

Dirt, water, and wine: deciphering soil-water interactions and their implications for viticulture in the Walla Walla Valley, American Pacific Northwest

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ABSTRACT

This study aims to decipher major soil-water interactions in the Walla Walla Valley and interpret them in the context of viticulture. To assess these interactions, variations in precipitation, soil texture, soil permeability, soil moisture, and soil chemistry in the Valley were quantified. Results indicate that increased precipitation at higher elevations due to orographic lifting creates a soil moisture gradient in the Valley and increases the weathering of silt to clay. Soil chemistry data reflects differential soil weathering, with pH decreasing at higher elevations and available cations increasing due to higher clay content. Soil permeability plays no clear role in any of these interactions. These findings indicate that dryland vineyards are possible at higher elevations in the Valley and could potentially produce high quality fruit because the grapevines would benefit from mild water stress and increased nutrient availability.

Keywords: Walla Walla Valley, Viticulture, Rainfall Gradient, Soil Texture, Soil Moisture, Dryland

INTRODUCTION

For nearly two centuries, viticulturists, vintners, and wine connoisseurs have claimed that specific geological characteristics can profoundly influence the wine that is produced in a certain geographic area (Gladstones, 1992). Frequently, the French term “*terroir*” is invoked to express the complex interactions between wine, land, climate, and other environmental factors. Though it makes intuitive sense that the *terroir* of an area should influence the wine it produces, rigorously studying exactly how it does so has rarely been done. In the Walla Walla Valley of southeastern Washington and northeastern Oregon, it is clear that the geology and climate of the area influences wine production, but the specific role they play is only partially understood. Consequently, this study examines how geology and climate in the Walla Walla Valley relate to wine production by quantifying soil-water interactions in the region and putting the results in the context of viticulture.

This study is of particular relevance because the wine industry in the Walla Walla Valley is experiencing significant growth while at the same time facing considerable water supply problems. Because of the rising costs associated with obtaining water rights in the area, a major component of this study looks at the plausibility of dryland viticulture in the Valley and the potential benefits and problems associated with it. The role of water on soil chemistry is also explored, as it too is of major concern to the wine industry.

BACKGROUND

Geologic Setting

The 3,266 km² Walla Walla Valley is a distinct subsection of the greater Columbia Valley along the eastern Washington-Oregon border (Fig. 1 a, b). The Valley is bounded on the east by the Blue Mountains, which trend from southwest to northeast, and create a ~1370 m (4,500 ft) elevation gradient from the Valley's lowest point near the Columbia River to its highest at Lewis Peak (Unknown, 2008). The southern boundary of the Valley is defined by a high, linear escarpment called Vansycle Ridge (Pogue, 2008), while the remaining boundaries are defined by the Valley's two major waterways, the Walla Walla and Touchet rivers. Both rivers have their headwaters in the Blue Mountains and flow westward into the Columbia.

Of particular concern to those associated with the wine industry in the Valley is the boundary of the Walla Walla American Viticultural Area (AVA). Generally synonymous with international term "appellation," an AVA is a wine-grape growing region designated by the United States government that has distinct geographic characteristics. The Walla Walla AVA generally coincides with the geographic boundaries of the Valley, although it is limited to elevations below 450 m on Vansycle ridge and 610 m (2,000 ft) in the Blue Mountains (Fig. 1 b). The AVA encompasses 122,822 hectares, with grape cultivation occurring on 500 hectares and increasing (Gregutt, 2007).

The bedrock of the Walla Walla Valley is almost exclusively flood basalt. As a part of the greater Columbia Valley, the Walla Walla Valley is encompassed by the Columbia River Plateau, a large igneous province located between the Cascade and

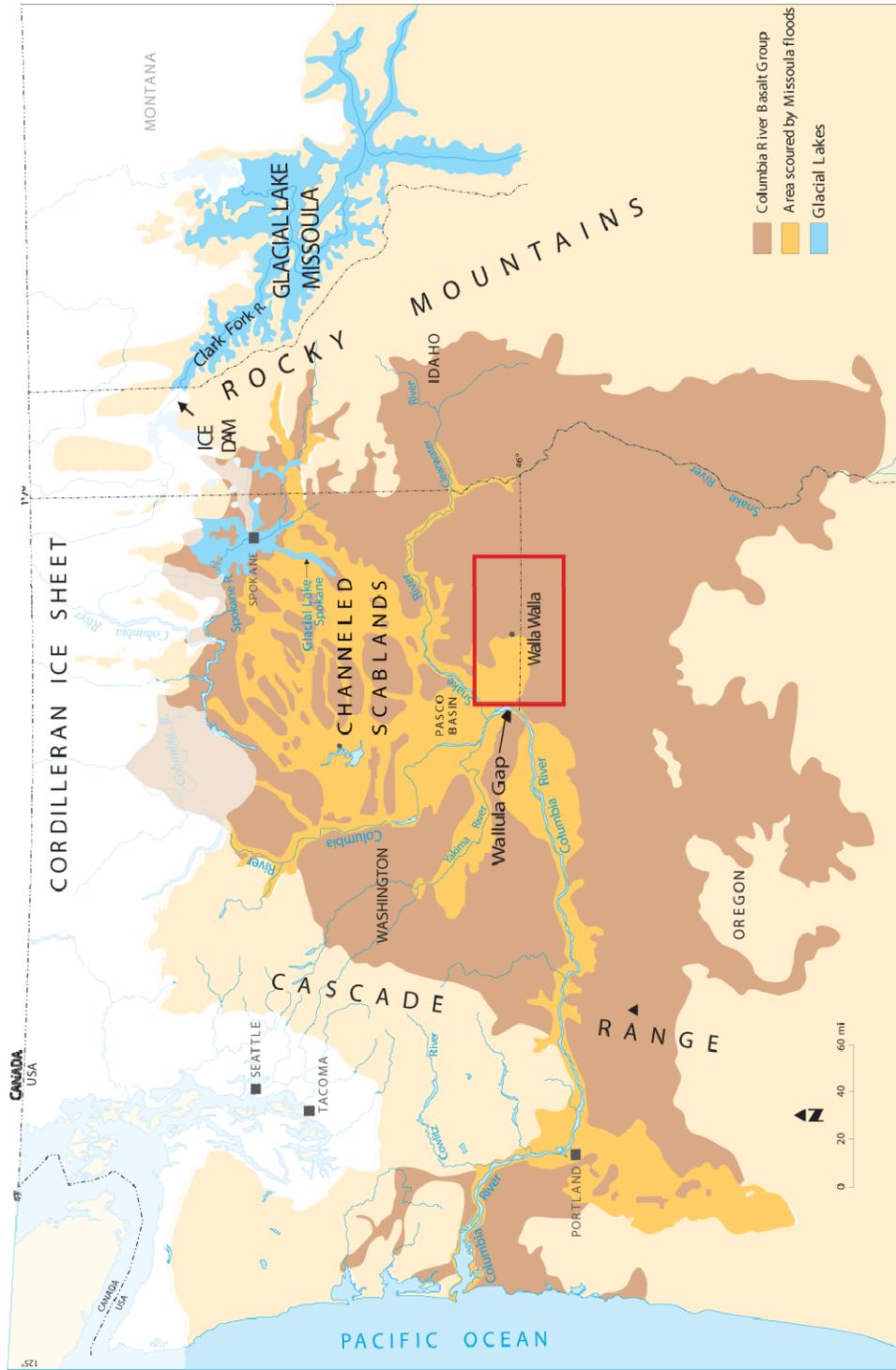


Figure 1 a. Map of Pacific Northwest displaying major geological features including the extent of the Columbia River Basalts, Glacial Lake Missoula, and areas scoured by the Missoula floods. Inset displays the Walla Walla Valley in detail. Modified from Waitt, 1985, Weis and Newman, 1989, and Norman and Roloff. 2004. Extent of the Columbia River Basalt Group from Reidel and others. 1994.

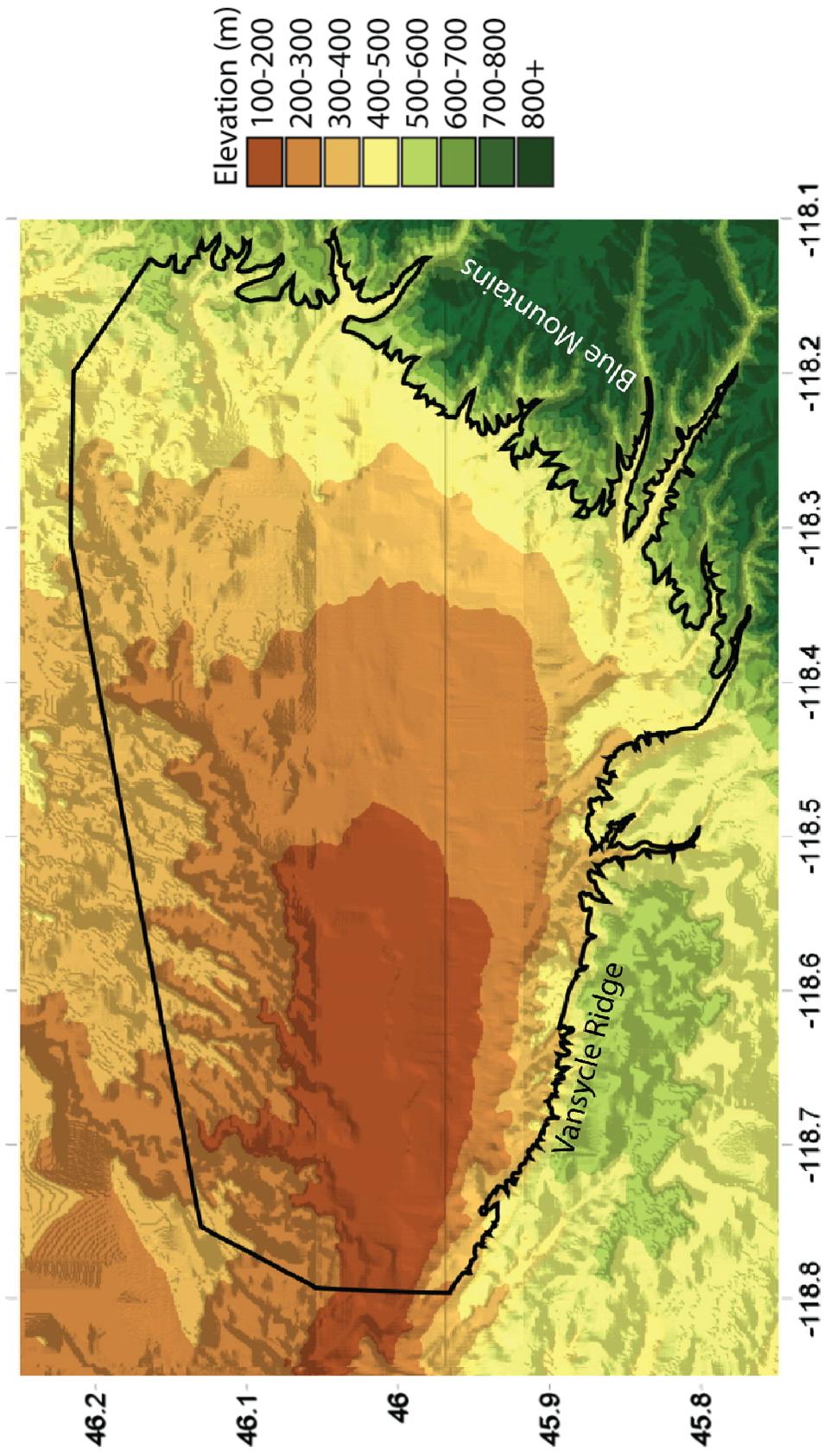


Figure 1b. Digital elevation model of the Walla Walla Valley with AVA boundary.

