Developing a Wine Grape Site Evaluation Decision Support System for the Inland Pacific Northwestern United States

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SUMMARY. Site selection is critical in wine grape (*Vitis vinifera*) production. The wine grape industry is expanding in the inland Pacific northwestern United States (IPNW) using traditional means of site evaluation including on physical examination of topography, geomorphology, soil characteristics, and analysis of long-term observations from weather stations. Through the use of modeled spatial data, we present a geographic information system (GIS) representing environmental features important for evaluating vineyard site suitability for the production of wine grapes. Elevation, slope, insolation, heat accumulation, growing season length, extreme minimum temperature and the soil parameters of drainage, available water-holding capacity (AWC), depth to restrictive layer, and pH combine to represent composite topographic, edaphic, and overall production suitability. Comparing modeled site suitability predictions with existing vineyards, we found modeled data on site properties aligned with vineyard manager perceptions of production quality in established vineyards. Although remote spatial evaluation will never replace physical site examination for addressing specific site conditions, it allows an efficient, spatially extensive, initial assessment of sites that can direct attention to potentially problematic or distinguishing environmental characteristics.

The IPNW has emerged as a premium European wine grape growing region with Washington State as the dominant producer. Washington is second only to California in wine grape production in the United States [U.S. Department of Agriculture (USDA), 2011a]. In 2011, nearly 44,000 acres of wine grapes existed in Washington, a 395% increase over the last 18 years (USDA, 2011b). The region hosts 13 American Viticultural Areas (AVAs) acknowledged by the U.S. Alcohol and Tobacco Trade Bureau on the basis of national or local name

recognition, usage, and distinguishing features (U.S. Alcohol and Tobacco Tax Trade Bureau, 2013). Several larger AVAs contain open land currently not planted to wine grape (Fig. 1).

Climate is the determinant limiting factor in wine grape production. Growing-degree day (GDD) accumulation is one common method of reporting climate and allows comparison between different locations under similar macroclimate. GDD accumulation for wine grapes is calculated as the summation of average temperatures [i.e., (maximum temperature + minimum temperature)/2] less a threshold of 10 °C between 1 Apr. and 31 Oct. In a major U.S. wine region, five grape type categories were developed based on this index of heat accumulation (Amerine and Winkler, 1944).

In temperate climates where heat accumulation is adequate to ripen wine grapes, winter cold damage may be the limiting factor for vineyard survival. Phenology, cultivar, and temperatures preceding potentially damaging low temperatures all influence risk of cold damage (Ferguson et al., 2011). Sites with lower extreme minimum temperatures will generally be at greater risk for cold damage, which can range from loss of fruitful buds to outright death of the entire vine. The typical minimum temperature threshold at peak dormancy for most wine grape cultivars is around –23 °C (Ferguson et al., 2011). Frost-free days (FFDs), the period between the last spring and first autumn frosts (0 °C), is frequently examined in determining the suitability of an area for wine grape production (Jackson and Cherry, 1988; Wolf and Boyer, 2003). FFDs indicate growing season length and serves as a proxy of the period over which wine grapes can develop and ripen.

Topography also plays a role in site suitability. Topographic suitability relates to the physical ability to manage a vineyard (i.e., ability for machinery to safely operate on a site) and influence over mesoclimatic (sub-regional to vineyard scale) conditions. Slope and aspect are both readily quantified topographic characteristics. In the Northern Hemisphere, slopes with a southern aspect have higher levels of insolation, and consequently heat accumulation, and are typically considered ideal; however, wine grapes can be successfully grown on aspects that are often considered “undesirable” (Wolfe, 1999). Because of this, the degree of slope is generally given greater consideration. Moderate slopes (5% to 15%) are considered the best sites for wine grape production as they allow air drainage without hindering equipment operation (Jones et al., 2004). Sloped sites can reduce cold air pooling as they promote air

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
1.6093	mile(s)	km	0.6214
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Fig. 1. American Viticultural Areas (AVAs) of the inland Pacific northwestern U.S. AVA boundaries digitized from official descriptions in the Federal Register and corresponding georeferenced U.S. Geological Survey topographic maps.

drainage to alternate locations. Sites located above potential cold air pools may also benefit from additional elevation through lower daytime temperatures, which can promote fruit quality in hot regions (Gladstones, 1992). Unfortunately, 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 (Jackson and Schuster, 2001).

Wine grapes tolerate a range of soil conditions. Waterlogged soils retard vine growth, hinder mechanical operations in the vineyard, and favor the development of several root diseases and chlorosis in calcareous soils (Davenport and Stevens, 2006). Free-draining soils maintain oxygen concentrations near roots and facilitate moderate water stress with proper irrigation management (Foss et al., 2010). Unrestricted soil drainage to a depth of at least 2 to 3 m is recommended for vineyards in most situations (Gladstones, 1992; Jackson, 2008). Failla et al. (2004) found grapevine (*Vitis* sp.) roots at depths

of over 3 m in soil surveys in northern Italy. Vines may grow roots to depths of 30 m or more if no impenetrable barriers are present (Keller, 2010). Only under severe water stress will wine grapes access substantial water from greater than 2 m. Shallow soils above parent material or other impenetrable barriers where root penetration is problematic are considered unsuitable for grape production and increase the likelihood of waterlogging (Foss et al., 2010; Jackson, 2008). Well-drained soils, along with greater soil depth, encourages the growth of robust, perennial root structures. While the AWC of soils in the IPNW is relatively low to moderate, directed applications of irrigation allow for consistently high-quality grape production.

