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Applying GIS to Determine Suitability for Viticulture in Washington State

Contents

1. Introduction

1.1 Background

Wine is big business in today's United States. In 2016 alone, wine sales grew 10.7% in the United States, to a total sales value of $16.42 billion. Wine grapes cover 419,000 hectares of land in the United States, composed of 8,702 distinct wineries. On average, wine grapes gross between $3,000 and $6,000 per acre, out competing almost all other agricultural products, with the exception of tobacco (Statista). It seems inevitable that as the industry continues to grow, so too will the number of wine enthusiasts looking to plant their own vines.

All of this is not to say that developing a vineyard is not a risky proposition. Weather, pests, natural disaster, and soil issues can all render even a well-established vineyard barren. Thus, it is important that those looking to establish a new vineyard understand fully the variables affecting the health and productivity of their vineyard.

1.2 Objectives

This paper aims to amass the key topographic, climatic, and soil variables, to demonstrate how they affect the suitability for viticulture on a given plot. The paper analyzes two vineyards that are already well-established, yet unique in climate, topography, and soil. GIS tools are used to collect data on the relevant variables, and the data and their implications are discussed in detail. Suitability analyses are completed for each vineyard using the existing weight-rating score model, and the results are discussed relative to each vineyard. Limitations of the study, and potential future work are then identified.

1.3 Vineyard Selection

1.3.1 Bainbridge Vineyards

Bainbridge Vineyards are located on Bainbridge Island, WA, on the west coast of the Puget Sound. Their GPS coordinates are (47.68 N, 122.53 W). The vineyard is a small one, covering a total of seven acres. The main grape varietals grown here include Pinot Gris, Pinot Noir, and Muller-Thurgau. The first vintage was grown at Bainbridge Vineyards in 1982, and they now produce on average 1,200 cases of wine per year. Interestingly, Bainbridge Vineyards is the only vineyard on Bainbridge Island that grows and produces its own wine. One of the founders, Gerard Bentryn, was instrumental in the certification of the Puget Sound American Viticultural Area (AVA) appellation in 1995 (Bainbridge Vineyards).

Figure 1: Bainbridge Vineyards Orientation View

Figure 2: Bainbridge Vineyards Close-Up

The Puget Sound AVA is characterized by dry, warm summers, and high quantities of precipitation from November through April. This appellation, however, only comprises a tiny fraction of Washington's total viniferous plantings with less than 200 total acres planted in 2011 (Washington State Wine).

1.3.2 Red Mountain Estate Vineyards

Red Mountain Estate Vineyards are located in Benton City, WA, which is within the renowned Yakima Valley. The vineyards' GPS coordinates are (46.28 N, 119.45 W). The vineyard is moderately sized, covering a total of approximately 32.45 acres. The primary grape varietals grown here are Cabernet Sauvignon, Merlot, and Cabernet Franc. Red Mountain Estate, and the whole of the Red Mountain Estate AVA is characterized by southwest slopes. The AVA has a desert climate, receiving on average less than eight inches of rain annually. The wines produced at Red Mountain Estate are typically higher alcohol, and have superb concentration and depth due to an extremely dry growing and harvesting season (Red Mountain AVA Alliance) (EveryVine).

Figure 3: Red Mountain Estate Orientation View

Figure 4: Red Mountain Estate Close-Up

2. Data Collection

2.1 Topographic Considerations

Topography plays a substantial role in grape production. Gladstones suggested that the best vineyards minimize their diurnal temperature fluctuation. They do so by planting on slopes with excellent drainage, and/or directly facing the sun during part of the day. This work suggests that slope, aspect, and heat load index are the key topographic parameters characterizing suitability for viticulture (Gladstones). We explore the aforementioned variables for our vineyards of interest below.

2.1.1 Slope

Wolf and Boyer suggest that steep slopes induce better surface and internal water drainage. However, excessively steep slopes become problematic due to increased incident of soil erosion; slopes in excess of 15% cause roll-over risk for towed equipment (Boyer and Wolf).

The data shown below in Table 1 were derived from NED30m elevation data in ArcGIS Pro.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Slope	% Drop	10.12	7.27	3.84	9.43

Table 1: Average slope values for Bainbridge and RME vineyards and block groups

The above data show the average slope value for Bainbridge Vineyards is roughly 2.5 times greater than that of Red Mountain Estates Vineyards. These data suggest that relative to Red Mountain Estate, Bainbridge would drain more effectively, while still being below the threshold for erosion and roll-over risk. Please see Appendix 4.1.1 for a geospatial representation of slope values.

2.1.2 Aspect

Aspect refers to the orientation of a slope. A value of zero degrees represents true north, and a value of 180 degrees represents true south. The value of aspect is that it allows for calculations regarding total incident solar energy, discussed in further detail in section 2.1.4. For now, it is sufficient to state that it is widely accepted in industry that southern-facing aspects tend to receive more intense solar radiation than do northern-facing aspects, holding all other factors constant. The below data in Table 2 were derived from NED30m elevation data in ArcGIS Pro.

Category	Units	Bainbridge Vineyards Average	Bainbridge Vineyards Block Group Average	Red Mountain Estate Vineyards Average	Red Mountain Estate Block Group Average
Aspect	Degrees	270.5 (W)	168.31 (SE)	234.107 (SW)	187.5 (S-SW)

Table 2: Average aspects values for Bainbridge and RME vineyards and block groups

The above data show that Bainbridge Vineyards has a nearly due West aspect, on average, whereas Red Mountain Estate Vineyards has a largely southwest aspect. These data suggest that holding all other things equal, we would expect Red Mountain Estate to receive more intense solar radiation on average than would Bainbridge. Please see Appendix 4.1.2 for a geospatial representation of the aspect data.

2.1.3 Elevation

Wolf and Boyer have shown that large variations in elevation can lead to development of “thermal belts” that can affect grape productivity both between and within vineyards (Boyer and Wolf). However, the data below in Table 3 show there is relatively little elevation differential between the two sites. It is my stance that we capture the elevation effects on vineyard productivity in our other metrics; thus, for analysis sake, elevation is ignored. Regardless, the geospatial elevation data can be found in Appendix 4.1.3.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Elevation	Meters	74.39	53.66	216.05	212.15

Table 3: Average elevation values for Bainbridge and RME vineyards and block groups

2.1.4 Heat Load Index

McCune and Keon developed a model for transforming elevation, slope, and aspect, into a metric for potential direct incident radiation: the heat load index. This index shifts the axis of symmetry for aspect from zero degrees being due North, to zero degrees being due Northeast. Thus, zero degrees (Northeast) represent the coolest slopes, while 180 degrees (Southwest) represent the warmest slopes. Utilizing this so-called "folded aspect" we are able to calculate a potential direct incident radiation index from elevation data, with units of $MJ*cm^{-2}*yr^{-1}$ (McCune and Keon). The below Table 4 shows the heat load index values for our vineyards of interest.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Heat Load Index	$MJ*cm^{-2}*yr^{-1}$	0.736	0.667	0.714	0.696

Table 4: Average heat load index values for Bainbridge and RME vineyards and block groups

The above analysis suggests Bainbridge Vineyards is predicted to receive slightly more direct incident solar radiation than is Red Mountain Estate Vineyards. However, one must be cautious drawing conclusions from these data alone, as the model does not account for cloud cover, differences in the atmospheric coefficient, and shading from adjacent topography (McCune and Keon). Please see Appendix 4.1.4 for a geospatial representation of the heat load index data.

2.2 Climate Considerations

There is a saying in viticulture communities that "climate is constant, but weather is volatile." For this reason, our analysis explores climate and not weather patterns. Climatic parameters of particular interest are: frost, temperature, and precipitation. Each variable greatly influences vineyard productivity, explored in detail below.

2.2.1 Frost-Free Period

The USDA defines the frost-free period as the expected number of days between the last freezing temperature in spring and the first freezing temperature in fall. The number of days is based on the probability that the values for the standard period will be exceeded in five years out of ten. If this frost-free period is not sufficiently long, grapes simply will not ripen. In addition, mid-season frosts can damage vines as well as fruit, causing long-term loss of productivity. Wolf and Miller demonstrated that for a diverse set of grape varietals in Virginia, the average duration from budbreak to fruit harvest ranged from 144 to 179 days (Wolf and Miller). Thus, a number of frost-free days less than 144 will almost certainly be problematic for viticulture. The below data shown in Table 5 were calculated in ArcGIS Pro from ESRI's compilation of SSURGO data produced by the Natural Resources Conservation Service (NRCS).

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Frost-Free Period	Days	184.8	185.95	172.57	167.54

Table 5: Average frost free period values for Bainbridge and RME vineyards and block groups

The above data show that Bainbridge Vineyards has approximately twelve more frost-free days than does Red Mountain Estate Vineyards, on average. However, it is of note that both values are relatively high in comparison to the time to harvest data collected by Wolf and Miller in Virginia. Bainbridge, being in the Puget Sound region, likely benefits from relatively heavy cloud cover and thus fewer winter temperature extremes, whereas Red Mountain Estate likely sees larger daily temperature diurnals due to its exposed nature. Please see Appendix 4.2.1 for a geospatial representation of the above data.

2.2.2 Growing-Degree Days

Growing-degree days measures the availability of warm temperatures for crop ripening. Mathematically, growing-degree days (GDD) are defined as follows:

$$GDD = \sum_{all\ days\ April\ 1\ to\ Oct\ 31} \left[\frac{(T_{max,day} - T_{min,day})}{2} - 50\right]$$

This definition uses 50 degrees Fahrenheit as a reference temperature because respiration and photosynthesis essentially stop below that temperature. The below Table 6 represents the long-term average accumulated GDD for each vineyard's respective AVA (Washington State University).

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Growing-Degree Days	Days	No data	1600	No data	3172

Table 6: Long-term average growing degree days values for Bainbridge and RME block groups

As demonstrated above, Bainbridge Vineyards has approximately half the accumulated growing-degree days as does Red Mountain Estate Vineyards, on average. These data are very important as higher values of accumulated GDD increase the likelihood of fruit maturation. The above data are somewhat surprising, given the relatively high number of frost-free days calculated for Bainbridge Vineyards. However, it is likely that the same cloud cover that keeps temperatures mild in the winter similarly buffers temperatures in the growing season, decreasing the accumulated GDD. Please see Appendix 4.2.2 for a visual representation of accumulated GDD for each Washington AVA.

2.2.3 Annual Precipitation

Like any crop, precipitation is vital to grape productivity. However, the timing of the aforementioned rainfall is absolutely critical with respect to viticulture. Rain close to harvest time can lead to mold and fungus growth, root rot, and will produce a dilute, weak wine. Early season rains combined with high quantities of solar radiation allow grapes to mature quickly.

Rainfall varies hugely season-to-season and year-to-year, so this paper does not look at short-term rainfall data, but rather average annual precipitation data. The values displayed in the below Table 7 represent average annual rainfall in inches for the period of January 1971 through December 2009. These data were collected by the U.S. Geological Survey (USGS) compiled by ESRI, and analyzed in ArcGIS Pro.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Annual Precipitation	Inches	41.19	40.76	8.73	8.57

Table 7: Average annual rainfall values for Bainbridge and RME vineyards and block groups

The above data show a huge discrepancy in average annual precipitation between Bainbridge Vineyards and Red Mountain Estate Vineyards. Bainbridge receives roughly five times the rainfall than does Red Mountain Estate on average. This information allows us to make a few conclusions. First, Red Mountain Estate likely requires irrigation in the growing season. In contrast, Bainbridge Vineyards likely does not require irrigation, but likely does make efforts to reduce soil saturation and flooding in the vineyard. Please see Appendix 4.2.3 for a geospatial representation of the precipitation data

2.3 Soil Considerations

Soil is so vastly important to viticulture that entire books have been written on it. There are innumerable soil variables that may or may not have a profound effect on vineyard productivity and wine quality, so this paper focuses on three main variables: drainage, pH, and organic matter content. Another reason for limiting the number of soil variables analyzed is, as

Wolf and Boyer suggest, to avoid biasing the suitability analysis too heavily toward soil considerations (Boyer and Wolf).

2.3.1 Soil Drainage

Soil drainage is of paramount importance for viticulture. As previously mentioned, waterlogged soils lead to mold and fungus growth, and root rot, which makes well-drained soils desirable. Similarly, well-drained soils make for drought-resistant vines, as the vines are forced to develop deep root systems. Conversely, saturated soils make for shallow root systems, and vines that are at high drought risk.

