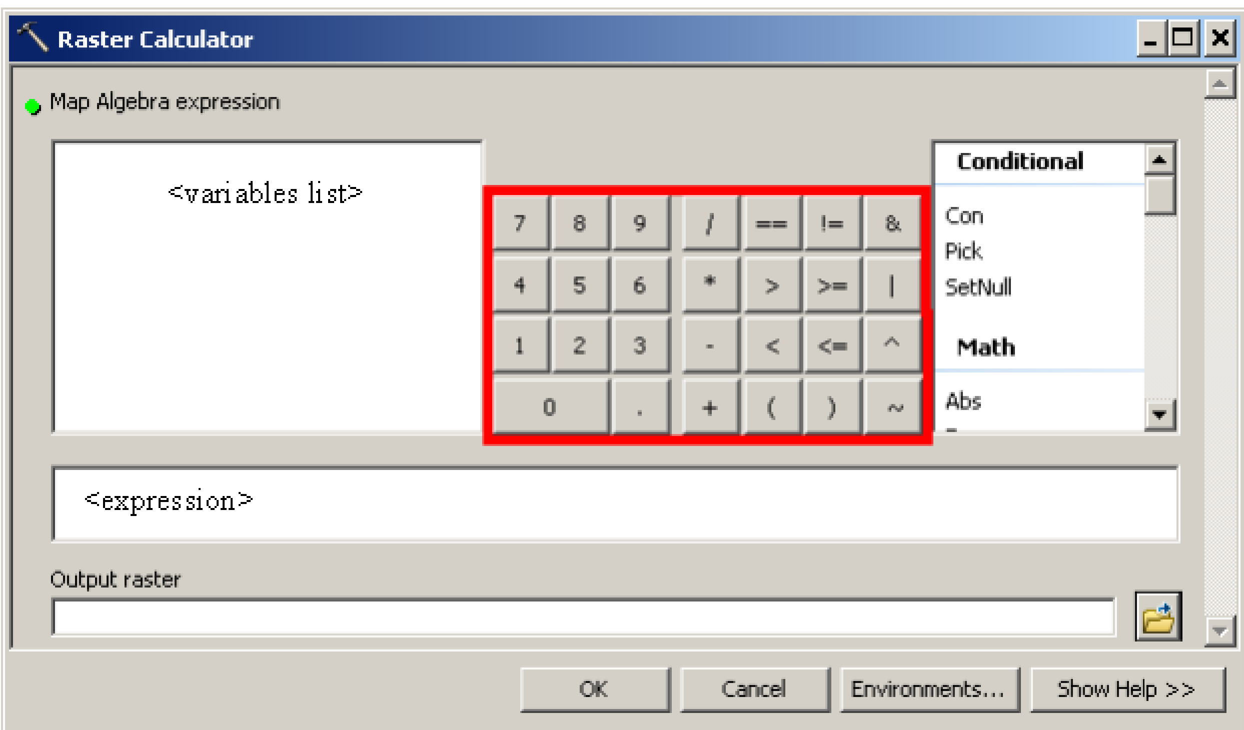
Spatial Analyst toolbox. The resolution of climate data is coarse enough that reclassification is performed over the entire study area once, not requiring the repetitive tediousness of reclassifying by county. Solar insolation calculations are extremely time consuming and calculations based on the digital elevation model are performed separately. The Reclassify tool dialogue is shown below:



An Input raster populates Reclass field. Once the desired field is selected, old values appear in the Reclassification portion of the dialogue. The Classify... button provides tools for dividing up data for reclassification such as different automated classification schemes, summary statistics and a histogram. Often, the same classification will be applied to each county. Save... and Load... classifications for quick reference. Care must be taken to consider minimums and maximums over the entire study area when saving classification schemes as they are rarely both found in one county.

Drainage class reclassification schemes cannot be saved under ArcGIS Desktop 10 Service Pack 2 (Build 3200). This version does not support reclassification of text fields, so reclassification must be based off numeric values. Unfortunately, raster conversions of Soil Survey Geographic thematic maps does not consistently assign numerical values to drainage classes, so each county's drainage class map must be reclassified uniquely. Refer to Tables 2, 3, 5 and 6 for rating and weighting schemes.

The Raster Calculator is used to add datasets together and add weights to create composite suitability surfaces:



Building expressions using the variable list and buttons will help ensure proper formatting. Following are expressions used for composite suitability surfaces. Note that items in the variable list will change when variables are renamed in the model:

V. vinifera topographic suitability

(.7 * "%Slope Reclass%") + (.3 * "%Radiation Reclass%")

V. vinifera soil suitability

(.4 * "%drainage%") + (.1 * "%awc%") + (.2 * "%pH%") + (.2 * "%restrict%")

V. vinifera composite suitability

Int(10 * ("%Topographic Suitability%" + (.3 * "%PPT Reclass%") + "%Soil Suitability%"))

+"%GDD Reclass%" + "%FFD Reclass%"

V. labruscana topographic suitability

(.6 * "%Slope Reclass%") + (.4 * "%Radiation Reclass%")

V. labruscana soil suitability

(.4 * "%drainage%") + (.075 * "%awc%") + (.15 * "%pH%") + (.15 * "%restrict%") + (.15 * "%caco3%")

V. labruscana composite suitability

Int(10 * ("%Topographic Suitability%" + "%Soil Suitability%")) + "%Concord Heat%"

Multiplying topographic and soil suitability and potential *U. necator* risk by ten and truncating to an integer using the function 'INT' creates a composite suitability surface with relative suitability in the tens and ones places while climatic classifications based on heat accumulation and growing season length are indicated in the thousands and/or hundreds places. Creating the surface as an integer allows more summary statistics to be calculated from the surface, for instance median.