Soil pH is also important in wine grape production in Washington State, as wine grape is grown on its own roots. Absorption of many nutrients for wine grape is optimal at soil pH of 6.6 to 7.2 (Meinert and Curtin, 2005). Overly alkaline soils lead to deficiencies of phosphorus, iron, manganese, boron, and zinc (Gladstones,

1992). Overly acidic soils can generate toxic levels of aluminum, copper, and manganese; induce phosphorus deficiency; restrict root growth; and lead to grapevine nutrient and soil microbial imbalances (Bargmann, 2003; Foss et al., 2010; Gladstones, 1992).

The expansion of the IPNW wine grape industry has resulted in the inability of viticulture consultants and university Extension to travel to every potential new vineyard location. Efficient remote assessment of a site is necessary to facilitate this expansion and avoid potential pitfalls of a site that need to be addressed before vine establishment. This project was designed to establish a decision support system (DSS) for wine grape production in the IPNW to help facilitate these remote assessments.

The specific objectives of this project were to: 1) establish a DSS for wine grape that includes information on common site characteristics, such as topographic, edaphic, and climatic parameters; and 2) begin preliminary evaluation of the effectiveness of the DSS to elucidate potential problematic components in wine grape

production by mapping existing vineyards and obtaining qualitative perceptions of vineyard performance from experienced viticulturists.

Materials and methods

DEVELOPMENT OF DATA LAYERS.

Spatial data sources are summarized in Table 1. Geographic information system software packages used were ArcGIS (versions 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 United Transverse Mercator Zone 11 North, North American Datum, 1983 using bilinear sampling for continuous data where necessary. Thematic maps were created from Soil Survey Geographic (SSURGO) databases using Soil Data Viewer (version 5.2; Natural Resources Conservation Service, Lincoln, NE).

TOPOGRAPHIC CHARACTERISTICS.

Slope and insolation were calculated using the National Elevation Dataset digital elevation model (DEM), 1/3 arc second resolution (≈ 10 m). Slope calculations were made in units of percent rise. Insolation calculations were performed using the mean latitude of each DEM to 10^{-12} decimal degrees, a sky size of 40,000 cells, 14-d and 2-h intervals.

Calculation guidelines recommend the extent of input DEMs be less than 1° latitude, but calculations of adjacent surfaces with combined extents of much less than 1° latitude showed notable differences in continuity. Most DEMs masked by county were too large for a single calculation of insolation. Digital elevation models

were divided vertically whenever possible to maintain relatively constant mean latitude for each county ($\pm 0.0001^\circ$). Vertical divisions were made with overlap to account for effects of adjacent topography and improved continuity.

Calculations were made from ordinal day 91 to 304 (1 Apr. to 31 Oct.). Thirty-two azimuth directions were used to calculate the viewshed. Eight zenith and azimuth divisions were used to calculate the sky map. A uniform sky diffuse radiation model was used with a diffuse proportion of 0.3 and transmissivity of 0.5, presumptive of generally clear sky conditions (Fu and Rich, 2002). Insolation surfaces do not represent actual solar accumulation over a climatically relevant period of record and are intended to represent sites' topographic exposure. Output surface units are Watt-hours per square meter.

Site exposure is traditionally characterized by aspect, typically divided symmetrically, establishing a hierarchy of desirable slope orientations (Jones et al., 2004; Smith, 2002; Wolf and Boyer, 2003). Simple aspect calculations do not account for dynamic shading from adjacent topography throughout a day and growing season, or solar angles at different latitudes. In a topographically dissected landscape, as is found in much of the wine grape growing regions of the IPNW, insolation calculations assess the effects of nearby landforms and provide a more continuous surface of site exposure (Beaudette and O'Geen, 2009; Jones and Duff, 2007; Jones et al., 2006).

SOIL CHARACTERISTICS. Thematic maps of soil characteristics were created for drainage class, depth to any restrictive layer, AWC (0 to 50 cm), and pH (0 to 50 cm). Dominant component or condition was used as the aggregation method. Counties represented with multiple SSURGO databases were merged and clipped to county boundaries. Vector data were converted to raster data with a resolution of 10 m to adequately represent soil map unit boundaries and match DEM resolution.

CLIMATIC CHARACTERISTICS. A surface of GDD accumulation was calculated using Parameter-Elevation Regressions on Independent Slope Model (PRISM) monthly normal summations from 1971 to 2000. PRISM produces official climate data sets for the USDA using 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). Monthly GDD information was calculated by taking the average of the monthly maximum and minimum temperature normals, subtracting a base temperature of 10°C , and multiplying by the number of days in the month. Heat accumulation was summed by this method for 1 Apr. through 31 Oct. (Amerine and Winkler, 1944).