Rocky mountain ranges that covers 164,000 km² of central Washington and northern Oregon (Hooper, 1997) (Fig. 1a). The Columbia River flood basalts erupted in a series of more than 300 flows thought to have been caused by the impingement of the Yellowstone hotspot on the base of the lithosphere near the present border between Nevada, Oregon, and Idaho (Hooper, 1997). Of the estimated 174,300 km³ of basalt that forms the Plateau, 99 percent erupted between 17 and 14 m.y.a., although minor eruptions continued until about 6 m.y.a. (Carson and Pogue, 1996; Swanson, 1978). In the Walla Walla area, the flows are as thick as 3 km and erupted primarily through fissures in the Blue Mountains, which are cored by late Paleozoic to early Mesozoic exotic terranes, late Mesozoic granitic intrusives, and Tertiary volcanics, but also contain Miocene basaltic dikes associated with the flood basalts (Carson, 2008).

Most soils in the Walla Walla Valley are poorly developed and are derived from a combination of foreign aeolian and fluvial sediments. The predominant soil type in the Walla Walla Valley is loess, which ranges in thickness from 1 cm to 75 m and is dominated mineralogically by quartz and feldspar (Busacca, 1991; Busacca and McDonald, 1994). Southwesterly prevailing winds may have been depositing loess in the area for about 2 million years from sediment sources in the Pasco Basin that include the Pliocene Ringold Formation and Columbia and Snake river sediments (Carson and Pogue, 1996).

Another sediment source for the loess is a set of rhythmites in the Walla Walla and Columbia valleys called Touchet beds. The genesis of Touchet beds is intimately tied to seminal research done on the landscape evolution of eastern Washington and Oregon. Beginning with the pioneering work of J. Harlen Bretz in the 1920's related

to curious geologic features in eastern Washington, it has been determined that Touchet beds are the result of approximately 40 catastrophic glacial floods occurring between about 15,300 and 12,700 y.a. (Waitt, 1985; Waitt, 1980). The source of these floods was the glacial Lake Missoula (Pardee, 1910), which formed when a lobe of the Cordilleran Ice Sheet blocked the Clark Fork River near Cabinet Gorge on the present Idaho-Montana border (Carson and Pogue, 1996; Waitt, 1985) (Fig. 1a). The lake that the ice dam created was massive, covering 7,800 km², with a volume of 2,500 km³, and a depth of 600 m near the dam (Waitt, 1985; Weis and Newman, 1989). By comparison, the lake was larger than modern-day Lake Ontario and Lake Erie combined (Perdue, 2005).

The stresses associated with containing such a large volume of water caused the ice dam to fail repeatedly, releasing jökulhlaups (glacial outburst floods) that rushed southwestward through northern Idaho, eastern Washington, and eastern Oregon en route to the Columbia River. Initially, the jökulhlaups were highly energetic and traveled at 95 km/hr and with a discharge 10 times the instantaneous flows of all of modern rivers in the world combined (Perdue, 2005). At this stage, the floods scoured the landscape, creating the famed Channeled Scablands of eastern Washington and other impressive topographic features (Fig. 1a). As the floods progressed, they became bottlenecked at the Wallula Gap on the Columbia River, causing them to slow down and pool. The backups repeatedly created the short-lived glacial Lake Lewis, which was 300 m deep and covered the Walla Walla Valley and much of the surrounding area (Carson and Pogue, 1996; Perdue, 2005). Although the lake drained in about a week, the floods were slowed down long enough for the

Touchet beds to be deposited, with their graded nature resulting from a continued decrease in flood velocity. It is generally thought that each flood was responsible for depositing one Touchet bed, although there is evidence in some places of multiple beds forming after surges in the same flood (Smith, 1993; Waitt, 1980). As noted, some sediment has been redeposited to form the loess soils; however, many beds remain relatively unaltered.

Climate

Climatically the Walla Walla Valley is fairly dry, as the Cascades block moist ocean air traveling from the west. However, some moisture does pass over these barriers, and although the summers are very dry, precipitation increases in the fall and peaks in midwinter before gradually declining through June (Harrison et al., 1964). The amount of precipitation, which falls as both snow and rain, increases from west to east with about 8 inches of precipitation falling annually near the confluence of the Snake and Columbia Rivers, 11 to 13 falling in the northeastern part of the Valley, 14 to 18 falling in the central part of the Valley, and 25 or more inches falling in the Blue Mountains (Harrison et al., 1964).

The Valley is characterized by warm summers and, for its latitude, relatively mild winters. In the summer, the average afternoon temperature is near 90 degrees Fahrenheit, and there are typically 35 to 40 days per summer with highs at or above this temperature; daily lows are typically in the 60s (Harrison et al., 1964). In the winter, afternoon temperatures are in the 30s and low 40s, with nighttime lows typically between 15 to 25 degrees (Harrison et al., 1964). Temperature also varies spatially over the Valley, with local topography and elevation showing considerable

effects. In general, lower elevations have higher average temperatures during the grape growing season and more growing degree days than higher elevations.

However, narrowing of the Valley in the west creates a nocturnal cool air pool that is most pronounced from August to October (Pogue, 2008). Areas below 300 m also experience a greater change in temperature during the winter, leaving vineyards more prone to vine damage (Pogue, 2008). This effect was especially evident in the winter of 2003-2004 when vineyards in the far western half of the Valley experienced significant vine losses, while those at higher elevations were less harmed. Other localized trends include lower growing season temperatures near major streams due to cool air descending from the Blue Mountains, and higher temperatures near the base of Vancycle ridge caused by adiabatic warming of prevailing down-sloping winds (Pogue, 2008).

METHODS

Precipitation: Rainfall data from the Natural Resources Conservation Service, Whitman College, and the National Weather Service were collected from the online databases for the period between July 1, 2006 to July 1, 2007 (roughly the year prior to sample collection). A contour map of the data was generated with Surfer™ mapping software by Golden Software, Inc. using the Kriging gridding method.

Sample Collection: Soil samples were collected at 21 sites throughout the Walla Walla Valley between July 25 and August 8, 2007. In selecting sites, care was taken to avoid irrigation sources, compacted areas, and other unnatural characteristics as these could potentially alter soil properties. Consequently, most sites were located in

uncultivated portions of vineyards, usually between vine blocks or along their periphery. A few sites were located in conservation areas or on other fallow land.

After sites were selected, basic site characteristics were observed and recorded. For all sites, latitude, longitude, and elevation, accurate to within 15 meters, were established using a handheld Garmin™ global positioning system unit. Nearly all sites were located on hillslopes or hilltops. For these sites, aspect and slope were determined using a Brunton compass. Vegetation and other unique occurrences were also noted. At all sites, soil samples were collected using a four-inch diameter bucket-style soil auger. Samples were collected at 0.5, 1.0, 1.5, and 2.0 meters depth, stored in airtight freezer bags, and promptly taken to the lab for analysis.

Soil Moisture: Gravimetric soil water content was determined for all samples using facilities in the Whitman College Hall of Science. Between 300 and 500 grams of soil from each sample were weighed using a digital balance accurate to ± 0.01 g. The samples were then desiccated in a drying oven for 24 hours at 200 ± 10 °F (93.3 ± 5.5 °C). The dried samples were re-weighed, and gravimetric soil moisture content was calculated by the equation: Gravimetric Soil Water Content = $(\text{Wet Mass} - \text{Dry Mass}) / \text{Dry Mass}$ (Bilskie, 2001; Gardner, 1986). Although the method was found to be less accurate, volumetric soil moisture content was also calculated by measuring the volume of the soil in a 2,000 ml graduated cylinder before samples were dried. Volumetric water soil moisture content was calculated from the equation: Volumetric water content (θ) = $(\text{Wet Mass} - \text{Dry Mass}) / (\text{density of water} * \text{wet volume})$.

Soil Permeability: Field saturated hydraulic conductivity and matric flux potential were determined at 17 of the 21 field sites as a means of quantifying soil permeability. This was done using a dual reservoir Model 2800K1 Guelph Permeameter, a constant-head device operating on the Mariotte siphon principle manufactured by the SoilMoisture Equipment Corporation. Infiltrometer readings were taken in close proximity to soil auger holes in areas without obvious irregularities from the surrounding soils such as tractor tracks or rodent burrows. At each site, a 15 cm deep by 8 cm diameter hole was augered, smoothed, and brushed. Brushing was done to disrupt and eliminate coherent clay surfaces that tended to develop on the sides of the holes during augering. After the sites were prepared, the infiltrometer was run at 5 cm and 10 cm heads until the hole became saturated and rate of decrease in the height of the water in the instrument's reservoir reached steady state.

From these rates, the field saturated hydraulic conductivity of the soil was calculated from the equation $K_{fs} = (0.0041)(X)(R_1) - (0.0054)(X)(R_2)$, where K_{fs} is field saturated hydraulic conductivity, X is a reservoir constant corresponding to the cross sectional area of both reservoirs of the instrument, R_1 is the steady state rate of fall in cm/sec for the 5 cm, and R_2 is the of fall for the 10 cm head. For the instrument used in this study, X had a value of $35.22 \pm 0.18 \text{ cm}^2$. The matric flux potential of the soil, Φ , is given by the equation $\Phi = (0.0572)(X)(R_1) - (0.0237)(X)(R_2)$. In some instances, the two head analyses yielded unrealistic results because R_1 and R_2 had very similar values. In these instances, less accurate single head analyses were done using R_1 and R_2 instead, and their results were averaged.

Soil Texture: To quantify soil texture, particle size analysis of the 0.5 meter deep samples was completed at Carleton College using the hydrometer method. The specific procedure used was based on the protocol described by Ashworth *et al* (2001), which in turn is based on protocols developed by Bouyoucos (1936, 1962) and Gee and Bauder (1979). (See appendix for why this particular protocol was selected.) Soil samples were desiccated in a drying oven at 200 ± 10 °F (93.3 ± 5.5 °C) for approximately 6 hours. From the dried samples, $50 \pm .01$ g of soil was pulverized using a mortar and pestle to breakup clay aggregates and added to 100 ml 5 % Sodium Hexametaphosphate dispersing solution. This was then diluted to 1000 ml with distilled water in a graduated cylinder homogenized. Following this, hydrometer readings were taken at 40 seconds and 6 hours using a standard soil hydrometer, ASTM model 152H. Particle sizes were calculated based on the formulas provided by Ashworth (2001).

Soil Chemistry: Seven 0.5 meter deep samples were sent to International Ag Labs, Inc. in Fairmont Minnesota for chemical analysis. Samples were selected to provide broad coverage of the Valley, while the 0.5 meter depth was selected because the majority of a grapevine's roots are located at shallow depths. Plant available levels of humus, nitrates, ammonia, phosphorus, potassium, calcium, magnesium, sodium, copper, iron, zinc, and manganese were determined using the lab's particular weak acid extract, the Morgan extract. Soil pH levels were also determined.