The Natural Resources Conservation Service (NRCS) classifies soil drainage class from 1-8, with 1 being subaqueous, and 8 being excessively drained. ESRI has compiled a layer of soil drainage data from the 2014 version of the SSURGO data. Those data were analyzed in ArcGIS Pro for our vineyards of interest and summarized below in Table 8.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Soil Drainage	n/a	5 (Moderately well-drained)	4.83 (Moderately well-drained)	6.62 (Well-drained/somewhat excessively drained)	6.17 (Well drained/somewhat excessively drained)

Table 8: Average soil drainage values for Bainbridge and RME vineyards and block groups

The above data show that both Bainbridge and Red Mountain Estate Vineyards are relatively well-drained. It is logical that the value for Bainbridge Vineyards is somewhat lower than that for Red Mountain Estate as Bainbridge receives five times the annual precipitation than does Red Mountain Estate, as outlined above. Despite the higher precipitation, the soil still manages to transport the water away from the surface layer relatively well. Thus we can conclude that both vineyards likely have vines that have low mold, fungus, and root rot risk, and are relatively drought resistant. Please see Appendix 4.3.1 for a geospatial representation of the soil drainage data.

2.3.2 Soil pH

Soil pH provides information on the acidity or alkalinity of a soil. Like most crops, grape vines flourish in a slightly acidic or neutral soil, within a pH range of roughly 5.5-7.0. More alkaline soils can create nutritional problems, while more acidic soils can increase disease incidence (Chen).

The NRCS Web Soil Survey data were used to evaluate soil pH for both vineyards of interest. The results are summarized below in Table 9.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Soil pH	S.U.	5.5	No data	7.45	No data

Table 9: Average soil pH values for Bainbridge and RME vineyards

This analysis shows that both Bainbridge Vineyards and Red Mountain Estate Vineyards have soil pH values that fall relatively close to the margins of the ideal soil pH range. However, soil pH is something that is relatively easily adjusted in-situ, and thus fringe values should not significantly impact grapevine productivity. Please see Appendix 4.3.2 for the complete NRCS Web Soil Survey results.

2.3.3 Soil Organic Matter

Kononova reports that soil organic matter is relevant to soil fertility for a number of reasons. "Besides being a source of nutrients for the plant, the most important factor in structure formation, organic matter has also a fundamental effect on the physical properties of the soil…and determines to a large degree the physic-chemical properties as the exchange capacity and buffer capacity" (Kononova). Thus, in general, the higher the value of organic matter, the more structure a soil has and the more nutrients it has available to provide to the vines.

The NRCS Web Soil Survey data were used to evaluate soil organic matter for the vineyards of interest, and the results are summarized below in Table 10.

Category	**Units**	**Bainbridge Vineyards Average**	**Bainbridge Vineyards Block Group Average**	**Red Mountain Estate Vineyards Average**	**Red Mountain Estate Block Group Average**
Soil Organic Matter	%	7.72	No data	0.92	No data

Table 10: Average soil organic matter values for Bainbridge and RME vineyards

The above data show that Bainbridge Vineyards has substantially more soil organic matter content than does Red Mountain Estate Vineyards. This result supports the previous results on soil drainage: despite the high levels of precipitation at Bainbridge Vineyards, the soil is able to maintain its status as moderately-well drained. This is likely attributed to the high organic matter content that gives the soil plenty of structure through which to move water. Like soil pH, soil organic matter can be supplemented in-situ by the addition of various fertilizers, as is likely the case at Red Mountain Estate. Please see Appendix 4.3.3 for the complete Web Soil Survey Results.

3. Suitability Analysis

The aim of this suitability analysis is to synthesize all of the above variables into a single, quantitative output that tells the user something about the suitability of a location for viticulture. The following sections attempt to outline the methodology to perform this synthesis, discuss the results in the context of the vineyards of interest, and identify shortcomings of the applied methods.

3.1 Methodology

Following the work of Ting Chen at the University of Nebraska, I chose to apply the weight-rating score model to the data as per for the formula below.

$$Score = \sum_{i=0}^{n} W_i * V_j$$

Where W_i = the weight of the i^{th} variable and V_j = the score of the j^{th} class in the i^{th} variable.

This approach was applied by Boyer in Virginia, Fiola in Maryland, Gregory in Oregon, and Day in Pennsylvania, and is thus the standard method for evaluating suitability for viticulture.

3.2 Variables and Weights

The first challenge in applying the weight-rating score model is assigning weights to each variable. Again, following Chen's methods, the below Table 11 shows the raw weight of each variable, and the normalized weight as a percentage of the total.

Variable	$\mathbf{W_{scale}}$	$\mathbf{W_{normalized}}$
Slope	6	9.83%
Aspect	5	8.2%
Heat Load Index	7	11.47%
Frost Free Period	9	14.75%
Growing-Degree Days	8	13.11%
Annual Precipitation	8	13.11%
Soil Drainage	10	16.4%
Soil pH	4	6.55%
Soil Organic Matter	4	6.55%
SUM	**61**	**100%**

Table 11: Variables, raw weight, and normalized weight for suitability analysis calculations

3.3 Score

The next step in developing the model is creating a scoring criteria for each variable. This has been carried out in numerous other studies, and those results are reported here. For variables of interest specific to this study, I created my own scoring criteria. The results of this effort are summarized below.

3.3.1 Slope

The rating system for slope was developed by Chen as follows:

- 0% = 3 points
- 1% - 3% = 5 points
- 3% - 10% = 10 points
- 10 – 15% = 7 points
- >15% = 1 point

3.3.2 Aspect

The rating system for aspect was developed by Chen as follows:

- Flat = 5 points
- Southwestern = 7 points
- Southern = 9 points
- Western = 5 points
- Northwestern = 2 points
- Southeastern = 10 points
- Northern = 2 points
- Eastern = 7 points
- Northeastern = 4 points

3.3.3 Elevation

No score was given for elevation, as it was determined insignificant for this study

3.3.4 Heat Load Index

I developed the following scoring system for heat load index:

- 0.03 – 0.244 = 1 point
- 0.244 – 0.458 = 3 points
- 0.458 – 0.672 = 5 points

- 0.672 – 0.886 = 7 points
- 0.886 – 1.1 = 9 points

3.3.5 Frost-Free Period

Chen developed the following scoring system for frost-free days:

- <150 days = 0 points
- 150 to 165 days = 5 points
- 165 to 180 days = 7 points
- >180 days = 10 points

3.3.6 Growing-Degree Days

Chen developed the following scoring system for growing-degree days:

- 2018 – 2425 GDDs = 3 points
- 2425 – 2832 GDDs = 5 points
- 2832 – 3238 GDDs = 7 points
- 3238 – 3645 GDDs = 9 points
- 3645 GDDs – 4052 GDDs = 10 points

3.3.7 Annual Precipitation

I developed the following scoring system for annual precipitation:

- >50 inches = 0 points
- 40 – 50 inches = 2 points
- 30 – 40 inches = 4 points
- 20 – 30 inches = 6 points
- 10 – 20 inches = 8 points
- 5 – 10 inches = 9 points

- 0 – 5 inches = 3 points

3.3.8 Soil Drainage

Chen developed the scoring system for soil drainage as follows:

- Poorly drained = 0 points
- Somewhat poorly drained = 3 points
- Moderately well drained = 8 points
- Well drained = 10 points
- Somewhat excessively drained = 6 points
- Excessively drained = 5 points

3.3.9 Soil pH

Chen developed the scoring system for soil drainage as follows:

- <5 = 0 points
- 5-7 = 10 pints
- >7 = 3 points

3.3.10 Soil Organic Matter

Chen developed the scoring system for soil organic matter as follows:

- <1% = 3 points
- 1% - 3% = 10 points
- 3% - 4% = 3 points
- >4% = 0 points

With these scoring criteria established, each vineyard was scored on each variable, and the results are summarized in the below Table 12. These results are displayed graphically in Figure 5, and the total vineyard weighted score out of 10 is shown in Table 13.

Variable	**Bainbridge Vineyards Value**	**Bainbridge Vineyards Score**	**RME Vineyards Value**	**RME Vineyards Score**
Slope	10.12	8	3.84	5
Aspect	270.5 (W)	5	234.11 (SW)	7
Heat Load Index	0.736	7	0.714	7
Frost Free Period	184.8	10	172.57	8
Growing-Degree Days	1600	1	3172	7
Annual Precipitation	41.19	2	8.57	9
Soil Drainage	5	10	6.62	8
Soil pH	5.5	10	7.45	10
Soil Organic Matter	7.72	0	0.92	5

Table 12: Variables and corresponding value and score for Bainbridge and Red Mountain Estate Vineyards

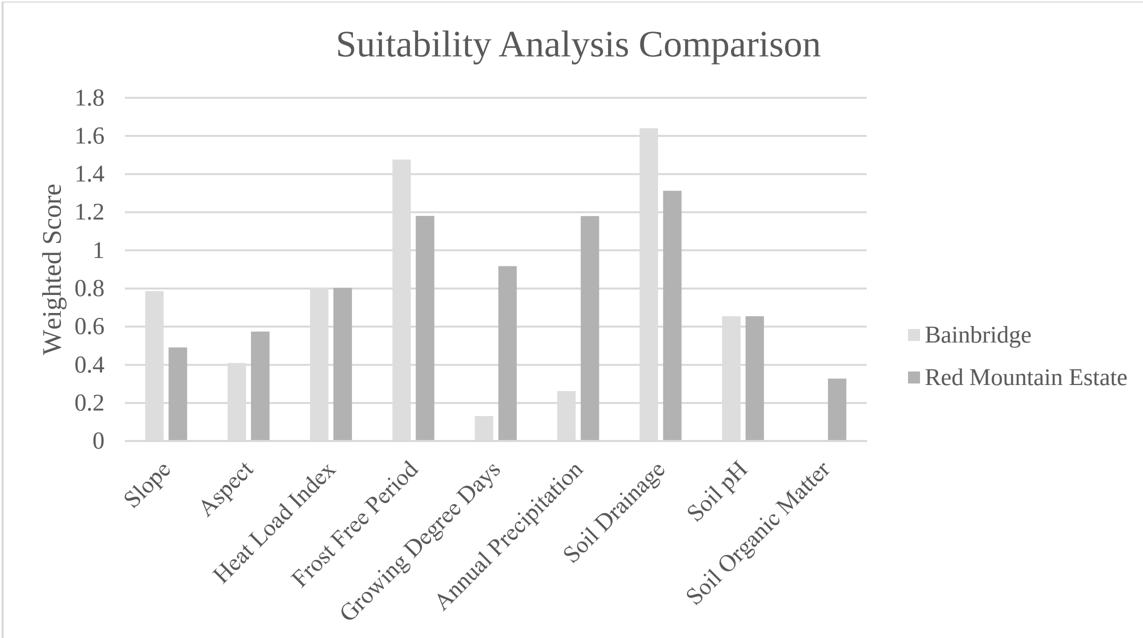

Figure 5: Weighted score for each variable of interest for Bainbridge and RME Vineyards

Location	Total Score
Bainbridge Vineyards	6.1636
Red Mountain Estate Vineyards	7.4413

Table 13: Total score for each vineyard based on the weight-rating score model

3.4 Discussion

The above Table 13 shows that the weight-rating score model predicts Red Mountain Estate Vineyards is 17.2% more suitable for viticulture than is Bainbridge Vineyards. The most severe discrepancies in weighted scores occurred in growing-degree days, annual precipitation, and soil organic matter, accounting for a majority of the score differential.

These results are reasonable given the land use data for the area surrounding Bainbridge Vineyards and Red Mountain Estate Vineyards, respectively. Those data are shown in Appendix 4.4. It is immediately apparent that Red Mountain Estate Vineyards is in a location where agriculture dominates, whereas the entirety of the Bainbridge Vineyards census block group does not even have agriculture listed as a land cover class. Thus, we would expect that the conditions for viticulture would be more favorable in Red Mountain Estate than in Bainbridge. Our analysis confirms this expectation.

This is not to say, however, that growing grapes is ideal at Red Mountain Estate and impossible at Bainbridge Vineyards. The differences in topographic, climatic, and soil considerations manifest themselves in various ways in the wines produced at each vineyard.

At Bainbridge Vineyards, the producers have chosen to grow mainly Pinot Gris, Muller Thurgau, and Pinot Noir grapes. As the below Figure 6 shows, these grapes are typically harvested early in the season, when, at a vineyard like Bainbridge, rain is the least likely, and direct solar radiation is most likely.