Surfaces of PRISM mean extreme minimum temperatures (MEMTs) from 1961 to 2000 were examined to rate cold damage risk. A surface of median FFDs from 1971 to 2000 was calculated by subtracting PRISM

Table 1. Summary of spatial data sources used in the development of a decision support system for wine grape site evaluation.

Data set ^a	Source ^a	Data type	Resolution/scale ^a
National Elevation Dataset	USGS	Raster	1/3 arc second (≈ 10 m)
Soil Survey Geographic database	USDA-NRCS	Vector	1:12,000 to 1:63,360
Parameter-Elevation Regressions on Independent Slopes Model (PRISM)	PRISM Climate Group, OR State University	Raster	15 arc seconds (≈ 400 m) ^x , 30 arc seconds (≈ 800 m) ^w , 1.25 arc minutes (≈ 2 km) ^v
Esri world imagery	Esri, i-cubed, USDA-FSA, USGS, AEX, GeoEye, AeroGRID, Getmapping ^z	Raster	≤ 1 m, $\geq 1:1$, 128 ^u

^aUSGS (U.S. Geological Survey), USDA-NRCS (USDA-Natural Resources Conservation Service), PRISM (OR State University, Corvallis), Esri (Redlands, CA), i-cubed (Fort Collins, CO), USDA-FSA (U.S. Department of Agriculture-Farm Service Agency), AEX (Aerials Express, Seattle, WA), GeoEye (Appollo Mapping, Boulder, CO), AeroGRID (Hartley Wintney, United Kingdom), Getmapping (Hartley Wintney, United Kingdom).

^u1 m = 3.2808 ft, 1 km = 0.6214 miles.

^wMedian last spring and first fall frosts.

^xMonthly mean maximum and minimum temperatures.

^vMean annual extreme minimum temperatures.

^zAerial imagery resolution and source is dependent upon the scale at which it is viewed.

surfaces of median last spring frost date from median first fall frost date. Monthly maximum and minimum temperature normals are available for free. Median frost date and MEMT surfaces were purchased from The Climate Source, Inc. (Corvallis, OR).

RANKING SITE CHARACTERISTICS FOR DATA LAYERS. The data layers discussed above were ranked into ranges indicating preference, designed to be used for quick evaluation of a given site. The site evaluation DSS also maintained data layers of raw information to allow the user to precisely determine why a particular component ranked high or low in a given category. This contrasts with more common Boolean approaches to site evaluation, which set ranges for parameters resulting in binary suitability surfaces indicating merely “suitability” or “unsuitability” (Foss et al., 2010; Jurisic et al., 2010).

Determining which spatial data sets to use in building a site evaluation GIS database is finding the intersection between what data are available and which parameters are most often perceived to be associated with site suitability (Ellis et al., 2000; Zucca et al., 2008). Understanding viticulture systems and prioritizing the influence of spatially represented parameters is the first step in designing intelligent, GIS-integrated analysis tools (June 2000). Component ratings are summarized in Table 2.

Slope rankings are the same as work done by Jones et al. (2006). Foss et al. (2010) allowed for much steeper slopes, up to 45° or 100%, in their Boolean analysis presuming nonmechanized operation for much of this range, but larger production in the IPNW is based on mechanization,

or the ability to mechanize as many vineyard operations as possible, favoring the Jones method. Insolation ratings were developed by using the midlatitude counties in the study area. Using ArcGIS, five quantile divisions were calculated and the mean value for each quantile was then ranked from 1 to 5.

Soil drainage classes were ranked similarly to Jones and Duff (2007), Jones et al. (2004, 2006), Kurtural et al. (2007), and Vineyard Site Suitability Analysis (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 received the lowest ranks (USDA, 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 are similar to those of Jones et al. (2004) and weighted more toward higher AWC than proposed values in Wolf and Boyer (2003). Jones et al. (2004) performed site suitability analysis in the Umpqua Valley, OR, where irrigation is not obligatory and therefore a minimum threshold of 0.10 cm·cm⁻¹ is proposed. We did not adhere to this threshold because of the necessity of irrigation in the IPNW. Depth to restrictive layer and soil pH follow rankings similar to those of Wolf and Boyer (2003) who give ideal ranges, but not specific numeric rankings. Similar minimum depths are recommended by Vineyard Site Suitability Analysis (2011).

Assessing a site evaluation model for wine grape is not as straightforward as for other agricultural crops. For most other commodities, the

primary production goal is typically maximizing yield while maintaining quality above a minimum threshold that is quantifiable with some objective metric. With “premium” wine grape, other factors beyond yield are the primary components of perceived quality. Perceptions of quality may be strongly influenced by marketing, and the relationship growers establish and foster with wineries (Spayd, 1999).