RESULTS

Precipitation: Despite the small sample size, analysis of precipitation data from six weather stations throughout the Walla Walla Valley from July 1, 2006 to July 1, 2007

clearly shows a strong correlation between elevation and precipitation in the Valley. The best linear fit line for elevation versus accumulated rainfall for the data has an R^2 value of 0.98 (Fig. 2). In addition, a Surfer™ generated contour map of the data gives strong visual evidence of the correlation between precipitation and elevation as precipitation clearly increases from east to west as elevation increases in the Valley, especially in the Blue Mountains (Fig. 3).

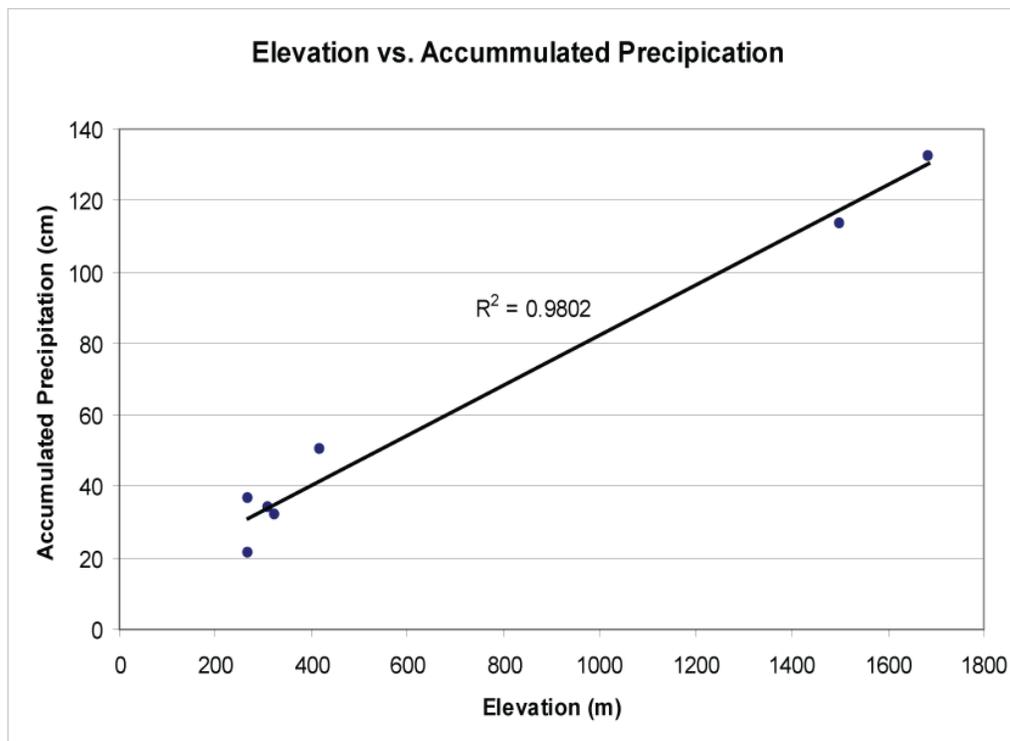


Figure 2. Plot of elevation against accumulated rainfall from July 1, 2006 to July 1, 2007 from seven weather stations in or near the Walla Walla Valley. Rainfall clearly increases with elevation.

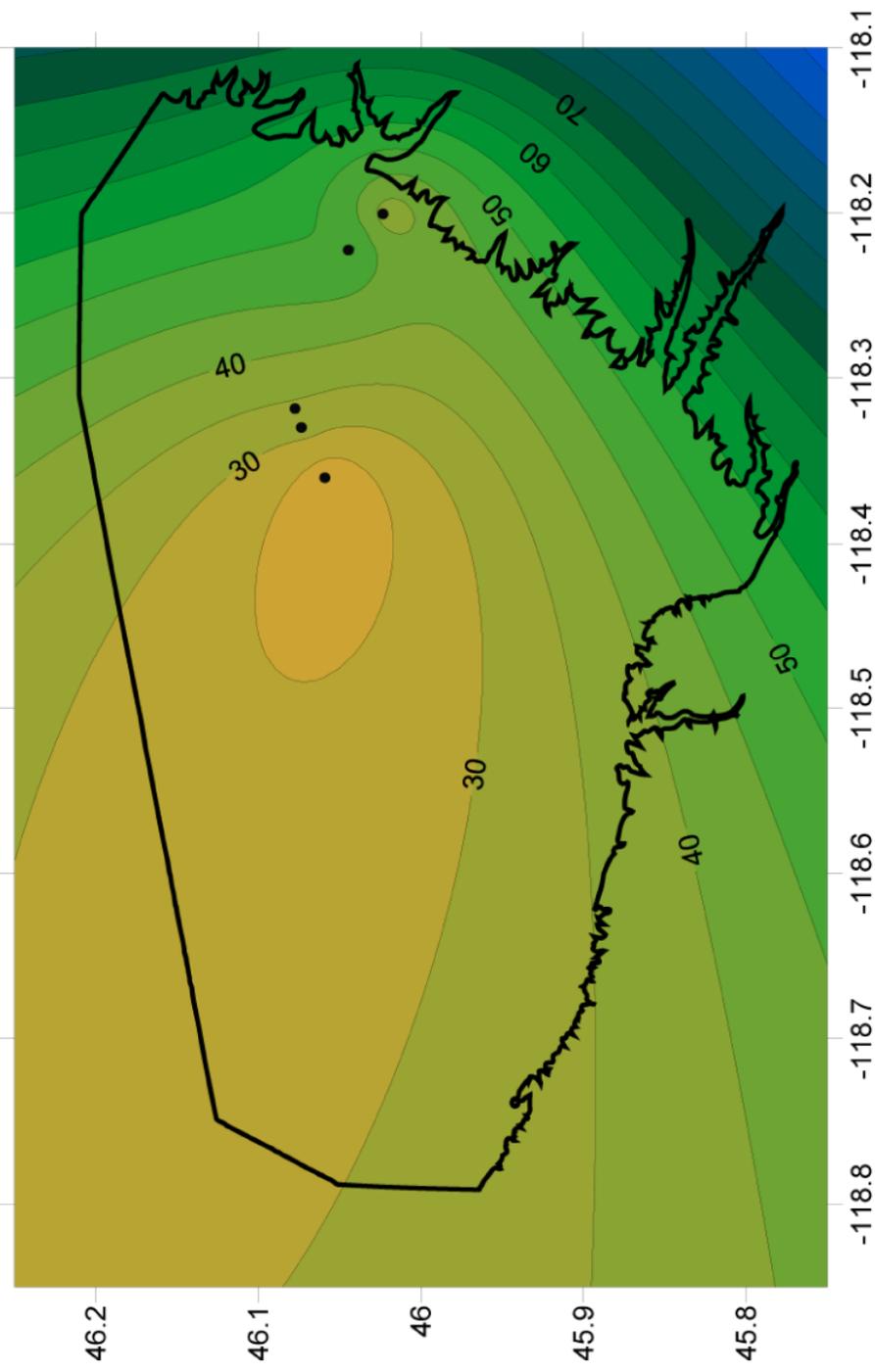


Figure 3. Contour map of accumulated rainfall in cm for the Walla Walla Valley from July 1, 2006 to July 1, 2007. Accumulated rainfall closely mirrors topography. The black dots represent the weather stations that provided the data for this figure; two are situated outside of the map area. The black line is the Walla Walla AVA boundary.

Particle Size: Particle size analysis of the 0.5 m deep samples shows that the viticultural soils of the Walla Walla Valley are predominantly silty loams based on the USDA soil texture classification scheme. Of the samples tested, 19 out of 21 are silt loams, while one is a sandy loam and the other is a silt (Fig. 4). By weight, sample sand content has a mean value of $21.0 \pm 10.8 \%$, mean clay content is $10.1 \pm 5.7 \%$, while silt fraction makes up the majority of most samples with an average of $68.9 \pm 8.1 \%$.

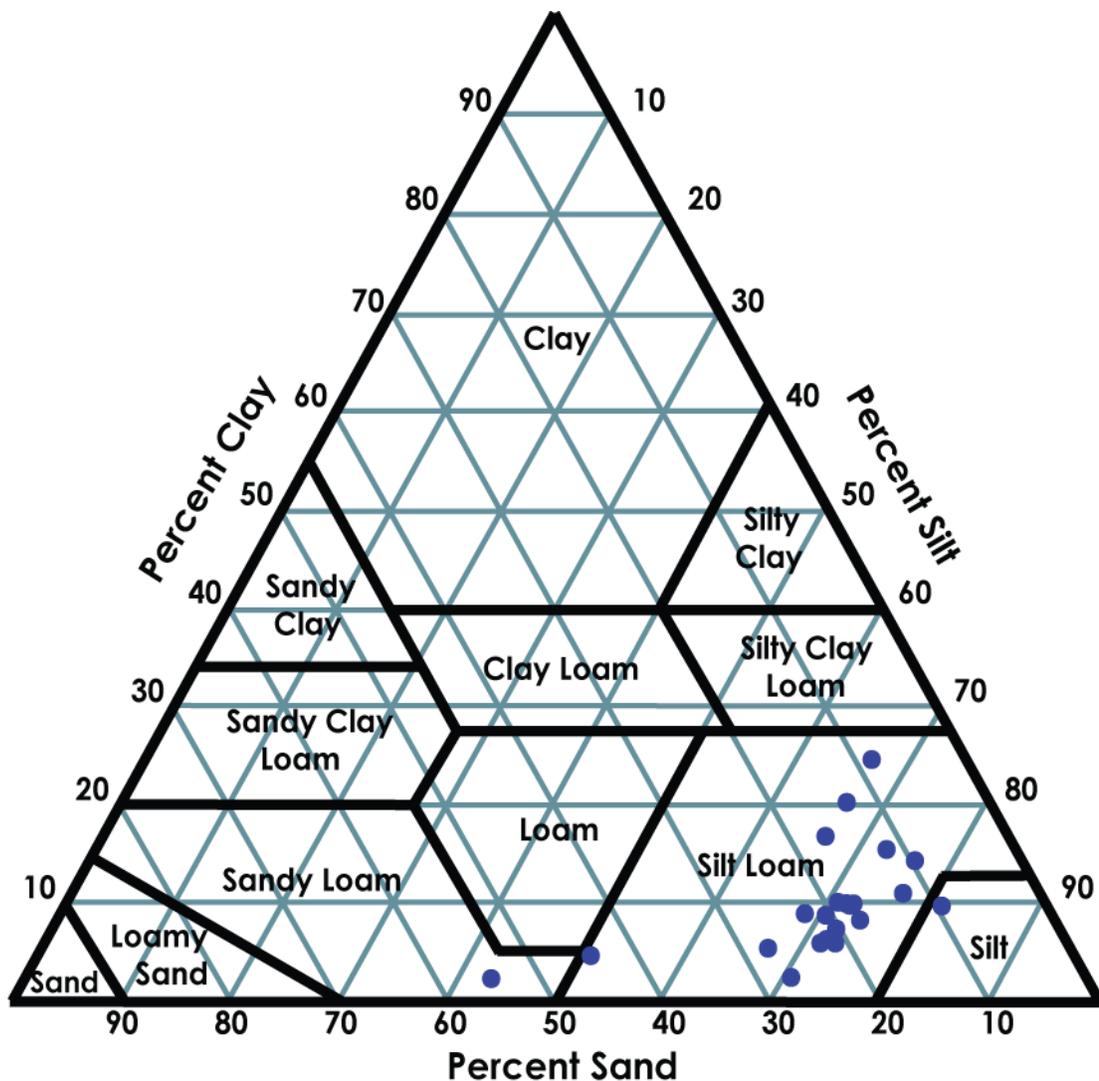


Figure 4. Ternary plot of soil texture for all 0.5 meter deep samples, based on United States Department of Agriculture classification categories. The two samples with high sand content are interpreted as Touchet Bed soils, while the remainder are interpreted as loess.