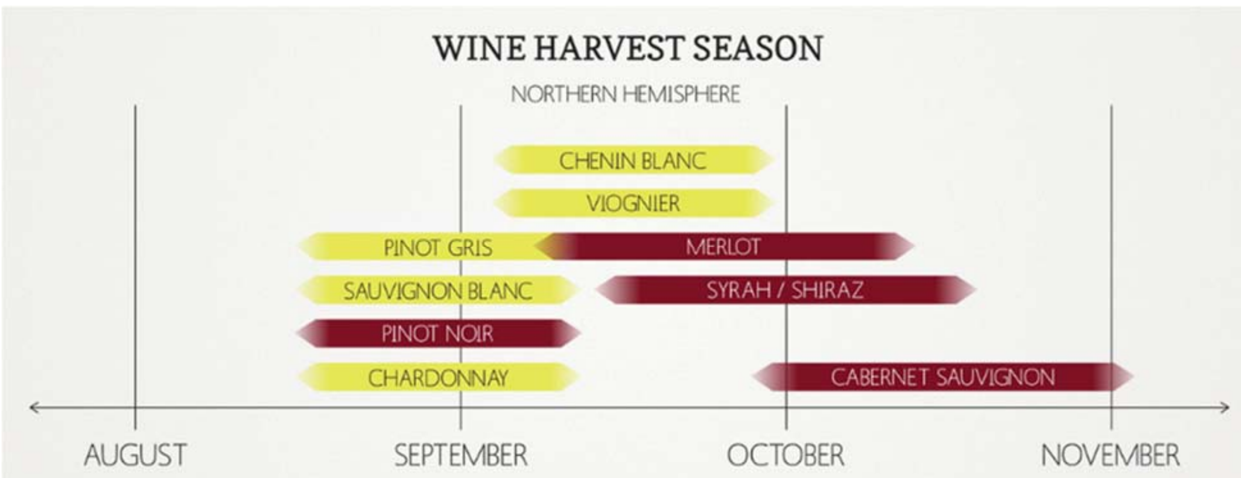

Figure 6: Harvest season for various grape varietals (Wine Folly)

Conversely, Red Mountain Estate Vineyards grows Cabernet Sauvignon, Merlot, and Cabernet Franc, all of which are late-harvested grapes. The lower precipitation risk and high number of growing-degree days in the end of September through October allow Red Mountain Estate to reliably grow and harvest these grape varietals. These wines are consequently much sought after due to their highly concentrated and robust flavors.

Along the same lines, three of the ten wines produced at Bainbridge Vineyards are blends of more than one grape varietal. This allows them to create a salable product despite potential low yields due to the non-ideality of their vineyard location. Red Mountain Estate Vineyards, on the other hand, produces no blends, due to relatively consistent yields in its more ideal vineyard location.

All of this is to say that a vineyard's productivity is inextricably tied to its topography, climate, and soil. This study demonstrates that for these input variables, Red Mountain Estate Vineyards is 17.2% more suitable for viticulture than is Bainbridge Vineyards. This fact does not preclude Bainbridge Vineyards from making wine, however. The general conclusion from this study is that a vineyard with a higher weight-rated score (i.e. closer to 10) can expect less volatility in their yields from year to year and have more flexibility with respect to grape varietals selection. Lower weight-rated scores will force producers to consider carefully the correct grape varietal to grow based on the specific characteristics of their plot's terroir. These conclusions are shown definitively in the wines produced at Bainbridge Vineyards and Red Mountain Estate Vineyards, respectively. GIS tools were instrumental in informing these conclusions.

3.5 Further Work

Substantial improvement of the weight-rating score model is possible. For one, this study simply applied the accepted weights and values for general viticulture to the vineyard data. A better model would have a complete set of weights and values for each grape varietal, so that the analysis could output the suitability of a given vineyard to produce a specific varietal. Similarly, an automated GIS function that takes a user-defined polygon as an input and outputs the weight-rated scores for each grape varietal allowing the user to quickly and clearly see the “ideal” grape varietal for their plot would be an ultimate goal.

As is the case with many models, identifying additional key parameters to suitability for viticulture would serve to improve the model so long as the impacts of the parameter on viticulture were well described. As experiential knowledge is gained, I suspect that these variables will be identified and applied.

Finally, transforming the output from the weight-rating score model from a dimensionless quantity from 0-10 into something more tangibly useful, for example, predicted annual percent yield would allow users of the model to make increasingly informed decisions prior to setting down roots.