VINEYARD SITES FOR DSS EVALUATION. The ability of the DSS to indicate potential issues for wine grape production was examined in 13 Washington vineyards, representing the Yakima Valley, Horse Heaven Hills, Red Mountain, Wahluke Slope, Walla Walla Valley, and Ancient Lakes AVAs. These existing vineyards were mapped by wine grape cultivar with a combination of GPS, aerial imagery, and georeferenced maps provided by growers. Sites were selected based on perceived wine grape quality, age of the vineyards, or frequency of damaging weather events. Growers were interviewed between Sept. 2010 and Sept. 2012 regarding perceptions of vineyard performance, specifically issues relating to mapped environmental variables, and planting dates. Ground truthing focused largely on qualitative assessment and viticulturists’ responses during interviews. This method of model evaluation was specifically chosen over a more empirical approach because of the inherent nature of vineyard variability that is introduced when considering management and reactionary production approaches of different vineyard managers. In total, ≈570 ha were mapped. A summary of the vineyards used in ground truthing are in Table 3.

Table 2. Rating system for wine grape site suitability used in the decision support system. Here, a “0” indicates low suitability and a “4” indicates high suitability for the production of wine grapes.

Site characteristic ^z	Rating					NoData ^y
	0	1	2	3	4	
Slope (%)	<1, 26–30	1–5, 16–25	6–15	—	—	>30
Insolation (kW·h/m ²)	<969	970–1027	1028–1065	1066–1104	>1104	—
Drainage ^x	ED, SPD, PD, VPD	SED	WD MWD	—	—	—
AWC (cm·cm ⁻¹)	<0.075, >0.25	0.21–0.25	—	0.16–0.20	0.075–0.15	—
Depth (cm)	0–50	51–100	>100	—	—	—
pH	<6.0, >8.0	6.1–6.5, 7.6–8.0	6.6–7.5	—	—	—

^z1 kW·h/m² = 0.0929 kW·h/ft², 1 cm = 0.3937 inch.

^yA rating of “NoData” removes an area from consideration.

^xED = excessively drained, SPD = somewhat poorly drained, PD = poorly drained, VPD = very poorly drained, SED = somewhat excessively drained, WD = well drained, MWD = moderately well drained, AWC = available water-holding.

Table 3. Summary of vineyards and their locations used to ground truth a wine grape site evaluation decision support system for the inland Pacific northwestern United States. Additional outstanding or notable features are also included.

	Area (ha) ^z	Predominate cultivar(s)	Planting date(s)	Outstanding features
Yakima Valley AVA ^y				
Vineyard 1	21.7	Cabernet Sauvignon, Merlot	1991	Atypical placement of wind machines
Vineyard 2	58.5	Chardonnay, Pinot Gris, Riesling	1986, 2006, 2008	Shift toward white cultivars, high soil pH
Horse Heaven Hills AVA				
Vineyard 3	46.5	Cabernet Sauvignon, Merlot	2006, 2007	Cold damage
Red Mountain AVA				
Vineyard 4	54.5	Cabernet Sauvignon, Syrah	1975–1998	Price premium, changes in cultivars, cultivar diversity
Vineyard 5	49.6	Cabernet Sauvignon, Merlot	1984–2010	Price premium
Wahluke Slope AVA				
Vineyard 6	26.7	Riesling, Cabernet Sauvignon	1999	Cold damage
Vineyard 7	37.4	Cabernet Sauvignon	2003	Soil depth, insolation
Vineyard 8	49.2	Cabernet Sauvignon, Merlot, Syrah	2000	Available water-holding capacity, insolation
Vineyard 9	33.2	Cabernet Sauvignon	1999	Heat accumulation, bulk production
Walla Walla Valley AVA				
Vineyard 10	0.4	Cabernet Sauvignon	2000	Cold damage, warmer
Vineyard 11	3.5	Cabernet Sauvignon	1999	Cold damage
Ancient Lakes AVA				
Vineyard 12	3.9	Roussanne	1991–2003	Heat accumulation, cultivar selection
Vineyard 13	182.1	Riesling, Chardonnay, Gewürztraminer	1999–2002, 2005, 2010	Soil depth, cultivar diversity

^z1 ha = 2.4711 acres.^yAVA = American Viticultural Area.

Results and Discussion

Topographic characteristics

Although slope and insolation were the two derived surfaces primarily used in rating sites, aspect was also maintained in the GIS so users can determine if low insolation at a site is due to slope orientation or hillshade effects. Insolation surfaces revealed greater insolation at lower latitudes despite longer daylength at higher latitudes because of solar angle (Fig. 2).

Elevation is also an important consideration in vineyard site suitability. Ideal elevation ranges should be low enough to ensure adequate heat accumulation for consistent fruit ripening while avoiding frost pockets that result from katabatic cold air flow (Foss et al., 2010; Jones et al., 2004; Kurtural et al., 2007; Wolf and Boyer, 2003). These ranges are region specific and depend on mesoclimate and local topographic variability. Over a large, topographically diverse area like the IPNW, elevation range ratings would vary based on subregion. Sites have not been rated based on

elevation, but elevation is always examined when this DSS is used by practitioners for site assessment.

Soil characteristics

Soil map units in the SSURGO database are discrete units and the soil characteristics we examined often showed abrupt differences in adjacent map units. Although this is certainly possible, it is more common to see more gradual shifts in soil characteristics not easily represented in the original vector data. We converted the vector data to raster data to facilitate reclassification to component ratings, but these data sets should not be misinterpreted as continuous data sets.