Although the relatively small standard deviations suggest that the samples are similar in composition, there are two major outliers that can be seen in figure 4. One, the sole sandy loam sample, has a sand content of 54.9 %, a silt content of 42.9 %, and a clay content of 2.2 %, all of which are one standard deviation or more away from the mean values. Similarly, one of the silty loams is 45.02 % sand, 50.28 % silt, and 4.64 % clay. In this case the sand and silt are both more than one standard deviation away from the mean values.

Soil texture in the Walla Walla Valley has a number of distinct spatial trends related primarily to elevation. Sand content generally decreases with elevation, while clay content increases with elevation (Figs. 5 and 6). The linear best-fit line for sand and elevation has an R^2 value of 0.57 when the two major outliers are excluded, while the best-fit line for clay and elevation has an R^2 value of 0.84 for the same samples. With silt content the relationship is less obvious. However, when only the fines are considered, silt content is shown to generally decrease with elevation (Fig. 7). In this case the best linear model for elevation and percent silt has an R^2 value of 0.75.

Soil Permeability: Data collected using the Guelph infiltrometer yield a mean field saturated hydraulic conductivity of 5.64×10^{-4} cm/hr with a standard deviation of 4.22×10^{-4} cm/hr for the 17 sites tested, while the soil matric flux potential for the sites has a mean value of 5.98×10^{-3} cm/hr with a standard deviation of 4.29×10^{-3} cm/hr.

Although their values range widely, hydraulic conductivity and matric flux potential exhibit no clear relationships to elevation, soil texture, or soil moisture.

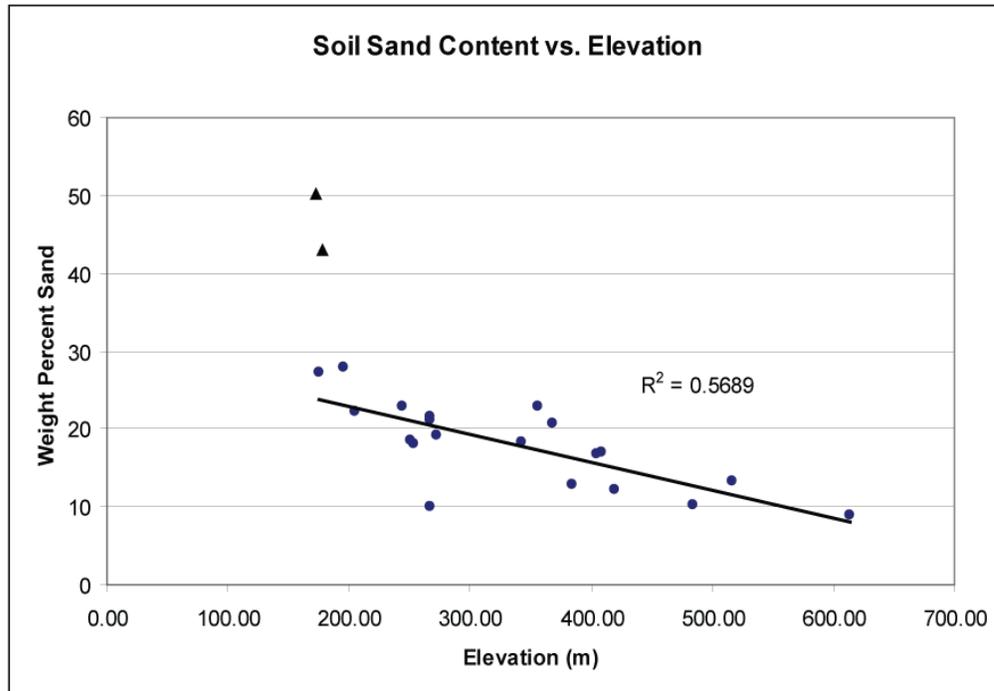


Figure 5. Plot of weight percent sand against elevation. Soil sand content generally decreases with elevation. Two major outliers interpreted as Touchet bed soils are shown with triangular points.

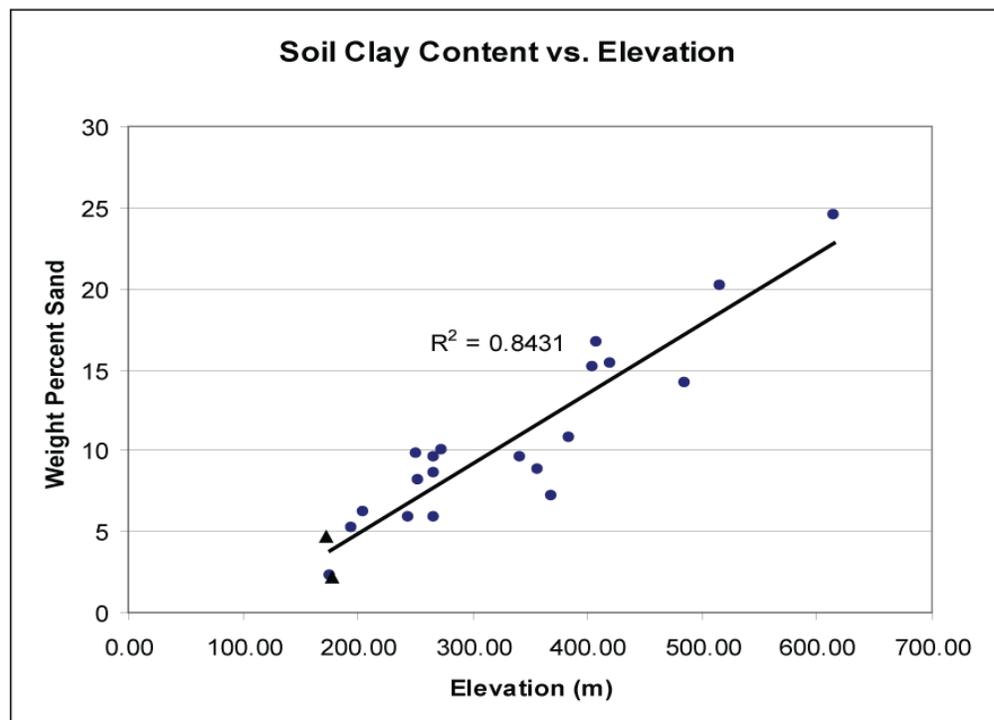


Figure 6. Plot of weight percent clay against elevation. Clay content has a strong positive correlation with elevation. The two Touchet bed samples, represented by triangular points, are not outliers in this case.

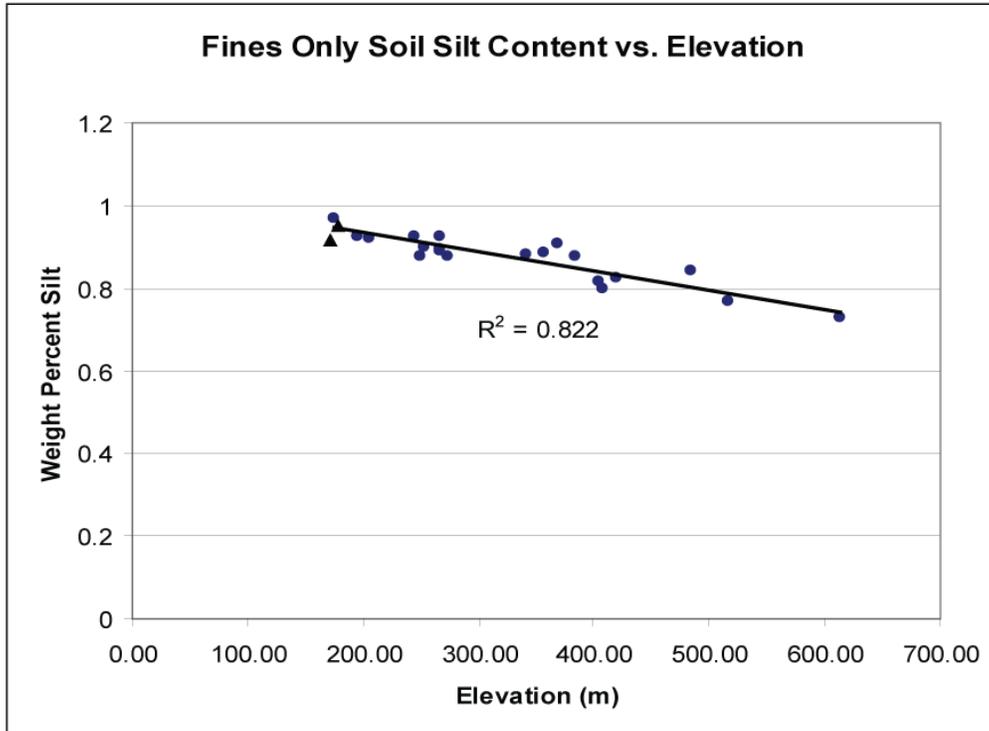


Figure 7. Plot of weight percent silt against elevation when only the fines are considered. When sand is included, R^2 drops from 0.822 to 0.057.

Soil Moisture: Soil moisture generally increases with depth, with the mean gravimetric moisture values being 7.8 % for 0.5 m, 9.0% for 1.0 m, 10.3% for 1.5 m, and 11.5% for 2.0 m. Although moisture did not always increase every half-meter for many sites, only three sites had a moisture content at 2.0 m that was lower than at 0.5 m. To simplify interpretation and reduce the importance of site abnormalities, average gravimetric soil moisture content for the 22 sites sampled was calculated by taking the average of the values for all four depths at each site. This yields a mean value of 9.6% with a standard deviation of 3.2% and maximum and minimum values of 16.2% and 5.6%, respectively.

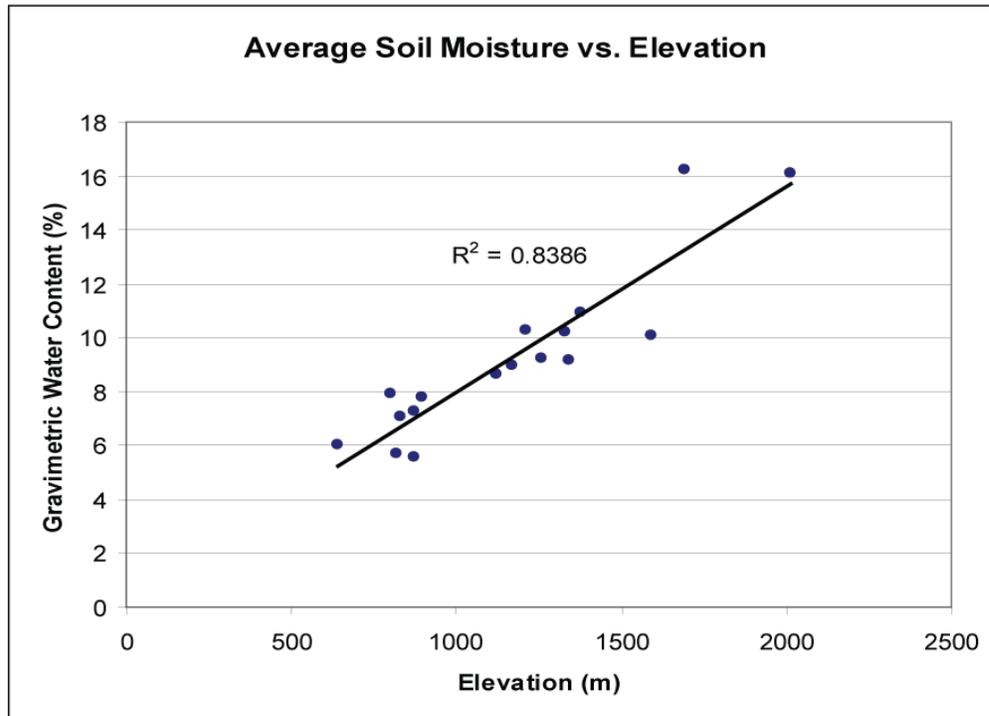


Figure 8. Plot of soil moisture against elevation for minimally-altered loess soils. Correlation is lower when Touchet bed soil and anthropogenically altered soils are included.