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4. Appendix

4.1 Topographic Considerations

4.1.1 Slope

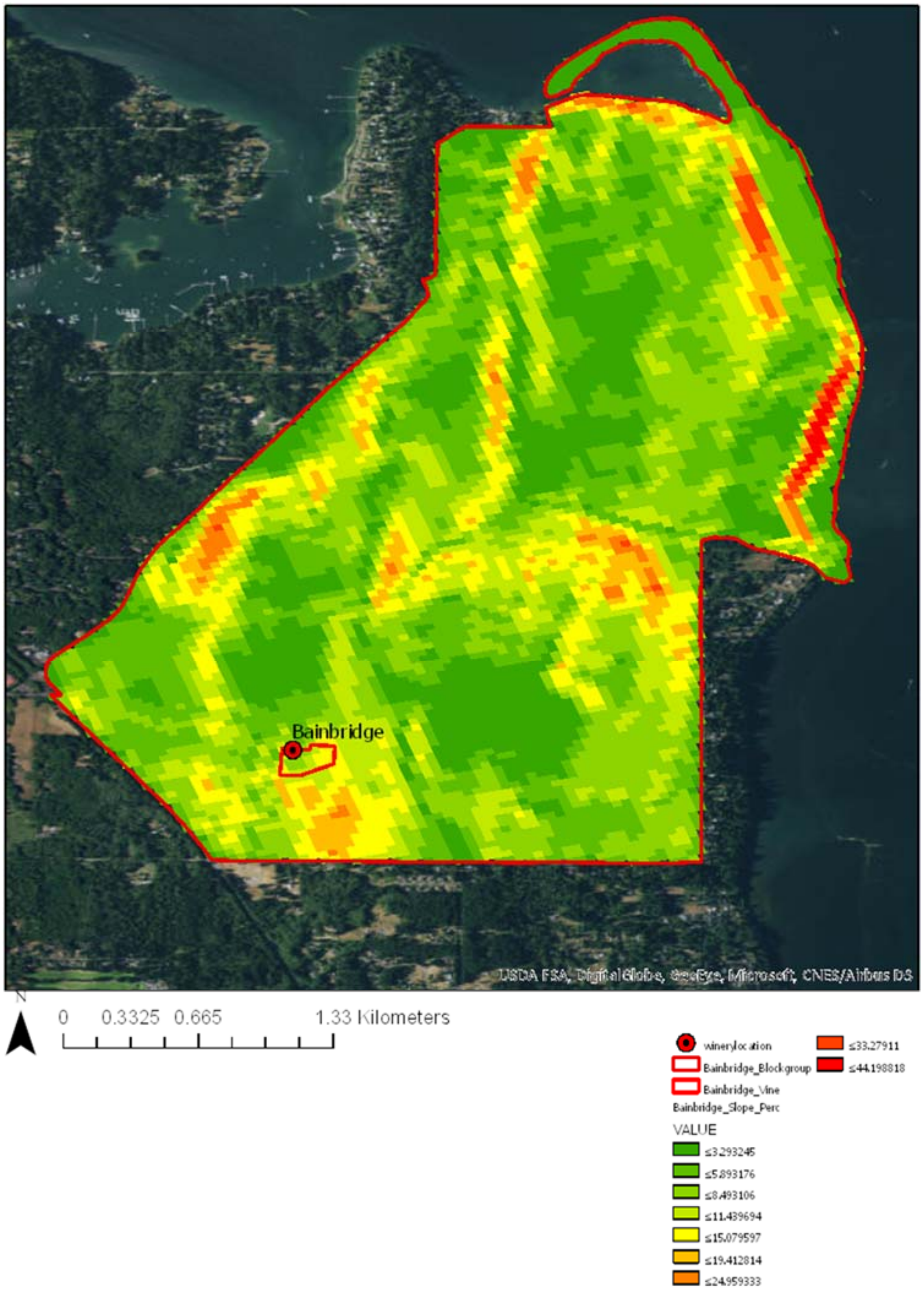


Figure 7: Bainbridge Vineyards Slope Percent

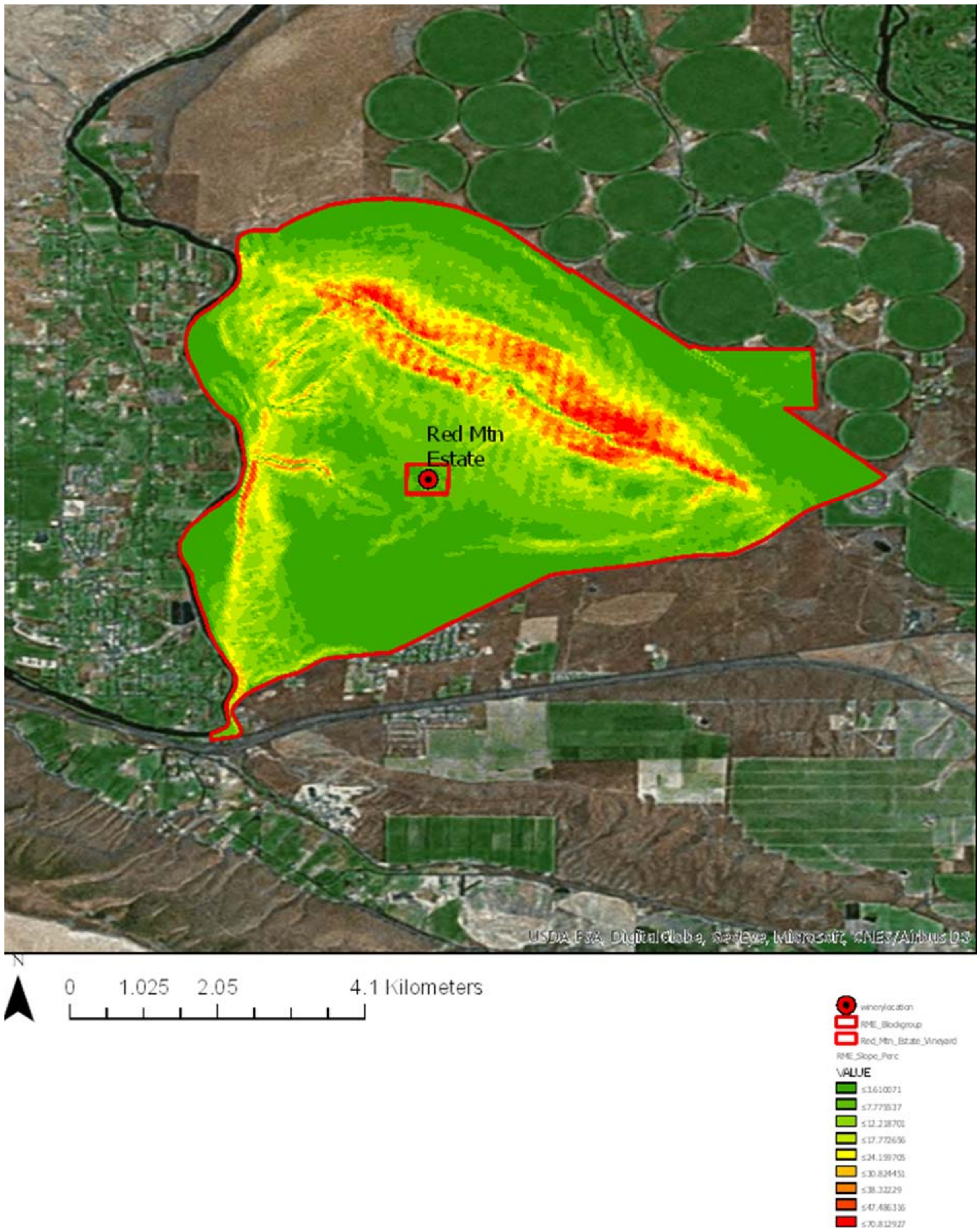


Figure 8: RME Vineyards Slope Percent

4.1.2 Aspect

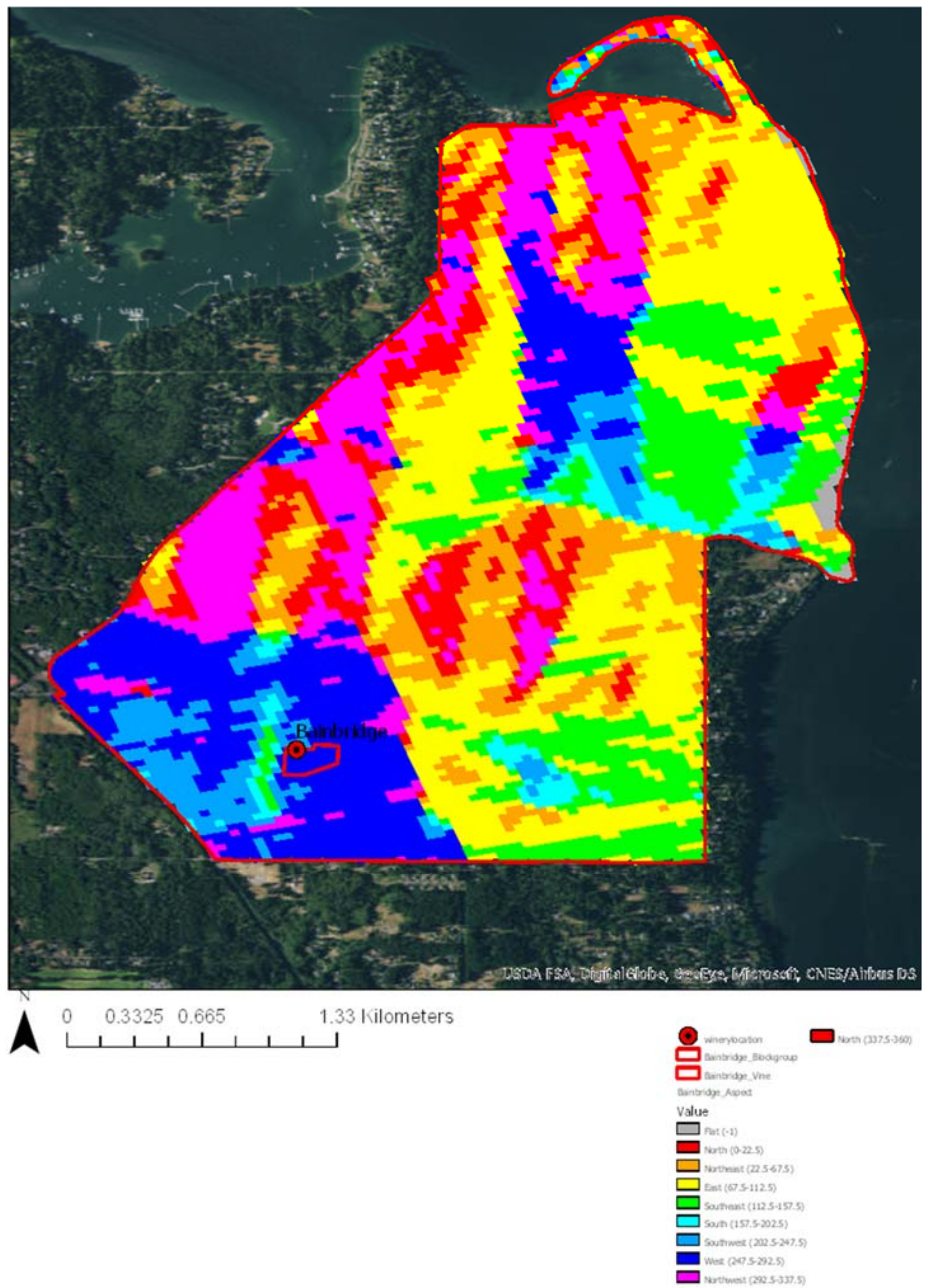


Figure 9: Bainbridge Vineyards Aspect

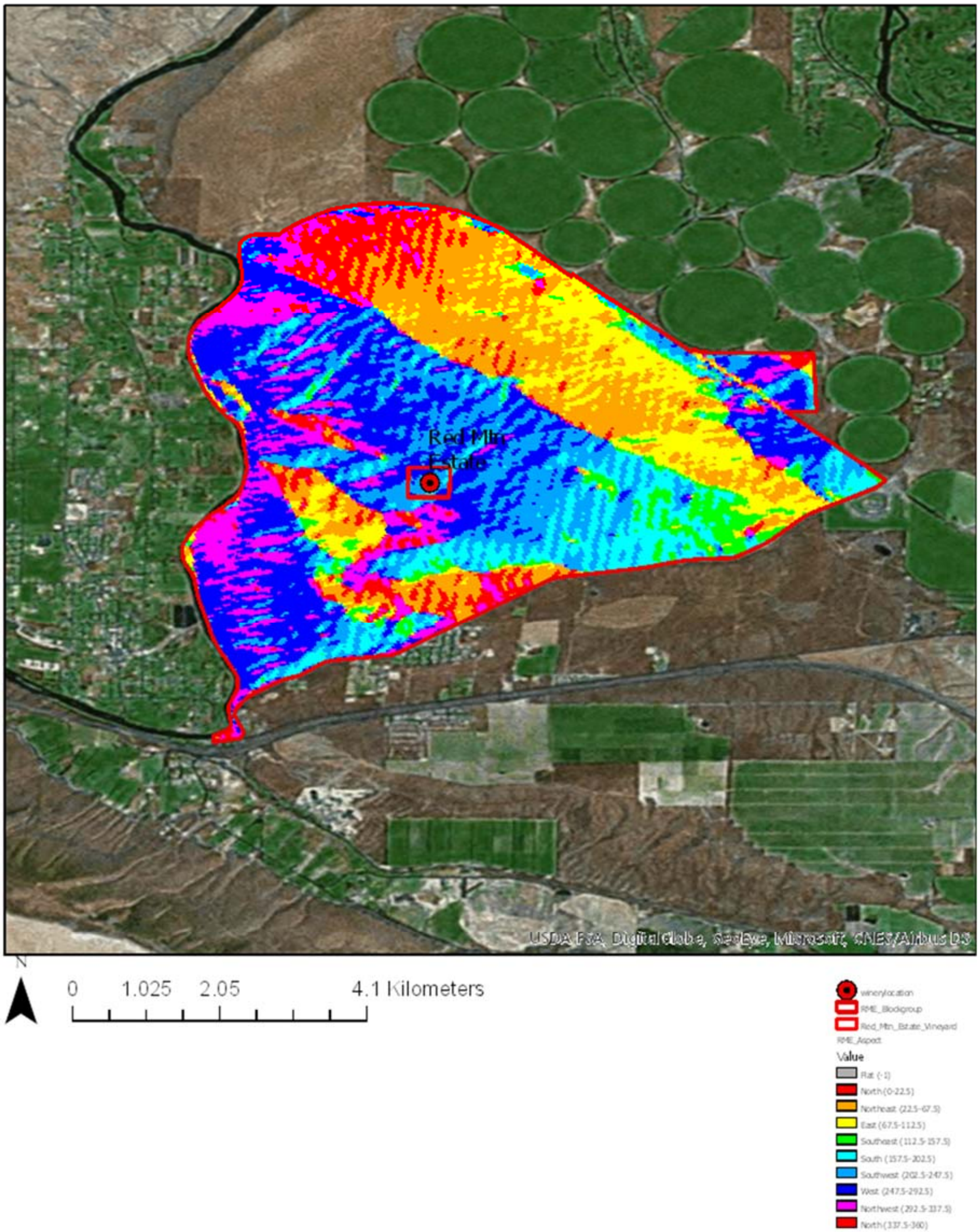


Figure 10: RME Vineyards Aspect