Climatic characteristics

Assessing the capability of a site to ripen wine grape and its risk of cold damage is best done at the mesoclimatic scale, ideally with multiple weather stations within a single vineyard. Topographic features can have substantial influences on a site's mesoclimatic characteristics (e.g.,

insolation, heat accumulation, cold air pooling, or air drainage). The varied spatial resolutions of the three climatic data sets all provide information at meso- to macroclimatic scales. Therefore, it is important to examine climate data at sites through the context of topographic features with an understanding of weather dynamics for a more realistic prediction of site conditions.

Vineyard sites for DSS evaluation

GDD and FFD surface extractions for mapped cultivars are summarized in Table 4. Cultivars with more than 10 ha mapped were summarized individually; all else were aggregated into “other reds” and “other whites.”

The most widely planted of the 24 mapped wine grape cultivars, Cabernet Sauvignon was ranked second for greatest mean GDD (1505 °C), and third for greatest mean FFD (175 d). ‘Riesling’, the second-most planted cultivar, recorded the fifth greatest mean GDD (1408 °C) and was tied with three other cultivars at

Fig. 2. Solar insolation summation from 1 Apr. to 31 Oct. for the inland Pacific northwestern U.S. calculated from 10-m (32.8 ft) National Elevation Dataset digital elevation model. Solar insolation is higher at lower latitudes despite longer daylength at higher latitudes because of solar angle; $1 \text{ kW-h/m}^2 = 0.0929 \text{ kW-h/ft}^2$.

Fig. 3. Comparisons between raw data and site characteristic ratings for ground truthing Vineyard 1 as viewed in ArcGIS (Esri, Redlands, CA). Note that the rating scale is from 0 (low) to 4 (high) for degree of suitability for wine grape production: Cha = 'Chardonnay', CS = 'Cabernet Sauvignon', Mer = 'Merlot'; $1 \text{ kW-h/m}^2 = 0.0929 \text{ kW-h/ft}^2$, $1 \text{ cm} = 0.3937 \text{ inch}$.

Table 4. Summary of growing-degree day (GDD) and median frost-free day (FFD) for the period of 1971 to 2000 by wine grape cultivars in vineyards used for ground truthing a wine grape site evaluation decision support system.

Wine grape cultivar	Area (ha) ^z	GDD (°C) ^y		FFD (d)	
		Mean	Range (±)	Mean	Range (±)
Cabernet Sauvignon	142.4	1505	383	175	67
Merlot	65.1	1500	387	173	35
Syrah	44.7	1532	258	177	20
Other reds ^y	47.3	1491	258	174	19
Riesling	106.5	1408	203	174	20
Chardonnay	74.8	1397	204	171	29
Gewürztraminer	29.1	1394	69	174	16
Pinot Gris	28.6	1391	63	169	16
Sauvignon Blanc	14.4	1402	154	171	16
Other whites ^x	14.6	1483	286	176	24

^z1 ha = 2.4711 acres, $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

^yWine grape cultivars classified as “other red” in descending order by area mapped: Malbec, Cabernet Franc, Grenache, Mourvèdre, Sangiovese, Petit Verdot, Roussanne, Barbera, Dolcetto, Durif, Zinfandel, Nebbiolo, Pinot Noir, and Cunoise.

^xWine grape cultivars classified as “other whites” in descending order by area mapped: Sémillon and Viognier.

fourth for greatest mean FFD (174 d). ‘Chardonnay’, the third-most planted cultivar, recorded the sixth greatest GDD (1397 °C) and was tied with Sauvignon Blanc as the eighth greatest mean FFD (171 d). ‘Merlot’, the fourth-most represented cultivar, ranked third greatest mean GDD (1500 °C) and seventh in greatest mean FFD (173 d). All rankings were based on main cultivars and did not include the red and white “other” categories.

Many of the wine grape cultivars mapped in this study comprise a small area. Several cultivars only represented small blocks within single vineyards. Sixteen of the mapped cultivars covered less than 10 ha. This is the beginning of an effort to further understand ranges of climatic requirements of the large number of wine grape cultivars capable of producing premium wines in the IPNW. As more vineyards are mapped by cultivar with an understanding of crop quality and past cultivar changes, recommendations of climatic requirements may be more specifically developed for the IPNW and its subregions.

Ground truthing vineyards are discussed below with regard to features noted by viticulturists and how they compare with mapped characteristics.

Yakima Valley AVA

VINEYARD 1. An example of large-scale maps of Vineyard 1 is presented in Fig. 3. Reclassified, rated surfaces in the GIS database provide a quick assessment of a site and raw data explain the ratings. This vineyard was unusual in that the placement of

its wind machines was at the highest elevation in the vineyard. Past vineyard managers observed the greatest cold damage at the top of this vineyard. Typically, wind machines are placed at the lower elevations where cold air is anticipated to accumulate to help break and mix atmospheric inversions, preventing damaging frosts and freezes (Evans and Alshami, 2009). However, this unusual placement was due to a valley to the north of Vineyard 1 that fills with cold air, which frequently spills over to the top of the vineyard.

Mean extreme minimum temperatures were slightly lower (0.2 °C) in the northern end of Vineyard 1 where the wind machines are placed compared with the southern end. FFD data also indicated a slightly shorter growing season at the northern end of Vineyard 1, 149 d compared with 151 d at the southern end of the vineyard. This is an unusual circumstance, but these relatively small differences over a relatively short distance in data sets of these spatial resolutions are not inconsequential.