When all samples are considered, there is no clear relationship between soil moisture and elevation as the best linear fit line for the two variables has an R^2 value of only 0.08. However, when only sites consisting of wind derived loess free from anthropogenic alteration (i.e. field pans) are considered, the relationship between elevation and soil moisture becomes much stronger, and R^2 increases to 0.84 (Fig. 8). A similar effect is also seen when soil moisture and soil texture are compared. When all sites are considered, average moisture versus weight percent sand has an R^2 value of 0.03, moisture versus clay a value of 0.20, and moisture versus silt a value of 0.01. When the non-loess and modified sites are excluded, however, R^2 values for moisture versus sand increase to 0.49, moisture versus clay to 0.75, and moisture versus silt to 0.12. The slopes of the best-fit line indicate that moisture generally decreases with

higher sand content but increases with high clay content (Figs. 9 and 10). These trends can be seen visually in Surfer™ generated contour maps of weight percent clay, weight percent sand, and average soil moisture (Figs. 11-13). For silt and moisture, however, there is still no clear relationship even when only the loess sites are considered.

Soil Chemistry: Soil pH in the samples ranges from 6 to 8 and generally decreases with elevation, with the best linear fit between the two parameters having an R^2 value of 0.82 (Fig. 14). There is also a clear positive correlation between elevation and most of the cations, including Ph, Ca, Mg, Fe, and Mn. All samples had low available Cu and Zn (<1.7 and 1.1 ppm, respectively). Fe was the most abundant of the cations, with two samples having values in the teens, and one having a value of 86.1 ppm (see appendix for complete results).

DISCUSSION

Data Interpretation

As expected, the rainfall data show a definitive increase in precipitation with increasing elevation, most profoundly in the Blue Mountains (Fig. 2). Despite the elevation change in the Valley (~4,500 ft) being small compared to many other mountainous areas, the increase appears great enough to induce precipitation by orographic lifting. Although other variables likely influence the precipitation distribution of the Valley, the high correlation between precipitation and elevation suggests that topography is the dominant controlling factor.

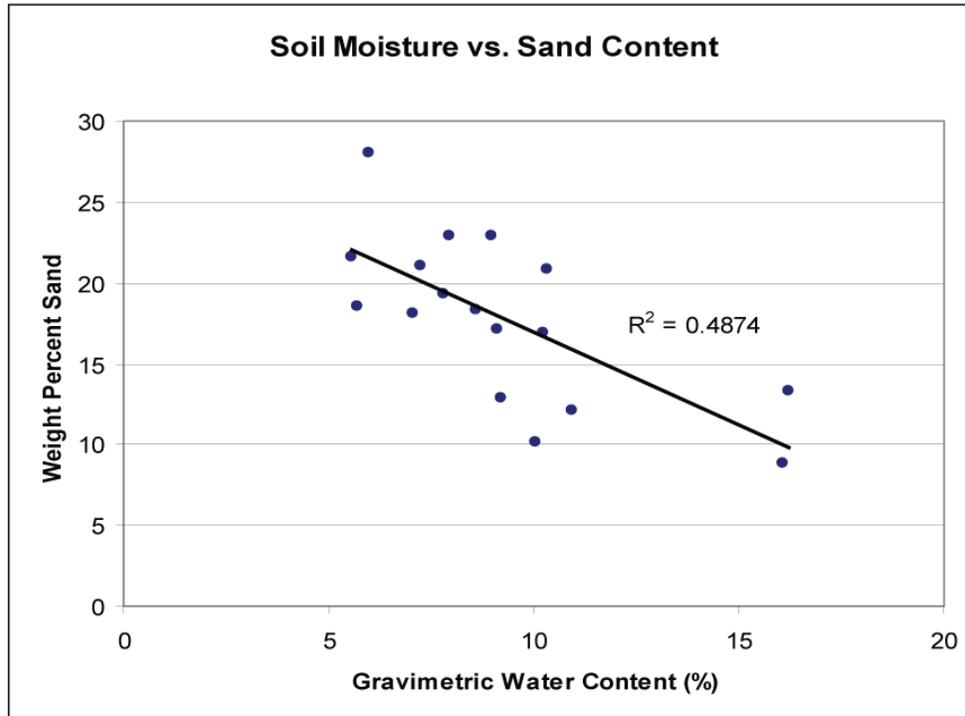


Figure 9. Plot of soil sand content against average gravimetric water content for unaltered loess soils.

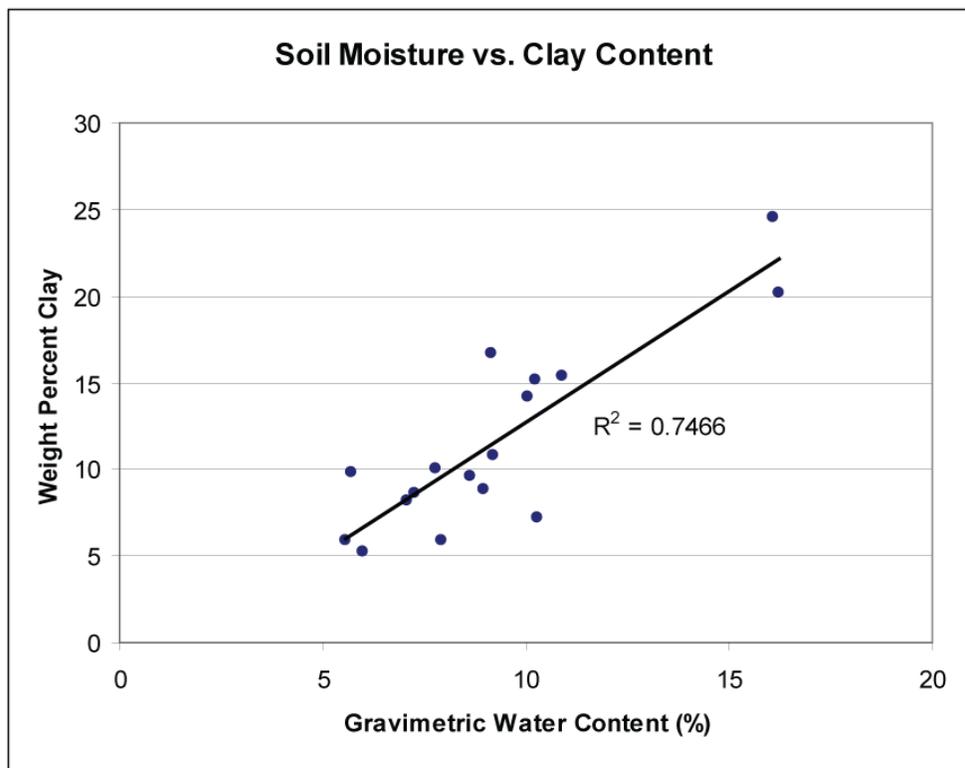


Figure 10. Plot of soil clay content against average gravimetric water content for unaltered loess soils.

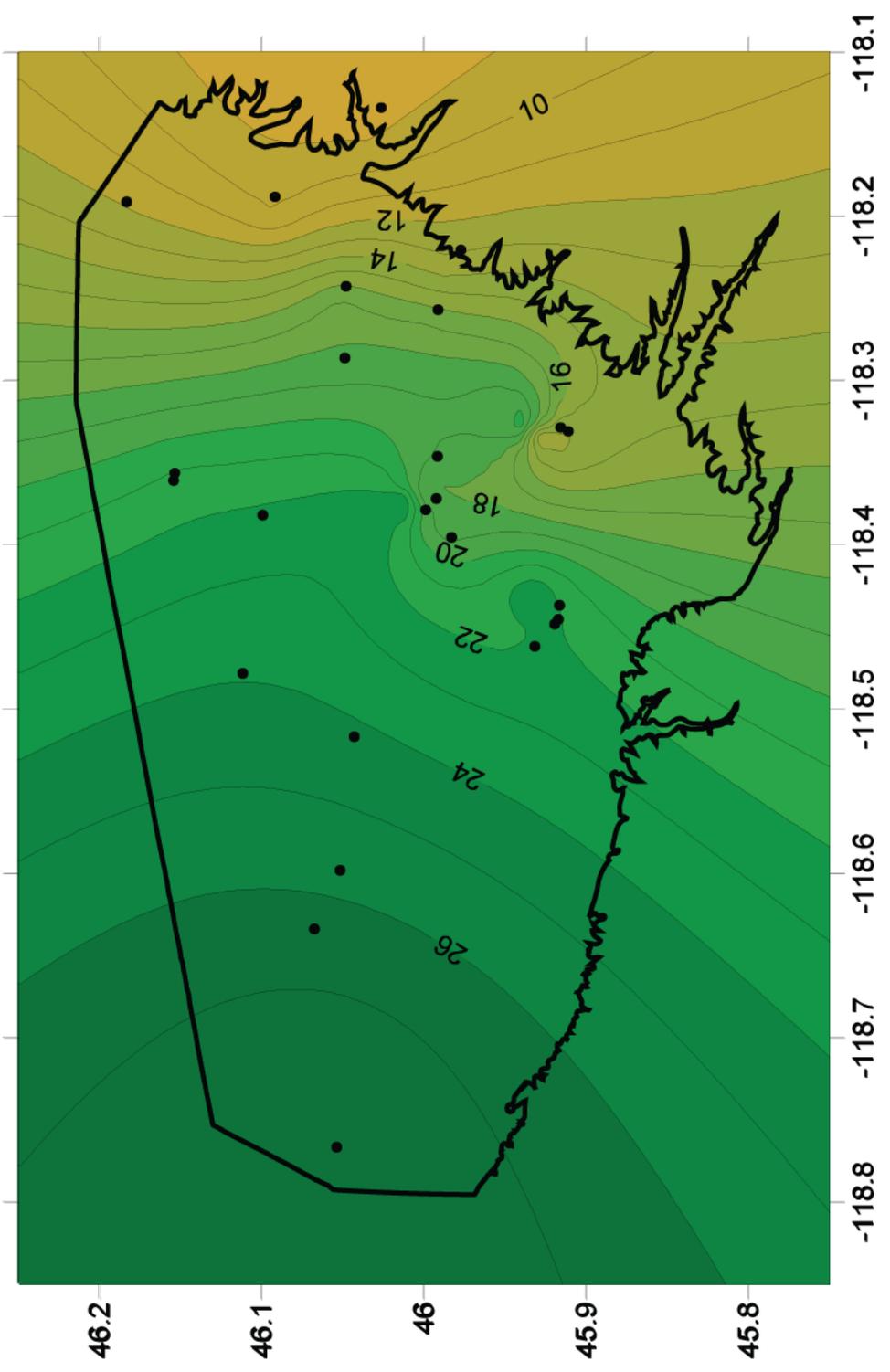


Figure 11. Contour map of weight percent sand in loess soils of the Walla Walla Valley. The dark line is the Walla Walla AVA Boundary; the black dots are sampling sites. Generated with Surfer mapping software by Golden Software, Inc. using the Kriging gridding method.