4.1.3 Elevation

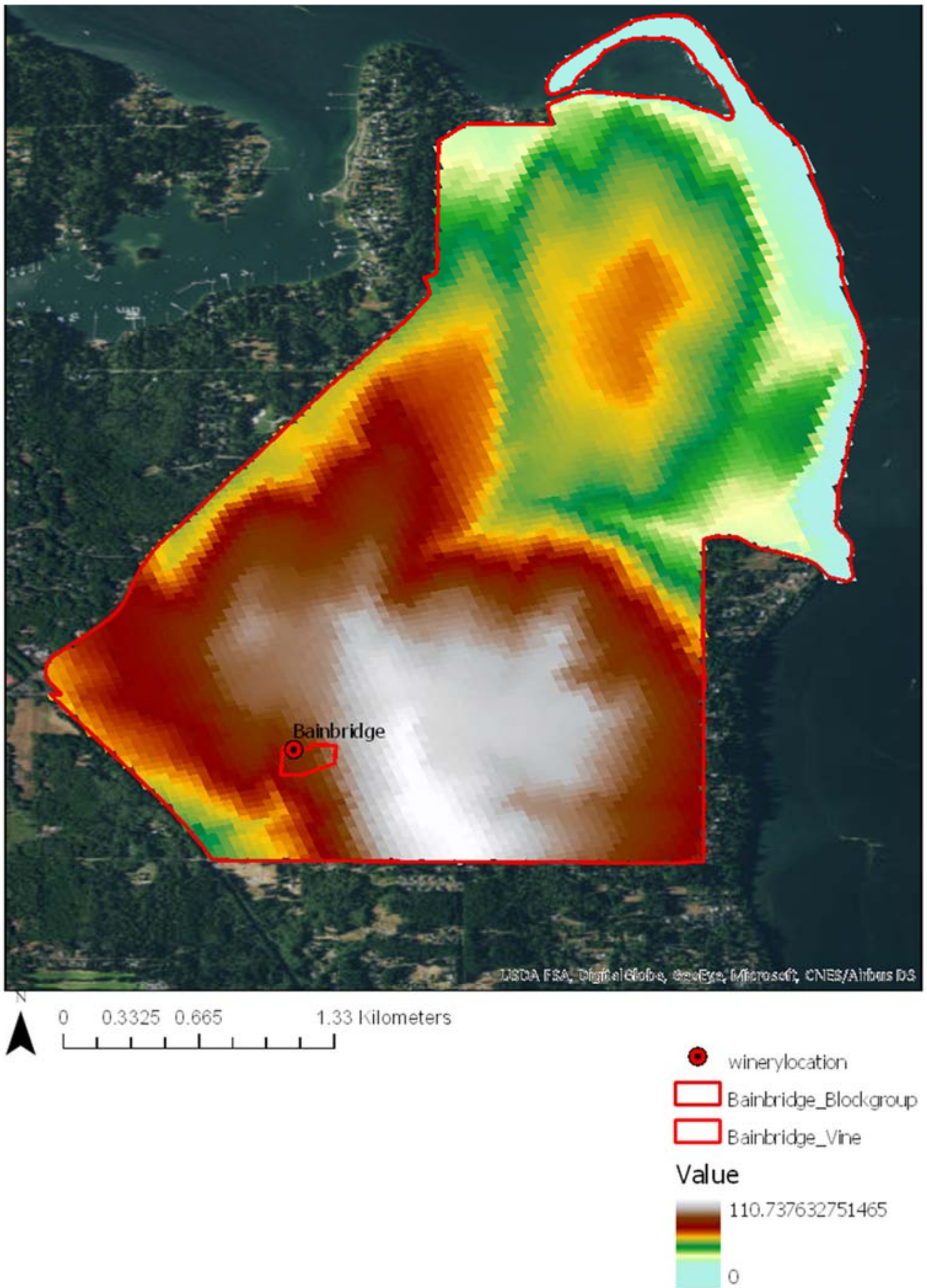


Figure 11: Bainbridge Vineyards Elevation

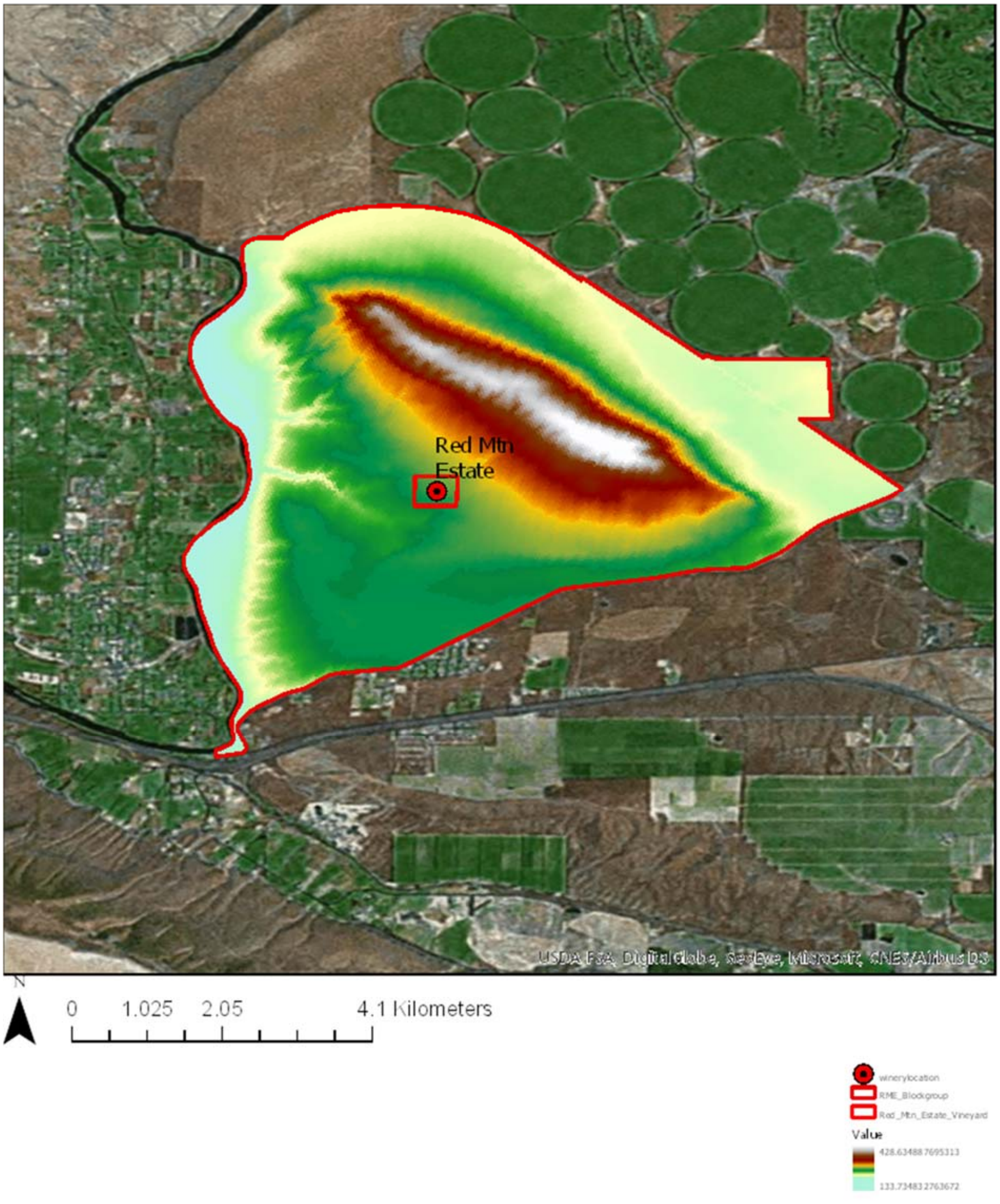


Figure 12: RME Vineyards Elevation

4.1.4 Heat Load Index

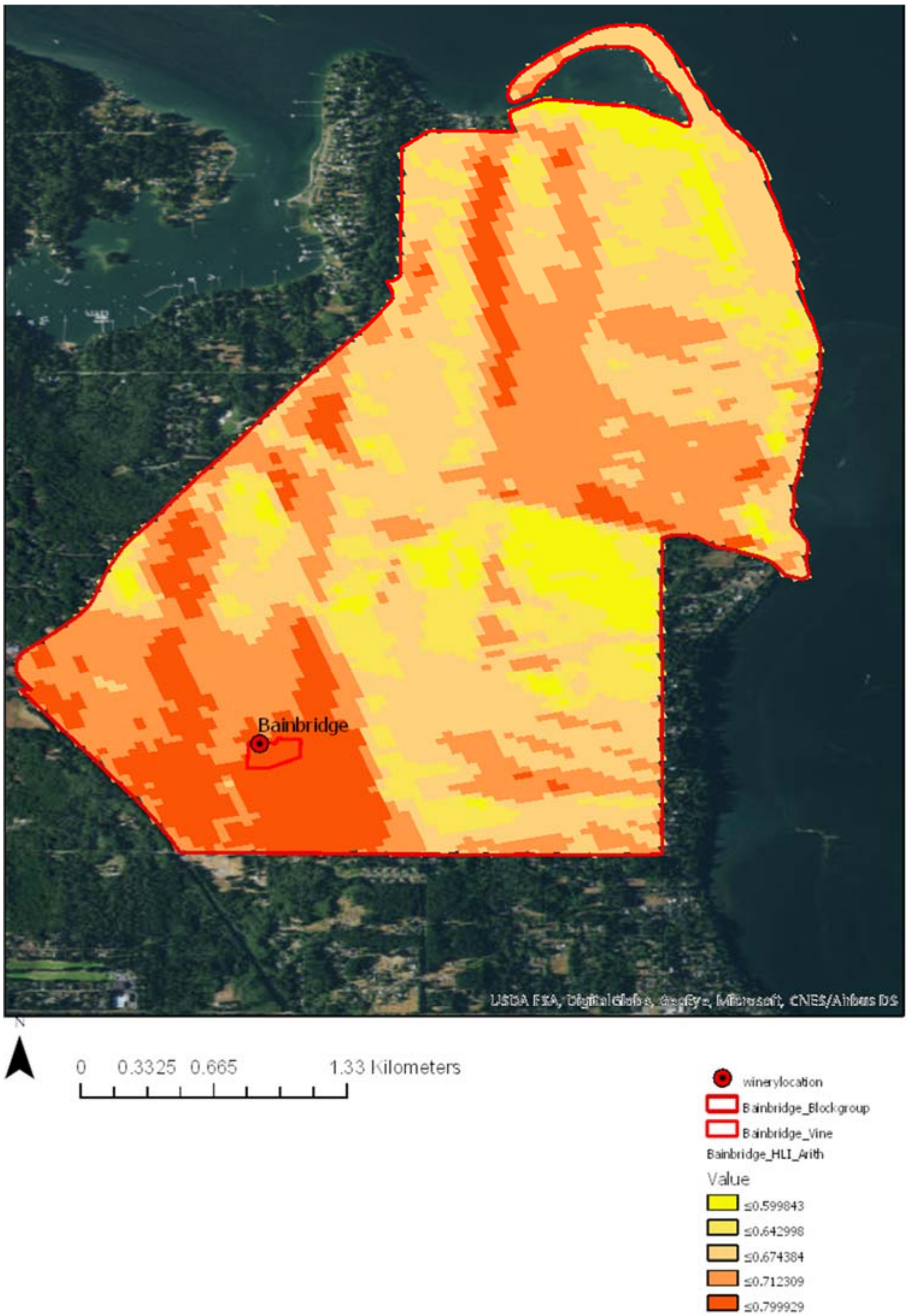


Figure 13: Bainbridge Vineyards Heat Load Index

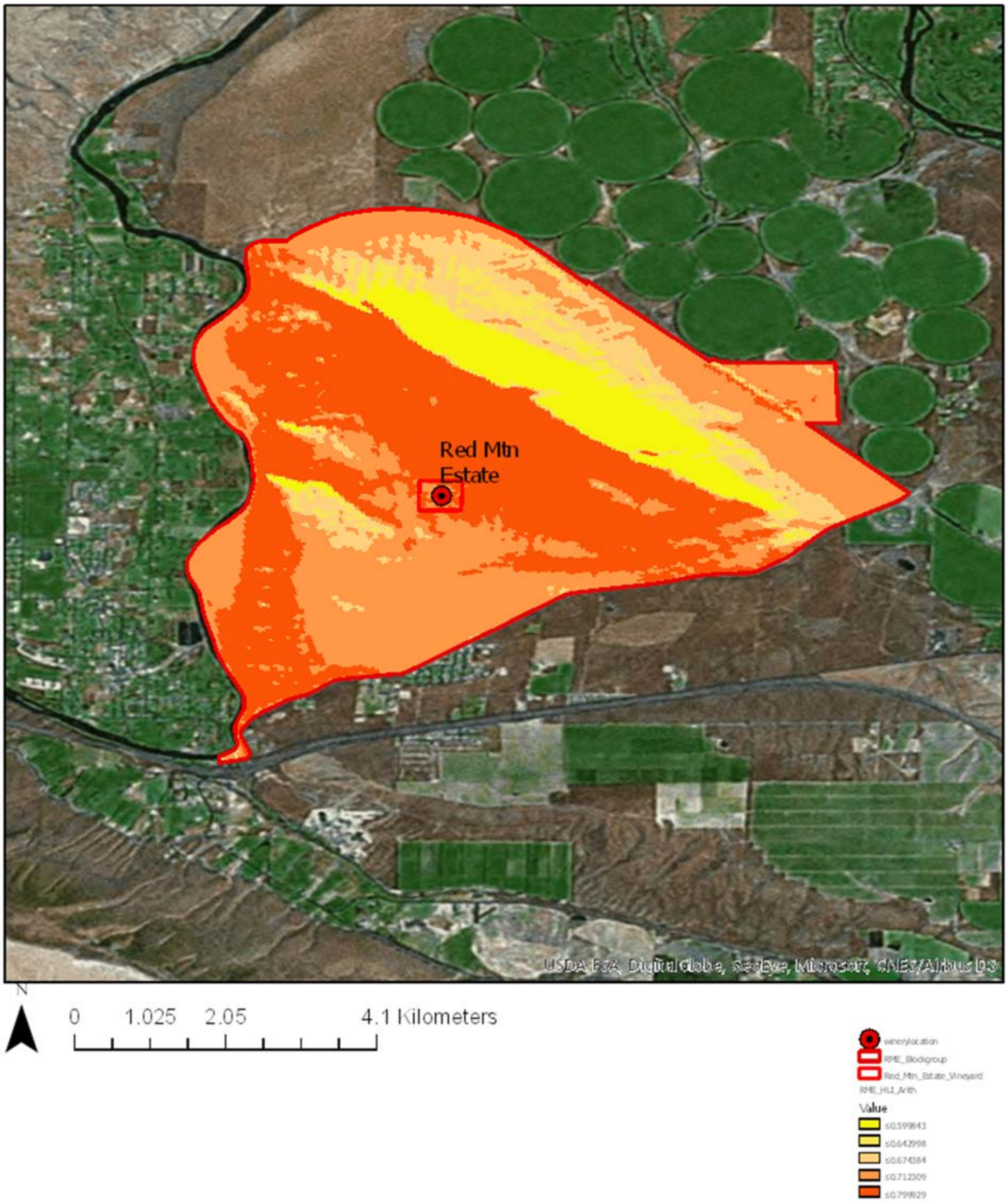


Figure 14: RME Vineyards Heat Load Index

4.2 Climate Considerations

4.2.1 Frost Free Days