Vineyard 1 had the fewest GDD (mean of 1258 °C) and the fewest FFD (mean of 150 d) of all ground truthing vineyards, indicating the broad climatic range capable of supporting certain wine grape cultivars. This site has grown ‘Merlot’ and ‘Cabernet Sauvignon’ for 20 years and is cooler than ground truthing vineyards producing ‘Gewürztraminer’ and ‘Pinot Gris’.

Data from the soil survey maps confirmed the viticulturist’s perceptions of good soil drainage and relatively shallow soils compared with

Vineyards 2 and 3. The vineyard soils are classed as well drained. Soil Survey Geographic data also corroborated the viticulturist’s observations of relative soil depth with a mean depth to restrictive layer of 94.4 cm compared with 140.3 cm in Vineyard 2 and at least 201 cm in Vineyard 3.

VINEYARD 2. A piece southeast of Vineyard 2 went unplanted after soil tests revealed high salinity and pH. Again, SSURGO data aligned with the viticulturist’s observations; the unplanted southeastern portion of the vineyard was mapped with a pH of 8.6. The ‘Riesling’ in Vineyard 2 was designated for late harvest requiring at least 24% soluble solids. Compared with Vineyard 1, Vineyard 2 recorded 10 more FFD (mean of 160 d) and 102 °C more GDD (mean of 1360 °C). These factors may contribute to the ‘Riesling’s’ designation for late harvest. Although MEMT were nearly the same as those found in Vineyard 1 (mean of -17.4 °C), cold damage was not noted as a feature in Vineyard 2.

Horse Heaven Hills AVA

VINEYARD 3. The viticulturist noted deep, uniform, sandy loam soils throughout the vineyard, greater AWC than Vineyard 1 and 100% primary bud loss following a Nov. 2010 freeze that dropped temperatures as low as -23 °C (AgWeatherNet, 2013). Mean AWC was nearly the same between Vineyard 3 and Vineyard 1, slightly higher in the former, but total available water increases with greater depth. Typical of the Horse Heaven Hills AVA, Vineyard 3 experienced a relatively long growing

season with a mean of 172 FFD. Compared with Vineyard 1, mean MEMT is 1.4 °C warmer in Vineyard 3 (mean of -16.1 °C). However, the vineyard's gentle slopes (mean of 1.8%) could exacerbate cold damage during extreme years by allowing cold air to linger. Although equipped with wind machines, frost protection beyond a certain threshold can be extremely costly or impossible. Heat accumulation was greater in Vineyard 3 than Vineyards 1 and 2 (mean of 1485 °C).

Red Mountain AVA

VINEYARD 4. The viticulturist noted outstanding performance from 'Roussanne' and 'Mourvèdre' and poor vigor and ripening in one 'Cabernet Sauvignon' block, which was under consideration for removal, potentially because of excessive soil drainage. Once again, SSURGO data corroborates viticulturist perceptions rating over half of the vineyard as having excessively drained soils, including the problematic 'Cabernet Sauvignon' block and slightly high pH (mean of 7.6). An area along the southwestern edge of the vineyard often experiences cold air drainage problems. A flat area extending to the west before declining briefly and flattening out again may not allow proper air drainage or there may be a feature too small for the 10 m DEM to capture. Slopes were also relatively shallow (mean of 2.8%), which may contribute to cold air pooling and the sixth least insolation of ground truthing vineyards (mean of 1015 kW-h/m²). Mean extreme minimum temperatures were comparable to those found in Vineyard 3 (mean of -16.5 °C).

Several blocks in Vineyard 4 have been converted to different wine grape cultivars over the vineyard's history. 'Chenin Blanc' was replaced with 'Merlot' and 'Grenache' because of low price, 'Chardonnay' and 'Gewürztraminer' performed well, but also were removed due to low price, and 'Riesling' was replanted with 'Syrah'. This again illustrates the malleability of cultivars to adapt to climatic conditions at a given site with the appropriate management.

VINEYARD 5. The viticulturist pointed out high vigor in southern blocks, an area that suffers from cold damage in a southeastern portion

of the vineyard and a segment of 'Cabernet Sauvignon' suffering from low vigor and poor fruit set (shatter), perceived to be related to excessive drainage and/or low AWC. Although the vineyard is found on the western edge of the Red Mountain AVA, which descends steeply to the west, much of the central, eastern, and northern portions of the vineyard are flat (mean slope of 3.3% and 1002 kW-h/m² of insolation). This may contribute to cold air pooling, which could result in cold damage during vine dormancy.

Soil Survey Geographic data did not reveal perceived vigor and shatter issues. AWC over the vast majority of the vineyard was 0.19 cm·cm⁻¹, 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⁻¹, which actually falls into the most highly rated range, but it is ≈300 m southeast of the area with shatter problems. One characteristic of this site not captured in modeled data are persistent wind, which may lead to higher evapotranspiration in vines, exacerbating water stress related to excessive soil drainage. Vineyard 5 had a mean GDD of 1520 °C, 177 mean FFD, and mean MEMT of -16.7 °C.