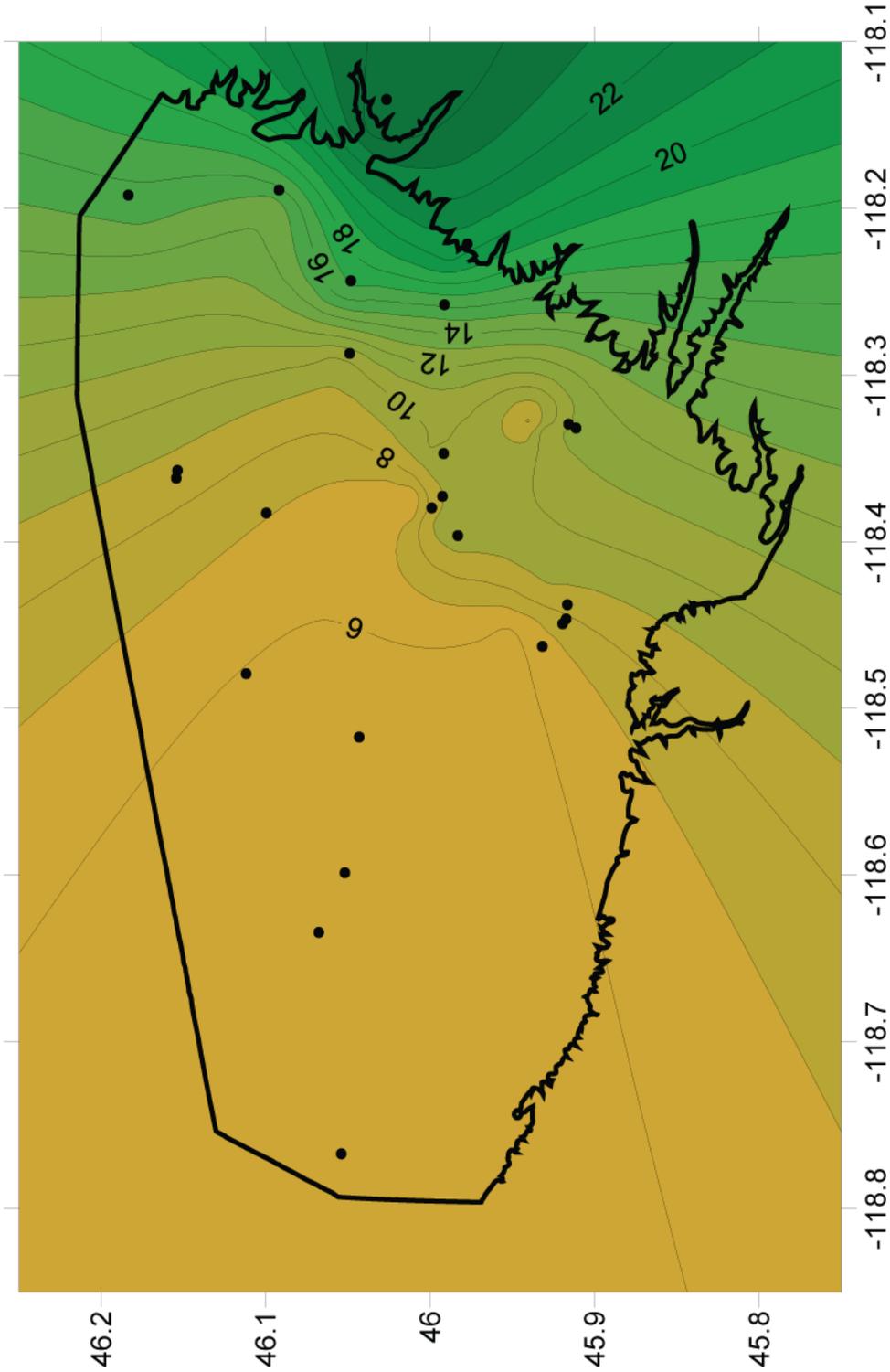


Figure 12. Contour map of weight percent clay in loess soils of the Walla Walla Valley generated with Surfer 8 mapping software by Golden Software, Inc. using the Kriging gridding method. The dark line is the Walla Walla AVA Boundary, while the dots represent sample locations.

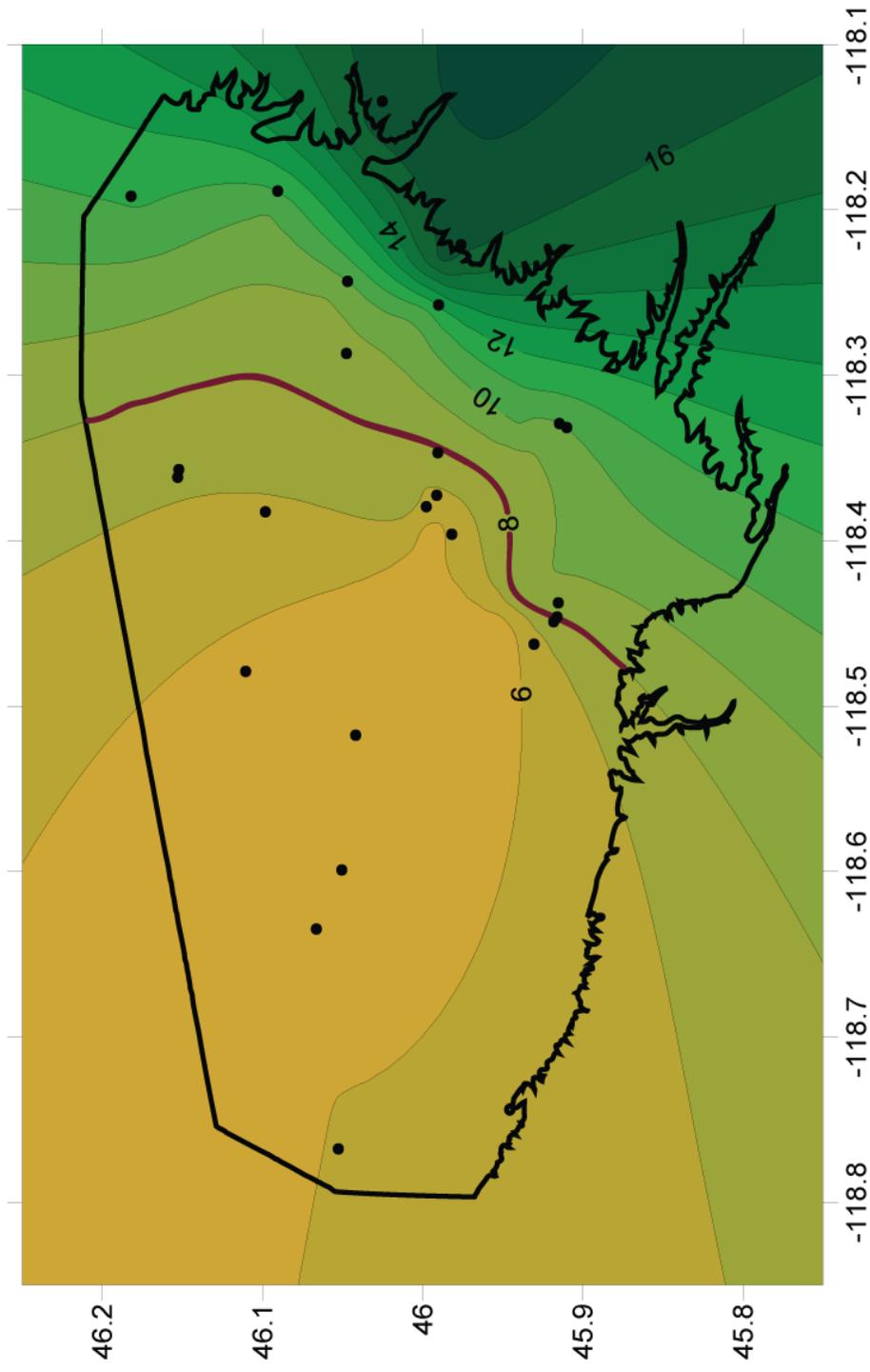


Figure 13. Contour map of average gravimetric soil water content in percent. Values represent the mean of water content values for 0.5m, 1.0m, 1.5m, and 2.0m depth. Contours were generated with Surfer 8 mapping software by Golden Software, Inc. using the Kriging gridding method. The dark line is the Walla Walla AVA Boundary while the black dots represent sampling sites. Maroon line represents approximate division between areas where dryland viticulture is not possible (left) and areas where it is (right).

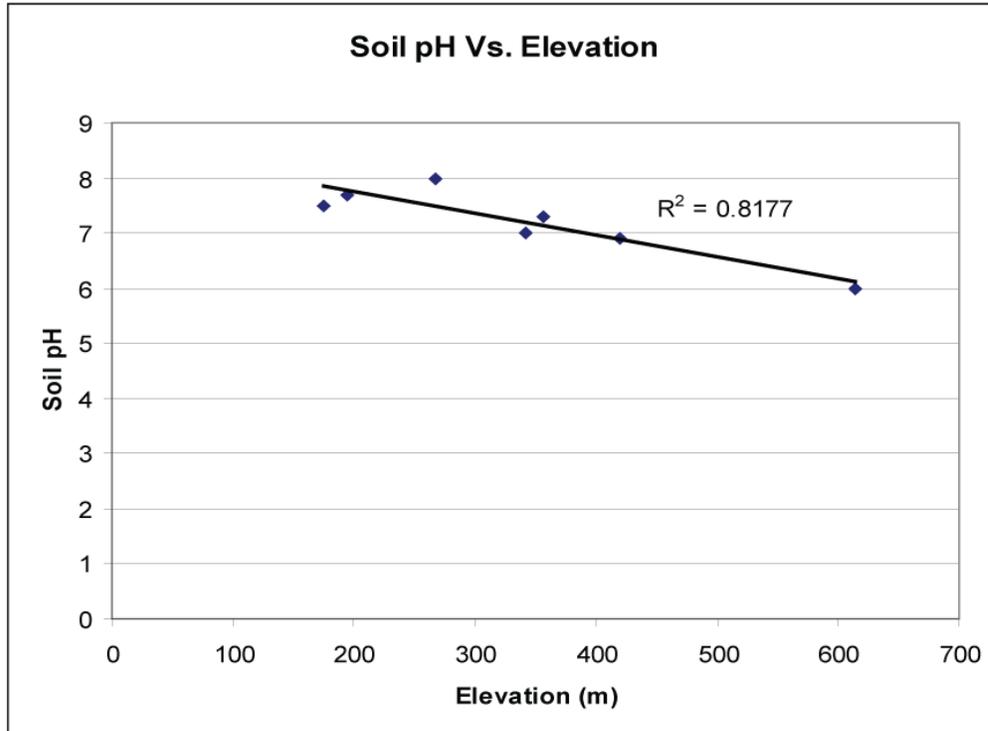


Figure 14. Plot of soil pH against elevation. Values for pH range from 6 to 8 and generally decrease with elevation.