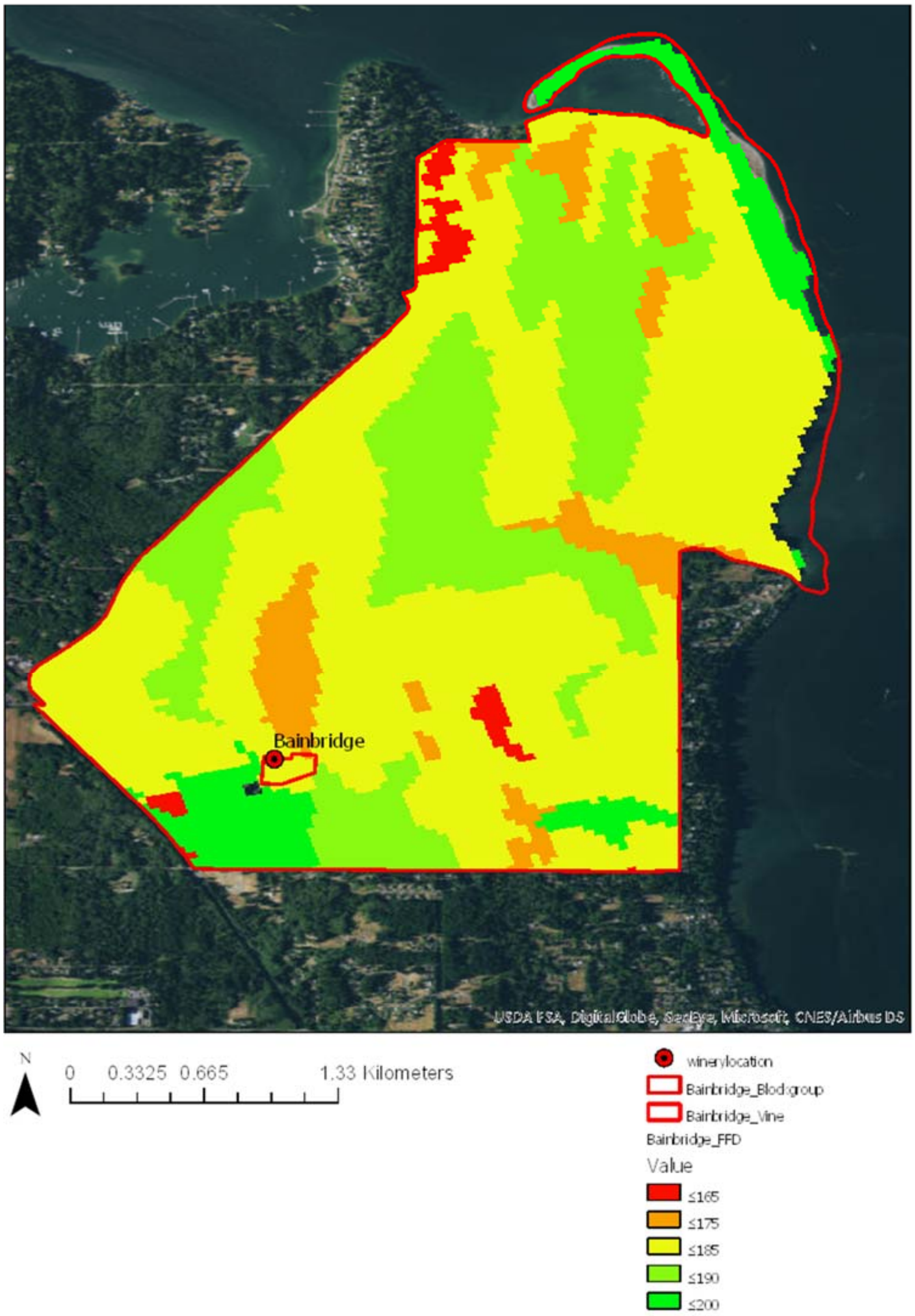


Figure 15: Bainbridge Vineyards Frost Free Days

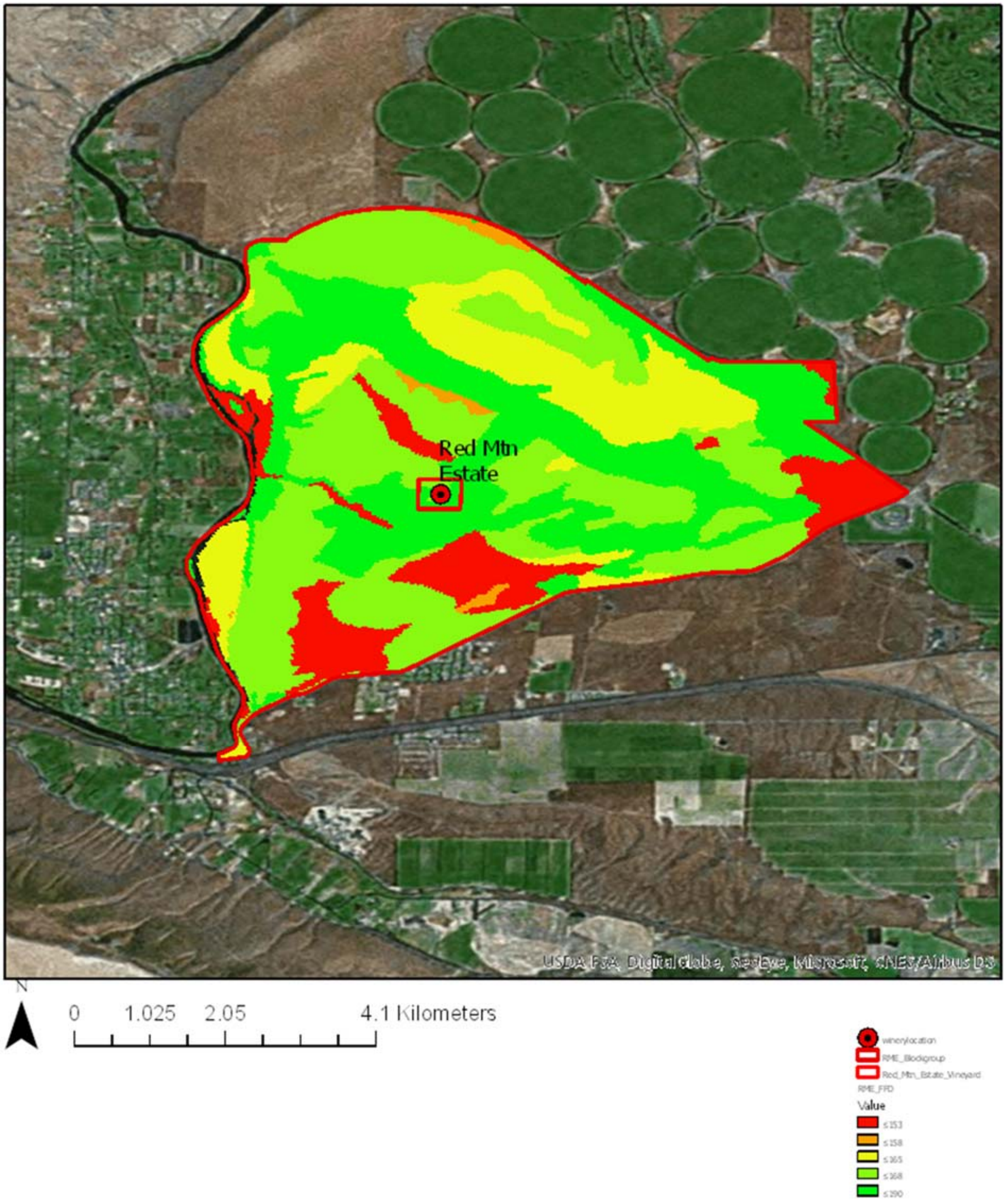


Figure 16: RME Vineyards Frost Free Days

4.2.2 Growing Degree Days

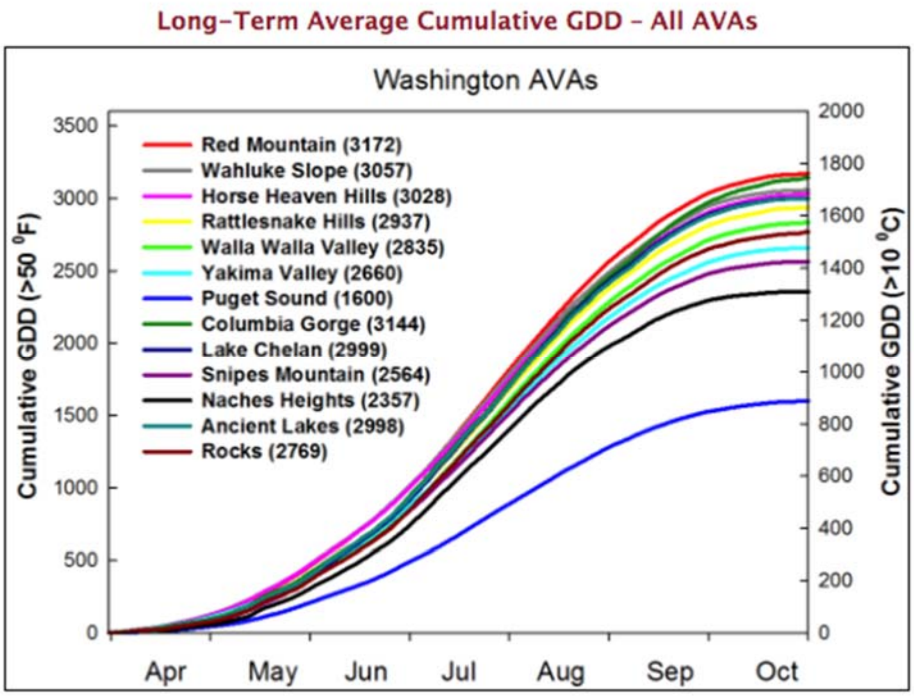


Figure 17: Long-term average accumulated GDD for all Washington AVAs. Bainbridge Vineyards is located in the Puget Sound AVA and Red Mountain Estate Vineyards is located in the Red Mountain AVA