Wahluke Slope AVA

VINEYARD 6. The viticulturist stated this vineyard was under consideration for removal because of persistent cold damage during vine dormancy. During the 23–25 Nov. 2010 freeze, 'Merlot', 'Cabernet Sauvignon', and 'Syrah' suffered 100% primary bud loss, whereas 'Riesling' was not severely damaged. Most telling in the spatial data were the exceptionally flat terrain, a mean slope of 0.5% and a maximum of only 1.7%, with shallow slopes surrounding the vineyard, preventing sufficient cold air drainage. Mean extreme minimum temperatures were comparable to Vineyards 1 and 2 (mean of -17.3 °C), but the growing season in Vineyard 6 was an average of 23 d longer (mean of 173 FFD), which may influence vine dormancy and ability to withstand low temperatures. Vineyard 6 recorded a mean GDD of 1534 °C.

VINEYARD 7. The vineyard sits atop shallow, ancient soils, which lies

above the depositional area of the Missoula Floods. The viticulturist noted that it is much warmer than Vineyard 6. Soil Survey Geographic data showed a mean depth of 68 cm in the vineyard, far less than the 174 cm mean in the Wahluke Slope AVA. Heat accumulation data actually shows Vineyard 7 was cooler than Vineyard 6, a difference of 115 °C. However, Vineyard 7 did have predominately south-southwest facing slopes, whereas Vineyard 6 was both flat and variable in aspect. Modeled climatic data offers insight of spatial extents 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.

Gentle slopes (mean of 3.6%) combined with latitude result in moderate insolation values (mean of 1039 kW-h/m²). Again, cold damage was not noted in Vineyard 7 despite an MEMT 0.3 °C lower than in Vineyard 6 (mean of -17.6 °C). A slightly shorter growing season (mean of 168 d) may once again contribute to the site's ability to withstand colder temperatures. Soil pH was high, 8.1 to 8.7 according to SSURGO data. About half the vineyard was classed as somewhat excessively drained.

VINEYARD 8. The viticulturist noted the site's low AWC in sandy soils, great depth to restrictive layer, and high heat accumulation. According to SSURGO data, the vineyard's soils were mostly excessively drained with small portions classed as somewhat excessively drained. Soils were also somewhat alkaline (pH 7.4 to 7.9) and AWC was relatively low (0.09 cm·cm⁻¹), but this actually falls into the ideal range according to our ratings. Soils were deep with a mean exceeding 200 cm. Vineyard 8 recorded the second highest GDD (mean of 1603 °C). The site was dominated by west- and southwest-facing slopes, which may additionally increase heat accumulation. Slopes were rated favorably for much of the vineyard, but the western and eastern

blocks lay on relatively gentle slopes (mean of 5.3%). Vineyard 8 had more FFD (mean of 181 d) and warmer MEMT (mean of -16.9°C) than other vineyards in the Wahluke Slope AVA.

VINEYARD 9. The viticulturist stated this vineyard primarily goes toward bulk production and noted high heat accumulation on the site. Vineyard 9 had the highest GDD (mean of 1605°C) of all ground truthing vineyards. Western-facing slopes may contribute to heat accumulation through collection of radiation in the afternoon, but the site was rated relatively low in insolation (mean of 1003 kW-h/m^2) because of gentle slopes and latitude. Declining in elevation from east to west, Vineyard 9 was rated as having favorable slopes in the center of the vineyard, but the eastern and western ends lie on relatively gentle slopes (mean of 4.3%). Soils were mostly excessively drained and somewhat alkaline (pH 7.4 to 7.6). Growing season length (mean of 182 FFD) and MEMT (mean of -16.5°C) were comparable to those in Vineyard 8.

Walla Walla Valley AVA

VINEYARD 10. The viticulturist noted cold damage during vine dormancy has been very problematic with the majority of vines suffering severe cold damage in three seasons. ‘Merlot’ and ‘Viognier’ have been removed from the vineyard because of persistent frost issues. The wind machine was noted as marginally effective. It was also noted soils were well drained. Soil drainage corresponds again with SSURGO data. Although much of the site is situated on slopes rated as ideal, an air drainage alley adjacent to the vineyard and the flat topography on the other side of the air drainage alley appear to cause frequent cold air pools at this vineyard. Steep slopes in the southwest portion decrease overall suitability in this small vineyard. North-facing slopes result in low insolation (mean of 1025 kW-h/m^2). Soil Survey Geographic data indicated relatively high AWC (0.19 to $0.20\text{ cm}\cdot\text{cm}^{-1}$), neutral soil pH, good drainage, and depths exceeding 200 cm. Vineyard 10 recorded the second-most FFD of the ground truthing vineyards (mean of 213 d) and was tied for the third lowest MEMT (mean of -18.1°C). The site recorded 1557°C GDD.