The results of this study suggest topography and its control of precipitation are the primary factors responsible for the soil moisture distribution of the Valley. The high correlation between soil moisture and elevation and the similarity between the rainfall and soil moisture distributions in the loess are evidence that this is the case. Soil texture may also play a role in controlling soil moisture, especially when both Touchet Bed and loess soils are considered. The observation of increased soil moisture at one site with a field pan suggests that human alteration of soil structure also plays a role. These factors likely account for much of the variability present when soil moisture and elevation are plotted against each other. On a valley-wide scale, however, these factors appear relatively unimportant. Major soil structure alteration was rarely observed in the field, and the strong correlation between soil

moisture and elevation in the loess despite the soil's variability suggest that the role of texture is relatively minor.

The relative unimportance of soil texture in controlling soil moisture is further demonstrated by the poor correlation between soil moisture and field saturated hydraulic conductivity/ matric potential. Although the correlations between soil moisture and clay and sand contents suggests that soil texture does have a significant effect, the correlations most easily explained by having one or several processes simultaneously influencing both soil moisture and soil texture. In the case of the positive correlation between clay content and soil moisture, it is probable that higher precipitation at greater elevations is increasing soil moisture while simultaneously causing increased weathering of silt to clay. This interpretation is consistent with the pH distribution results for the 0.5 m deep soils, which indicate greater soil weathering at higher elevations because soils are slightly acidic at this level, but slightly alkaline at lower elevations (Bohm et al., 2001).

Because sand is difficult to weather and because sand content decreases rather than increases with elevation, the increased weathering due to higher precipitation does not account for the correlation between sand content and soil moisture. Instead, the loess deposition process is most likely responsible. Since the prevailing winds in the Valley trend from west to east, we should expect to see higher sand content in the western (lower elevation) areas because larger particles are transported shorter distances by the winds than smaller ones. Consequently, it is reasonable that we should see a negative correlation between sand content and soil

moisture because deposition favors sand at lower elevations and precipitation increases at higher elevations.

As with sand, it is possible that the clay distribution in the loess soils is also a remnant of original deposition, in which case there is more clay at higher elevation because smaller particles were carried further by the prevailing eastward winds than larger grain sizes. However, the lack of correlation between elevation and soil silt content brings this process into question. Given the strong (negative) correlation between silt and elevation when sand is not considered (Fig. 7), it is more likely that deposition of the fines was relatively homogenous with regard to particle size, and only after deposition did clay content increase with elevation due to weathering. Deposition may have favored clay-sized particles at higher elevation to some extent, but overall the effect of this on soil texture is likely minor.

Although elevation is most clearly influencing soil moisture through its control of precipitation, the chemical data suggest that there is also a relationship between elevation, clay content, and available cations. Intuitively one might expect to see lower amounts of available cations in areas with greater precipitation due to leaching; however, this is often not the case as there is a clear positive correlation between available P, Ca, Mg, Fe, and Mn and elevation. While it is still possible that more leaching is occurring at high elevations, this effect is apparently offset by the greater proportion of clay in these areas because clays facilitate cation exchange while silt is less effective.

Viticultural Implications

The results of this study have several notable implications for viticulture in the Walla Walla Valley. The distribution of soil moisture in the Valley is an important aspect to consider when selecting future vineyard sites as soil moisture dictates how much irrigation, if any, a potential site will require. Optimal plant available water (=soil moisture at field capacity- soil moisture at wilting point) for wine grapes is somewhere between 15 and 30 % (Sivilotti et al., 2005). Based on field capacity and wilting point values given by McCraw (2005), this corresponds to volumetric soil water contents between ~2.5 and 5 % for silt loams. Although the volumetric water content values calculated in this study are not as accurate as the gravimetric water content values, all sites tested had values greater than 5 % (see appendix). This does not imply that all sites in the Valley are suitable for dryland viticulture since water content would decrease at these sites once vines were planted. However, it does leave open the possibility of dryland viticulture in at least some areas. Figure 13 outlines an approximate zone in the Valley that is suitable for dryland viticulture based on the gravimetric soil moisture values for sites that are near an established dryland vineyard in the Valley. Research investigating grapevine water consumption under conditions similar to those in the Walla Walla Valley would allow for a more precise delineation of this area, but the topic has yet to be explored.

Wine grapes are unique from most other crops in that their quality decreases if they have too much available water because a greater proportion of a vine's energy is expended on vine, root, and leaf growth rather than on fruit. In fact, numerous studies have shown that mild water stress can actually improve grape quality,

although in some cases total yield may decrease (des Gachons et al., 2005; Greven et al., 2005; Hardie and Considine, 1976; Kment, 2005; Koundouras et al., 2006; Santesteban and Royo, 2006). Highlighting this is a study by Koundouras et al. (2006) that looked at three non-irrigated vineyards in southern Greece with climates similar to the Walla Walla Valley. Water stress at these sites benefited the concentration of anthocyanins and total phenolics in berry skins, which they found translated into the wine they produced. More qualitatively, the dryland wines were preferred in tasting trials as well. Given this body of research, it is likely that dryland vineyards in the Walla Walla Valley would produce quality fruit since the lack of a constant water source would create mild water stress.

Coupled with their potential for quality fruit production, soils with higher moisture in the Valley have the added benefit of increased nutrient availability, presumably due to their higher clay content. Considerable debate exists concerning what role, if any, soil chemistry has on wine quality. Viticulturists have been suggesting for nearly two centuries that specific soil attributes have profound effects on wine characteristics and quality, an idea incorporated in the concept of *terroir* (Gladstones, 1992). Others have argued, however, that such claims of “minerality” derived from certain soils are largely false, or at the very least, poorly understood (Patterson, 2006). While it is beyond the scope of this paper to assess these assertions, it is clear at the very least that increased cation availability at higher elevations would promote vine health and reduce the need for fertilization.

Although the expense of obtaining water rights in the Walla Walla Valley and its potential fruit quality benefits make dryland viticulture appealing, it has a

number of potential problems that should be considered. First, establishing a vineyard without an irrigation source may prove difficult in areas that are only marginally suitable for dryland farming since vines are more sensitive to drought in their first two or three years because their roots have not developed (Nail, 2005). Similarly, although vines become more drought tolerant after their first two growing seasons, fruit from dryland vineyards will likely have less consistent quality than irrigated vineyards due to annual variations in precipitation. This will enhance differences between different vintages, which many vintners may not find desirable. Additionally, the water stress associated with dryland viticulture may reduce the total yield of a given grapevine compared to one that is irrigated, reducing the amount of wine a dryland vineyard can produce (Reynolds and Naylor, 1994).

Because established grapevines have great longevity and can produce fruit for multiple decades, the effects of global climate change should also be considered when establishing dryland vineyards. One relatively recent study examining the role climate change has had on grape-growing regions in the western United States from 1948-2002 found that growing seasons have gotten warmer as a result of higher minimum temperatures, greater heat accumulation, and less frost (Jones, 2005). This study expects the average growing season temperature to continue to increase by 1.7 °C over the next 50 years. Similarly, projections given by the Intergovernmental Panel on Climate Change and the United Kingdom Hadley Center's HadCM2 model predict average temperatures in Washington will increase by about 2.7 °C in the winter and summer and about 2.2 °C in the spring and fall over the next 100 years (Unknown, 1997). The Panel and model also predict precipitation to increase by

about 10 % in winter over the same period. Clearly such change will have profound implications for viticulture; however, the exact effects may be difficult to anticipate. Although precipitation will likely increase, average soil moisture over the Valley may actually decrease due to increased evapotrasporation, potentially creating more water stress than grapevines can tolerate. Future work would help clarify these interactions, although climate change clearly represents a potential threat to dryland viticulture.

A number of steps can be taken to minimize and prepare for the potential problems enumerated above. The increased vulnerability to vines during their first two or three years makes it highly beneficial to have a water source available during this period. Given the likelihood that a dryland farmer would not have water rights, such a source could be obtained by purchasing water, or perhaps by capturing and storing precipitation during the non-summer months. Using water from these sources for irrigation during severe drought years would also help ensure vine survival. Selecting sites with deep soils would also increase vines' resistance to drought because of their ability to root deeply and obtain water at depth. Careful canopy management and pruning could also increase water supply by limiting growth of the vines. Finally, planting vines ~10-14 inches apart instead of the accepted 8 inches (Nail, 2005) would increase water availability to the vines by reducing the number of roots in a given volume of soil.

CONCLUSION

Precipitation in the Walla Walla Valley is strongly influenced by topography, and areas at higher elevations receive significantly more precipitation than those at lower elevations due to orographic lifting. The precipitation distribution in turn

strongly influences soil moisture and soil texture. Greater precipitation is thought to increase the weathering of silt to clay at higher elevations, which increases cation availability because of clay's high cation exchange capacity. Although soil texture varies over the Valley, it has no apparent effect on soil moisture.

This study suggests that dryland viticulture is possible at high elevations in the Valley because natural soil moisture is great enough to support grapevines. Such vineyards could potentially produce high quality fruit because their vines would benefit from mild water stress and increased nutrient availability, although a number of other factors could potentially undermine their success.

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REFERENCES

- Ashworth, J., Keyes, D., Kirk, R., and Lessard, R., 2001, Standard procedure in the hydrometer method for particle size analysis: *Communications in Soil Science and Plant Analysis*, v. 32, no. 5-6, p. 633-642.
- Bilskie, J., 2001, *Soil Water Status: Content and potential*: Campbell Scientific, Inc.
- Bohm, H. L., McNeal, B. L., and O'Connor, G. A., 2001, *Soil Chemistry*: New York, Wiley, 307 p.
- Bouyoucos, G. J., 1936, Directions for making mechanical analyses of soils by the hydrometer method: *Soil Science*, v. 42, no. 3, p. 225-229.
- , 1962, Hydrometer method improved for making particle size analysis of soils: *Agronomy Journal*, v. 54, no. 5, p. 464.
- Busacca, A. J., 1991, Loess deposits and soils of the Palouse and vicinity, *in* V. R. Baker, B. N. B., and others, ed., *Quaternary geology of the Columbia Plateau*, *in* R. B. Morrison, ed., *Quaternary nonglacial geology - conterminous U.S.*, Geological Society of America DNAG *Geology of North America*, p. 216-228.
- Busacca, A. J., and McDonald, E. V., 1994, Regional sedimentation of late Quaternary loess on the Columbia Plateau; sediment source areas and loess distribution patterns: *Bulletin - State of Washington, Department of Natural Resources, Division of Geology and Earth Resources, Report: 80*, pp.181-190.
- Carson, R. J., 2008, *General Geology of Southeastern Washington*, available: <http://www.whitman.edu/geology/LocalGeo.html>.
- Carson, R. J., and Pogue, K. R., 1996, Flood basalts and glacier floods-Roadside geology of parts of Walla Walla, Franklin, and Columbia Counties, Washington: Washington Division of Geology and Earth Resources *Information Circular*, v. 90, p. 47.
- des Gachons, C. P., Van Leeuwen, C., Tominaga, T., Soyer, J. P., Gaudillere, J. P., and Dubourdieu, D., 2005, Influence of water and nitrogen deficit on fruit ripening and aroma potential of *Vitis vinifera* L cv Sauvignon blanc in field conditions: *Journal of the Science of Food and Agriculture*, v. 85, no. 1, p. 73-85.
- Gardner, W. H., 1986, Water Content, *in* Klute, A., ed., *Methods of Soil Analysis*: Madison, WI, American Society of Agronomy, Inc., Soil Science Society of America, Inc., p. 1188.