4.2.3 Annual Precipitation

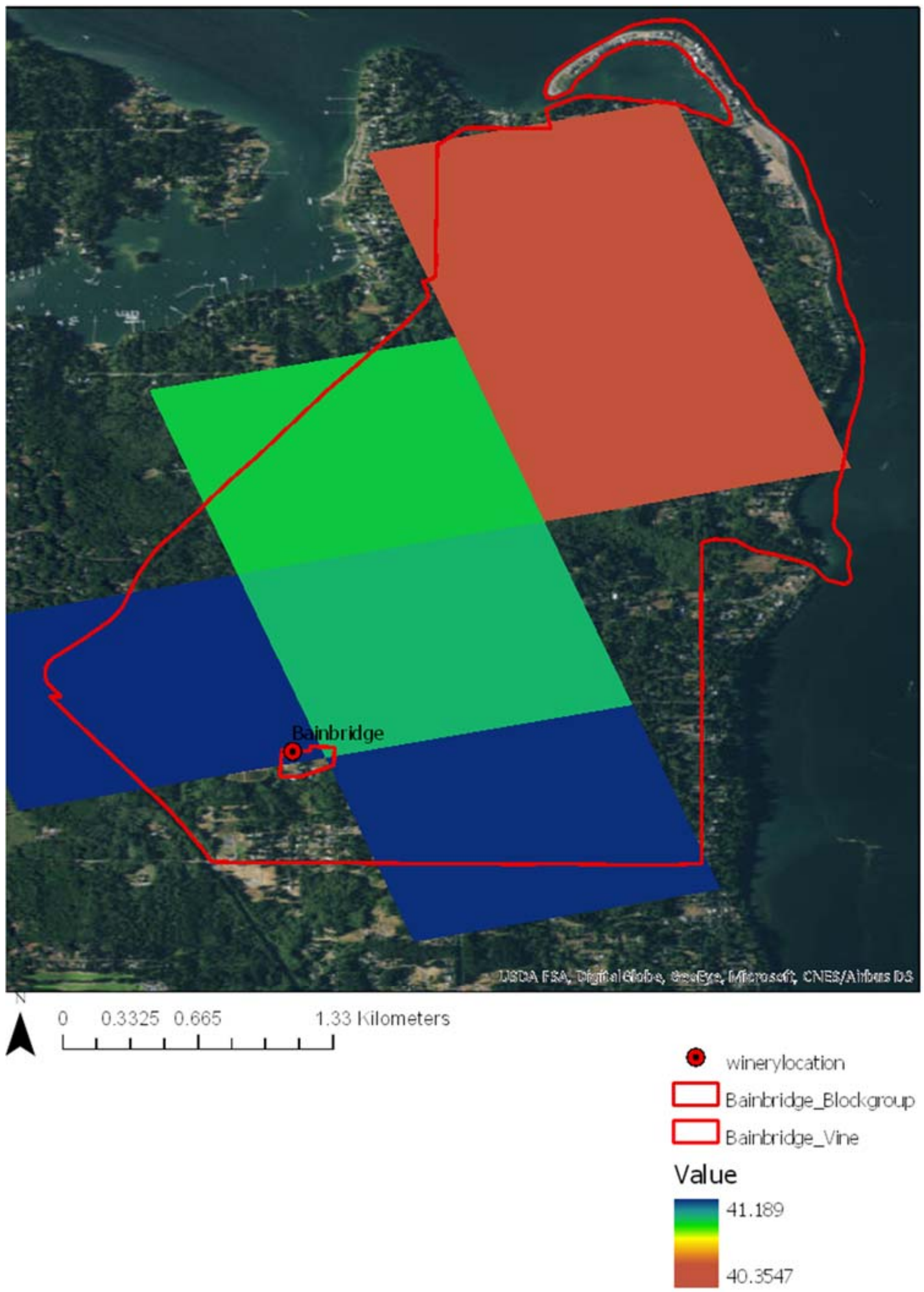


Figure 18: Bainbridge Vineyards Average Annual Precipitation

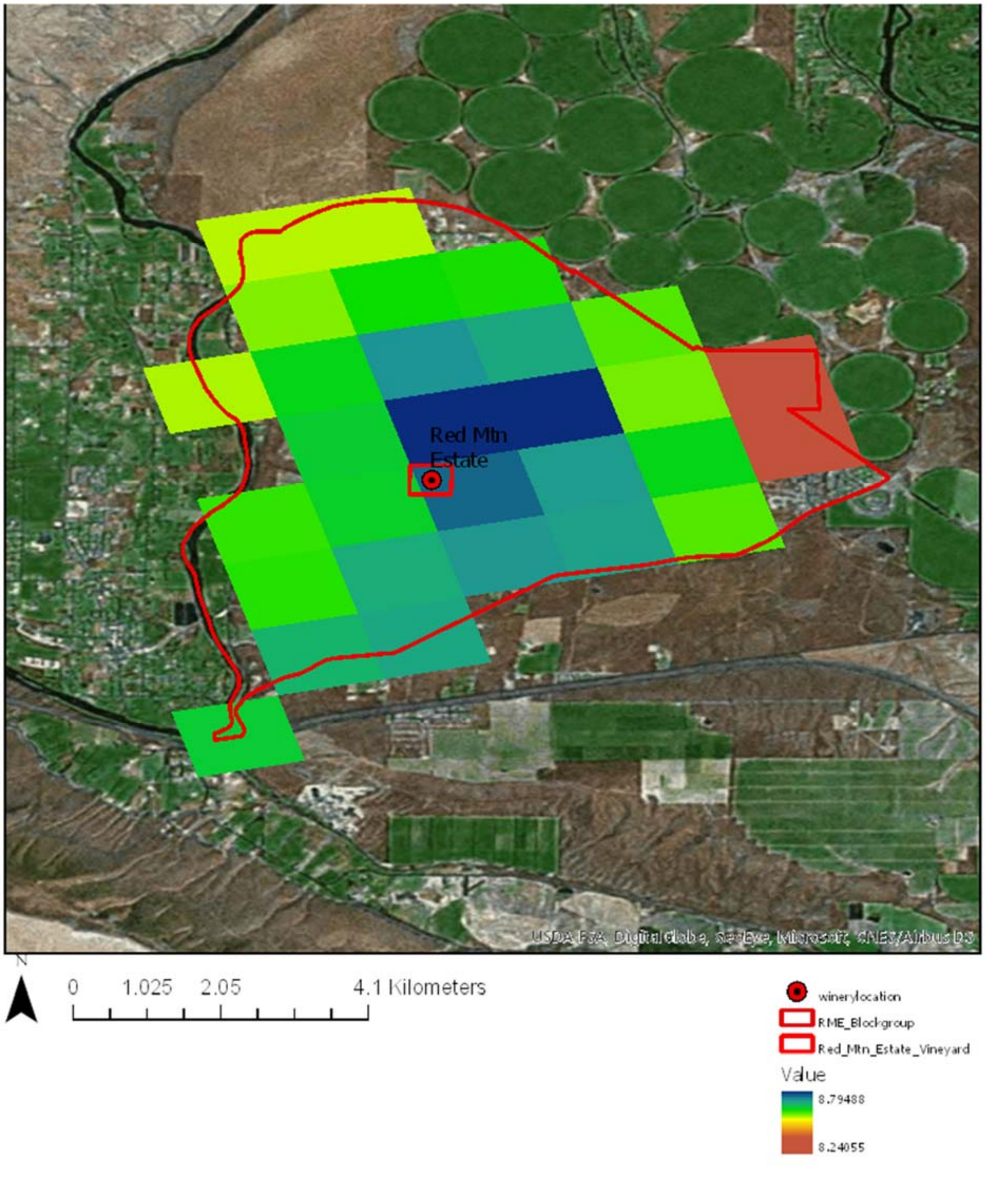


Figure 19: RME Vineyards Average Annual Precipitation

4.3 Soil Considerations

4.3.1 Soil Drainage

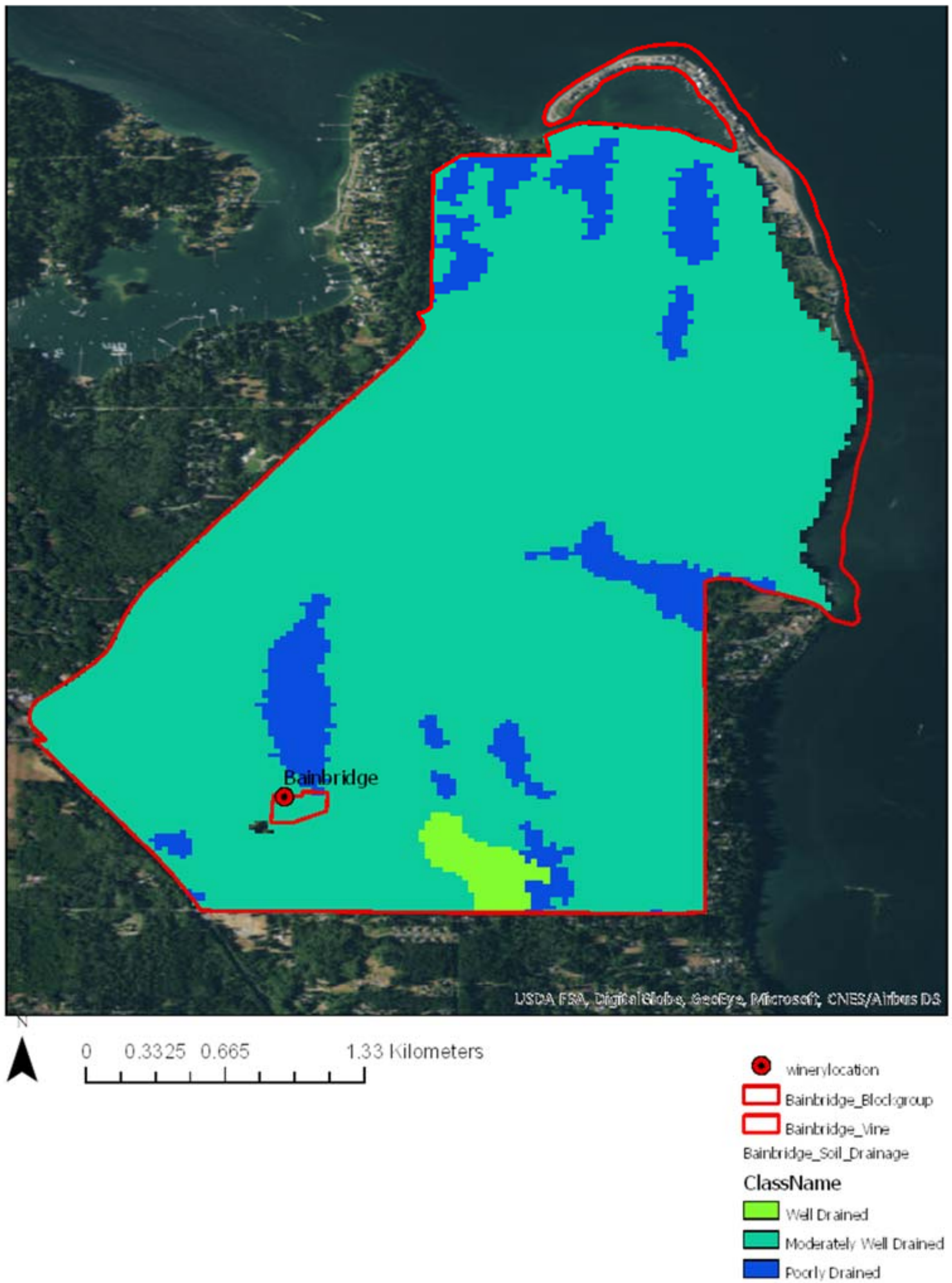


Figure 20: Bainbridge Vineyards Soil Drainage

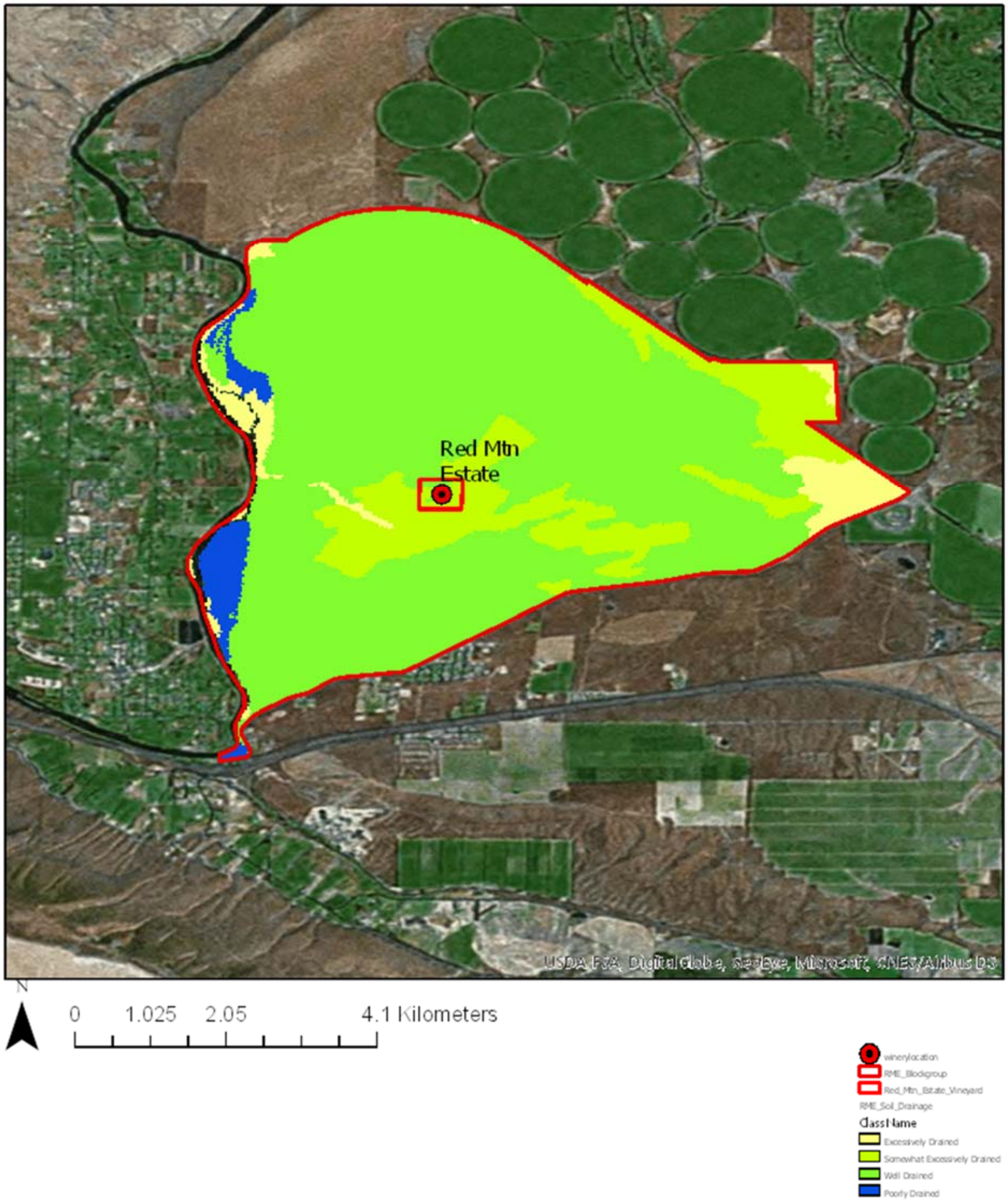


Figure 21: RME Vineyards Soil Drainage

4.3.2 Soil pH

pH (1 to 1 Water)—Kitsap County Area, Washington
(Bainbridge Vineyards)

Map Scale: 1:1,360 if printed on A landscape (11" x 8.5") sheet.