VINEYARD 11. The only noted feature of this vineyard is cold damage during vine dormancy. Vineyard 11 is a flat vineyard; the vast majority is $<2\%$ slope. This site recorded the most FFD with a mean of 217 d and is tied with Vineyard 10 as having the third lowest MEMT (mean of -18.1°C). The relatively long growing season and low MEMT in Vineyards 10 and 11 may contribute to persistent cold damage problems by not allowing adequate time for vines to harden (Keller, 2010). Predominately north-facing slopes result in moderate insolation ratings (mean of 1029 kW-h/m^2). According to SSURGO data, soils were well drained, moderately alkaline (pH 7.7), had AWC at the upper end of what is rated ideal and depth exceeding 200 cm. Vineyard 11 recorded 1603°C GDD.

Ancient Lakes of the Columbia Valley AVA

VINEYARD 12. Water demand in these vines is a persistent challenge. The viticulturist claimed the site is warmer than its immediate vicinity. ‘Roussanne’, ‘Syrah’, and ‘Cabernet Franc’ were noted as the best performers and the easiest to grow, whereas the ‘Merlot’ had proved more challenging. Soil Survey Geographic data classed most of the vineyard as somewhat excessively drained, and mean AWC over the vineyard is $0.11\text{ cm}\cdot\text{cm}^{-1}$, which again falls in our ideal range. Mean GDD in the vineyard was 1497°C and this decreases $\approx 150^{\circ}\text{C}$ within 1500 m to the northwest and southeast.

‘Cabernet Franc’ and ‘Syrah’ blocks received relatively high component ratings because of favorable slopes (mean of 13.8%) and insolation (mean of 1033 kW-h/m^2). The ‘Merlot’ blocks were rated lower because of slopes exceeding 15%. The ‘Roussanne’ blocks were rated slightly lower than the ‘Syrah’. A large block of ‘Roussanne’ was planted on alkaline (pH 7.6 to 7.8), shallow soil (mean of 36 cm) according to SSURGO data. Vineyard 12 tied for the lowest MEMT (mean of -20.3°C), but had a much shorter growing season (mean of 178 FFD) compared with the Walla Walla Valley AVA ground truthing vineyards.

VINEYARD 13. The viticulturist pointed out shallow soils featuring

fractured caliche (hardened deposits of calcium carbonate) on the ridge, where the vineyard is situated. Soil depth was again corroborated by SSURGO data, a mean of 55 cm and a minimum of 18 cm. Shallow soils were found on topographically high points, where AWC was also noted to be low. Soil Survey Geographic data showed a mean of $0.15\text{ cm}\cdot\text{cm}^{-1}$ and a minimum of $0.13\text{ cm}\cdot\text{cm}^{-1}$, both at the upper end of the ideal range.

Slopes were very gentle (mean of 1.1%) and insolation was highly variable (mean of 1030 kW-h/m^2) within Vineyard 13. Much of the site was rated lower because of gentle slopes. Despite the high latitude (47.121°N), the vineyard included areas rated moderately high in insolation (mean of 1032 kW-h/m^2). The southern half of the site is alkaline (pH 7.8 to 8.1) according to SSURGO data and the entire vineyard was classed as well drained. Vineyard 13 was tied with Vineyard 12 as having the lowest MEMT (mean of -20.3°C) and has a similar growing season (176 d), but recorded 88°C fewer GDD.

Conclusions

Vineyard site selection is a pre-planting process that influences commercial success of the vineyard (Smith, 2002). It is rare to find a site that is ideal in all facets of consideration; site selection optimizes the establishment of a vineyard-given location constraints. Nearly all factors given consideration have complex interactions with one or more other factors. Sites are selected based on a series of calculated risks associated with less-than-optimal conditions, and standard agriculture best practices are then superimposed to help alleviate site faults.

Spatial representation of environmental characteristics important for the successful production of wine grape provides a holistic, efficient means for initial remote site evaluation. This type of DSS and analysis has not been previously performed in the IPNW and should prove useful in assisting both new and existing growers with site evaluation and cultivar selection. It should also assist in spatially representative exploration of current and future wine grape production areas. Although this type of analysis will never replace onsite assessments, it

can help focus prospectors' attention on which site characteristics require greater scrutiny.

In initial assessments, soil characteristics and topographically driven climatic features generally corresponded to viticulturists' perceptions. However, a lack of distinction in soil survey data made identification of some problem areas more difficult than others. One common discrepancy between viticulturist interviews and soil characteristic rankings was AWC. Areas with lower than ideal AWC tended to fall into our ideal range suggesting our AWC ratings may need to shift to give greater weight to higher AWC.

This model focuses primarily on production characteristics necessary for wine grape. However, with the advancement of breeding programs focusing on short-season and/or cold-hardy wine grape cultivars in the United States, expansion of viticulture in the IPNW may reach beyond the currently described boundaries. Those locations falling in less-than-favorable categories for FFD and GDD for wine grape may prove to be ideal locations for these new cultivars.

The GIS tool described herein is the first step of a DSS that allows users to evaluate sites by individual components. From the identification of specific, potentially production-challenging site factors, onsite examination may be conducted prioritizing those factors most easily and affordably addressed with an idea of geographic areas of greatest concern. Use of this tool could help inform decisions regarding cultivar selection, wind machine placement, soil pH adjustments, drainage infrastructure, variable rate irrigation practices, ripping, erosion control practices, and other management-intervention tactics.

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