- Gee, G. W., and Bauder, J. W., 1979, Particle size analysis by hydrometer: a simplified method for routine textural analysis and a sensitivity test of measurement parameters: *Soil Science Society of America Journal*, v. 43, no. 5, p. 1004-1007.
- Gladstones, J., 1992, *Viticulture and Environment*: Adelaide, Winetitles, 310 p.
- Gregutt, P., 2007, *Washington Wines and Wineries, the Essential Guide*: Berkeley, University of California Press, 305 p.
- Greven, M., Green, S., Neal, S., Clothier, B., Neal, M., Dryden, G., and Davidson, P., 2005, Regulated deficit irrigation (RDI) to save water and improve Sauvignon Blanc quality?: *Water Science and Technology*, v. 51, no. 1, p. 9-17.
- Hardie, W. J., and Considine, J. A., 1976, Response of grapes to water-deficit stress in particular stages of development: *American Journal of Enology and Viticulture*, v. 27, no. 2, p. 55-61.
- Harrison, E. T., Donaldson, N. C., McReary, F. R., O., N. A., and Krashevski, S., 1964, *Soil survey of Walla Walla County*, Washington: United States Department of Agriculture, Soil Conservation Service.
- Hooper, P. R., 1997, The Columbia River flood basalt province : current status *in* Mahoney, J. J., and Coffin, M. F., eds., *Large igneous provinces : continental, oceanic, and planetary flood volcanism*: Washington, DC, American Geophysical Union, p. 438.
- Jones, G. V., 2005, Climate change in the western United States Grape Growing Regions: *Acta Horticulturae*, v. 689, p. 41-60.
- Kment, P., 2005, Differentiation of Czech wines using multielement composition - A comparison with vineyard soil: *Food chemistry*, v. 91, no. 1, p. 157-165.
- Koundouras, S., Marinos, V., Gkoulioti, A., Kotseridis, Y., and van Leeuwen, C., 2006, Influence of Vineyard Location and Vine Water Status on Fruit Maturation of Nonirrigated Cv. Agiorgitiko (*Vitis vinifera* L.). Effects on Wine Phenolic and Aroma Components: *Journal of Agriculture and Food Chemistry*, v. 54, no. 14, p. 5077-5086.
- Nail, W. R., 2005, Critical issues in early vineyard establishment, New England Vegetable and Fruit Conference: Manchester, NH.
- Norman, D.K., and Roloff, J.M., 2004, *A Self-Guided Tour of the Geology of the Columbia River Gorge -- Portland Airport to Skamania Lodge*, Stevenson, Washington: Washington State Department of Natural Resources, Division of Geology and Earth Resources, Open-File Report 2004-7, 13p.

- Pardee, J. T., 1910, The glacial Lake Missoula, v. 18, no. 4, p. 376-386.
- Patterson, T., 2006, Myths of minerality: Wines and Vines.
- Perdue, A., 2005, Forces of Nature: Wine Press Northwest, v. 8, no. 3, p. 33-39.
- Pogue, K. R., 2008, Temperature variations in the Walla Walla Valley American Viticultural Area (submitted).
- Reidel, S. P.; Tolan, T. L.; Beeson, M. H., 1994, Factors that influenced the eruptive and emplacement histories of flood basalt flows—A field guide to selected vents and flows of the Columbia River Basalt Group. *In* Swanson, D. A.; Haugerud, R. A., editors, Geologic field trips in the Pacific Northwest: University of Washington Department of Geological Sciences, v. 1, p. 1B 1 - 1B 18.
- Reynolds, A. G., and Naylor, A. P., 1994, Pinot-Noir and riesling grapevines respond to water-stress duration and soil water-holding capacity: *HortScience*, v. 29, no. 12, p. 1505-1510.
- Santesteban, L. G., and Royo, J. B., 2006, Water status, leaf area and fruit load influence on berry weight and sugar accumulation of cv. 'Tempranillo' under semiarid conditions: *Scientia Horticulturae*, v. 109, no. 1, p. 60-65.
- Sivilotti, P., Bonetto, C., Paladin, M., and Peterlunger, E., 2005, Effect of soil moisture availability on Merlot: From leaf water potential to grape composition: *American Journal of Enology and Viticulture*, v. 56, no. 1, p. 9-18.
- Smith, G. A., 1993, Missoula Flood dynamics and magnitudes inferred from sedimentology of slack-water Deposits on the Columbia Plateau, Washington: *Geological Society of America Bulletin*, v. 105, no. 1, p. 77-100.
- Swanson, D. A., 1978, Bedrock geology of the northern Columbia Plateau and adjacent areas, *in* Baker, V. R., and Nummedal, D., eds., *The Channeled Scabland-A Guide to the Geomorphology of the Columbia Basin*, Washington, U.S. National Aeronautics and Space Administration, p. 37-57.
- Unknown, 1997, *Climate Change and Washington*: United States Environmental Protection Agency, EPA 230-F-97-008uu.
- , 2008, *Geographic Names Information System*, United States Geological Survey.

- Waitt, R. B., 1985, Case for periodic, colossal jokulhlaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, v. 96, no. 10, p. 1271-1286.
- Waitt, R. B. R., 1980, About forty last-glacial Lake Missoula jokulhlaups through southern Washington: Journal of Geology, v. 88, no. 6, p. 653-679.
- Weis, P. L., and Newman, W. L., 1989, The Channeled Scablands of eastern Washington-The geologic story of the Spokane Flood, Eastern Washington University Press, 24 p.

APPENDIX

Hydrometer Method Protocol Selection: A variety of opinions exist concerning which protocol is best. The Bouyoucos hydrometer method is widely used due to simplicity and brevity, requiring only two measurements: one at 40 seconds to establish the sand fraction and another at 2 hours to determine the clay fraction (Bouyoucos, 1962). Although experimentation has shown that the 40 second reading does accurately represent the sand fraction, particularly in soils with less than 20 % sand, Gee and Bauder found the Bouyoucos method frequently overestimates the clay fraction ($2\ \mu\text{m}$) by 10 wt% or more and more closely represents the fine silt fraction ($\sim 5\ \mu\text{m}$) (Gardner, 1986; Gee and Bauder, 1979). While more accurate, the Gee and Bauder method requires extensive calculation and 24 hours to complete. For this reason, a slightly modified method of Ashworth *et al* was used for this study because it is simple, requiring measurements at 40 seconds and 6 hours, but significantly improves the clay fraction accuracy over the Bouyoucos method (Ashworth et al., 2001).

Elevation (m)	Latitude	Longitude	0.5 m		1.0 m		1.5 m		2.0 m		Average		Field Saturated Hydraulic Conductivity	Martic Flux Potential	Weight %Sand	Weight %Clay	Weight %Silt
			Gravimetric Water Content	Volumetric Water Content	Average Water Content												
172	46.071	-118.609	7.7	5.6	12.7	9.9	12.7	9.9	12.7	9.9	9.0	8.9	0.00032	0.00270	45.08	4.64	50.28
175	46.049	-118.502	8.4	11.6	15.5	18.4	15.5	18.4	15.5	18.4	13.5	13.3	0.00055	0.01118	27.36	2.28	70.36
178	46.057	-118.577	4.0	4.4	4.8	10.1	4.8	10.1	4.8	10.1	5.8	5.6	0.00162	0.01349	54.88	2.20	42.92
195	46.058	-118.731	4.0	4.7	6.5	8.8	6.5	8.8	6.5	8.8	6.0	6.1	0.00029	0.00788	28.00	5.28	66.72
205	46.111	-118.467	12.6	12.8	12.6	14.4	12.6	14.4	14.4	13.1	13.1	10.8			22.16	6.20	71.64
244	46.010	-118.375	6.7	6.7	8.5	9.7	8.5	9.7	9.7	7.9	7.9	7.5	0.00031	0.00354	22.88	5.84	71.28
250	45.995	-118.390	5.1	5.3	5.6	6.7	5.6	6.7	6.7	5.7	5.7	5.6	0.00075	0.00271	18.60	9.84	71.56
253	46.003	-118.369	6.7	6.0	6.9	8.6	6.9	8.6	8.6	7.1	7.1	6.9			18.16	8.20	73.64
267	45.948	-118.451	4.9	7.7	5.3	4.3	5.3	4.3	4.3	5.6	5.6	7.4	0.00081	0.00766	21.60	5.84	72.56
267	46.149	-118.355	6.6	6.6	8.0	7.8	8.0	7.8	7.8	7.3	7.3	6.8	0.00136	0.01135	21.00	8.64	70.28
267	46.100	-118.378	13.9	15.8	13.6	10.6	13.6	10.6	10.6	13.5	13.5	13.7			10.00	9.56	80.44
273	46.002	-118.345	5.9	6.7	8.0	10.7	8.0	10.7	10.7	7.8	7.8	8.2			19.28	10.00	70.72
342	46.054	-118.290	6.3	8.3	9.3	10.5	9.3	10.5	10.5	8.6	8.6	8.2	0.00034	0.01329	18.36	9.64	72.00
357	45.934	-118.428	9.4	8.7	8.9	8.8	8.9	8.8	8.8	9.0	9.0	11.2	0.00042	0.00350	22.88	8.84	68.28
369	45.933	-118.329	7.6	13.0						10.3	10.3	12.8	0.00019	0.00158	20.80	7.20	72.00
384	45.930	-118.331	8.2	10.2						9.2	9.2	11.4	0.00019	0.00158	12.88	10.84	76.28
405	46.003	-118.263	7.9	8.7	10.8	13.6	10.8	13.6	13.6	10.2	10.2	9.4	0.00103	0.00860	16.88	15.20	67.92
408	46.053	-118.251	6.8	6.7	10.9	12.1	10.9	12.1	12.1	9.1	9.1	8.7	0.00052	0.00434	17.08	16.64	66.28
420	46.175	-118.203	6.4	8.8	13.5	15.0	13.5	15.0	15.0	10.9	10.9	10.6			12.16	15.36	72.48
485	46.093	-118.201	7.9	8.5	11.3	12.6	11.3	12.6	12.6	10.1	10.1	9.1	0.00023	0.00366	10.16	14.20	75.64
516	45.989	-118.230	15.5	15.3	15.7	18.3	15.7	18.3	18.3	16.2	16.2	17.6	0.00035	0.00027	13.36	20.20	66.44
614	46.034	-118.151	9.7	16.7	19.1	18.9	19.1	18.9	18.9	16.1	16.1	18.5	0.00029	0.00437	8.88	24.56	66.56

Appendix Table 1. Report of various soil characteristics for the 21 sample sites sorted by elevation

Elevation (m)	pH	P	K	Ca	Mg	Na	Cu	Fe	Zn	Mn
175	7.5	93	102.4	841	221	12	0.4	2.4	0.1	1.1
195	7.7	12	416.1	877	263	24	1.5	3.5	0.1	3.3
267	8	4	280.0	792	550	2	1.1	5.8	0.1	2.2
342	7	10	166.7	1048	334	18	1.3	13.8	0.1	6.6
357	7.3	18	319.4	1020	307	6	1.0	5.5	0.2	3.9
420	6.9	12	166.0	1036	396	0	1.6	18.9	0.1	11.5
614	6	54	566.3	1178	197	2	1.5	81.6	1.1	38.1

Appendix Table 2. Soil pH and available cations. P, K, Ca, and Mg are reported in lbs./Acre; Na, Cu, Fe, Zn, and Mn are reported in ppm.