N

Meters: 0, 20, 40, 80, 120

Feet: 0, 50, 100, 200, 300

Map projection: Web Mercator   Corner coordinates: WGS84   Edge tics: UTM Zone 10N WGS84

MAP LEGEND

Area of Interest (AOI)

- Area of Interest (AOI)

Soils

Soil Rating Polygons

- Ultra acid (ph < 3.5)
- Extremely acid (pH 3.5 - 4.4)
- Very strongly acid (pH 4.5 - 5.0)
- Strongly acid (pH 5.1 - 5.5)
- Moderately acid (pH 5.6 - 6.0)
- Slightly acid (pH 6.1 - 6.5)
- Neutral (pH 6.6 - 7.3)
- Slightly alkaline (pH 7.4 - 7.8)
- Moderately alkaline (pH 7.9 - 8.4)
- Strongly alkaline (pH 8.5 - 9.0)
- Very strongly alkaline (pH > 9.0)
- Not rated or not available

Soil Rating Lines

- Ultra acid (ph < 3.5)
- Extremely acid (pH 3.5 - 4.4)
- Very strongly acid (pH 4.5 - 5.0)
- Strongly acid (pH 5.1 - 5.5)
- Moderately acid (pH 5.6 - 6.0)
- Slightly acid (pH 6.1 - 6.5)
- Neutral (pH 6.6 - 7.3)
- Slightly alkaline (pH 7.4 - 7.8)
- Moderately alkaline (pH 7.9 - 8.4)
- Strongly alkaline (pH 8.5 - 9.0)
- Very strongly alkaline (pH > 9.0)
- Not rated or not available

Soil Rating Points

- Ultra acid (ph < 3.5)
- Extremely acid (pH 3.5 - 4.4)
- Very strongly acid (pH 4.5 - 5.0)
- Strongly acid (pH 5.1 - 5.5)
- Moderately acid (pH 5.6 - 6.0)
- Slightly acid (pH 6.1 - 6.5)
- Neutral (pH 6.6 - 7.3)
- Slightly alkaline (pH 7.4 - 7.8)
- Moderately alkaline (pH 7.9 - 8.4)
- Strongly alkaline (pH 8.5 - 9.0)
- Very strongly alkaline (pH > 9.0)
- Not rated or not available

Water Features

- Streams and Canals

Transportation

- Rails
- Interstate Highways
- US Routes
- Major Roads
- Local Roads

Background

- Aerial Photography

pH (1 to 1 Water)

pH (1 to 1 Water)— Summary by Map Unit — Kitsap County Area, Washington (WA635)				
Map unit symbol	**Map unit name**	**Rating**	**Acres in AOI**	**Percent of AOI**
2	Alderwood gravelly sandy loam, 8 to 15 percent slopes	5.8	0.0	0.8%
16	Harstine gravelly ashy sandy loam, 15 to 30 percent slopes	4.5	0.1	2.5%
22	Kapowsin gravelly ashy loam, 0 to 6 percent slopes	5.6	4.3	89.0%
23	Kapowsin gravelly ashy loam, 6 to 15 percent slopes	5.6	0.1	2.0%
37	Norma fine sandy loam	5.8	0.2	4.2%
64	Water		0.1	1.6%
Totals for Area of Interest			**4.8**	**100.0%**

Description

Soil reaction is a measure of acidity or alkalinity. It is important in selecting crops and other plants, in evaluating soil amendments for fertility and stabilization, and in determining the risk of corrosion. In general, soils that are either highly alkaline or highly acid are likely to be very corrosive to steel. The most common soil laboratory measurement of pH is the 1:1 water method. A crushed soil sample is mixed with an equal amount of water, and a measurement is made of the suspension.

For each soil layer, this attribute is actually recorded as three separate values in the database. A low value and a high value indicate the range of this attribute for the soil component. A "representative" value indicates the expected value of this attribute for the component. For this soil property, only the representative value is used.

Rating Options

Aggregation Method: Dominant Component

Component Percent Cutoff: *None Specified*

Tie-break Rule: Higher

Interpret Nulls as Zero: No

Layer Options (Horizon Aggregation Method): Surface Layer (Not applicable)

pH (1 to 1 Water)—Benton County Area, Washington
(Red Mountain Estate)

MAP LEGEND

Area of Interest (AOI)

- Area of Interest (AOI)

Soils

Soil Rating Polygons

- Ultra acid (ph < 3.5)
- Extremely acid (pH 3.5 - 4.4)
- Very strongly acid (pH 4.5 - 5.0)
- Strongly acid (pH 5.1 - 5.5)
- Moderately acid (pH 5.6 - 6.0)
- Slightly acid (pH 6.1 - 6.5)
- Neutral (pH 6.6 - 7.3)
- Slightly alkaline (pH 7.4 - 7.8)
- Moderately alkaline (pH 7.9 - 8.4)
- Strongly alkaline (pH 8.5 - 9.0)
- Very strongly alkaline (pH > 9.0)
- Not rated or not available

Soil Rating Lines

- Ultra acid (ph < 3.5)
- Extremely acid (pH 3.5 - 4.4)
- Very strongly acid (pH 4.5 - 5.0)
- Strongly acid (pH 5.1 - 5.5)
- Moderately acid (pH 5.6 - 6.0)
- Slightly acid (pH 6.1 - 6.5)
- Neutral (pH 6.6 - 7.3)
- Slightly alkaline (pH 7.4 - 7.8)
- Moderately alkaline (pH 7.9 - 8.4)
- Strongly alkaline (pH 8.5 - 9.0)
- Very strongly alkaline (pH > 9.0)
- Not rated or not available

Soil Rating Points

- Ultra acid (ph < 3.5)
- Extremely acid (pH 3.5 - 4.4)
- Very strongly acid (pH 4.5 - 5.0)
- Strongly acid (pH 5.1 - 5.5)
- Moderately acid (pH 5.6 - 6.0)
- Slightly acid (pH 6.1 - 6.5)
- Neutral (pH 6.6 - 7.3)
- Slightly alkaline (pH 7.4 - 7.8)
- Moderately alkaline (pH 7.9 - 8.4)
- Strongly alkaline (pH 8.5 - 9.0)
- Very strongly alkaline (pH > 9.0)
- Not rated or not available

Water Features

- Streams and Canals

Transportation

- Rails
- Interstate Highways
- US Routes
- Major Roads
- Local Roads

Background

- Aerial Photography

pH (1 to 1 Water)

pH (1 to 1 Water)— Summary by Map Unit — Benton County Area, Washington (WA605)				
Map unit symbol	**Map unit name**	**Rating**	**Acres in AOI**	**Percent of AOI**
HeE	Hezel loamy fine sand, 0 to 30 percent slopes	7.6	25.3	61.7%
WdAB	Warden silt loam, 0 to 5 percent slopes	7.2	15.7	38.3%
Totals for Area of Interest			**41.1**	**100.0%**

Description

Soil reaction is a measure of acidity or alkalinity. It is important in selecting crops and other plants, in evaluating soil amendments for fertility and stabilization, and in determining the risk of corrosion. In general, soils that are either highly alkaline or highly acid are likely to be very corrosive to steel. The most common soil laboratory measurement of pH is the 1:1 water method. A crushed soil sample is mixed with an equal amount of water, and a measurement is made of the suspension.

For each soil layer, this attribute is actually recorded as three separate values in the database. A low value and a high value indicate the range of this attribute for the soil component. A "representative" value indicates the expected value of this attribute for the component. For this soil property, only the representative value is used.

Rating Options

Aggregation Method: Dominant Component

Component Percent Cutoff: *None Specified*

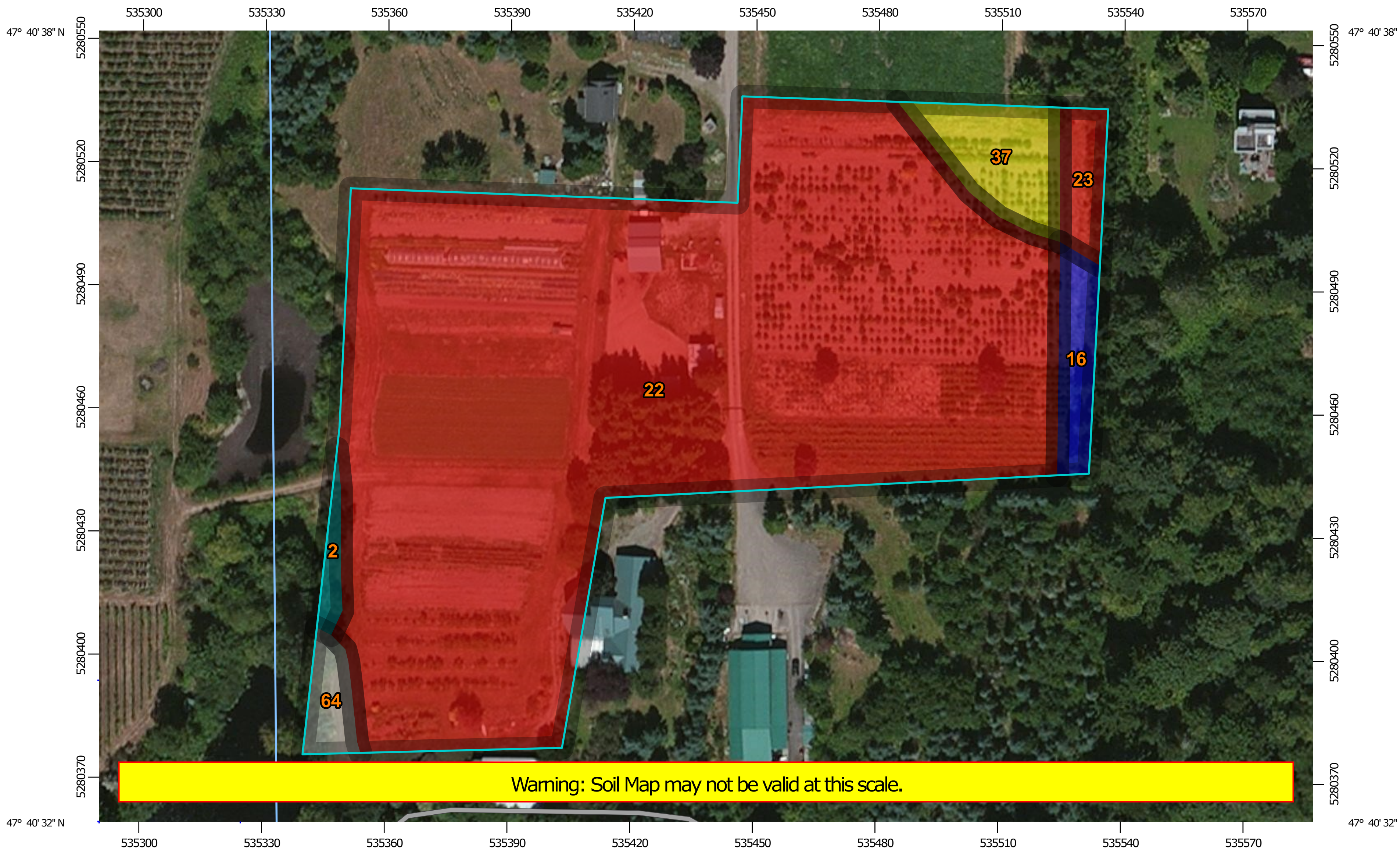
Tie-break Rule: Higher

Interpret Nulls as Zero: No

Layer Options (Horizon Aggregation Method): Surface Layer (Not applicable)

4.3.3 Soil Organic Matter

Soil Health - Organic Matter—Kitsap County Area, Washington
(Bainbridge Vineyards)



Map Scale: 1:1,360 if printed on A landscape (11" x 8.5") sheet.

N

0 20 40 80 120 Meters

0 50 100 200 300 Feet

Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 10N WGS84

MAP LEGEND

Area of Interest (AOI)

Area of Interest (AOI)

Soils

Soil Rating Polygons

<= 6.00

> 6.00 and <= 7.50

> 7.50 and <= 9.00

> 9.00 and <= 75.00

Not rated or not available

Soil Rating Lines

<= 6.00

> 6.00 and <= 7.50

> 7.50 and <= 9.00

> 9.00 and <= 75.00

Not rated or not available

Soil Rating Points

<= 6.00

> 6.00 and <= 7.50

> 7.50 and <= 9.00

> 9.00 and <= 75.00

Not rated or not available

Water Features

Streams and Canals

Transportation

Rails

Interstate Highways

US Routes

Major Roads

Local Roads

Background

Aerial Photography

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:24,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Kitsap County Area, Washington
Survey Area Data: Version 12, Sep 8, 2016

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Jul 9, 2010—Aug 20, 2011

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

Soil Health - Organic Matter

Soil Health - Organic Matter— Summary by Map Unit — Kitsap County Area, Washington (WA635)				
Map unit symbol	**Map unit name**	**Rating (percent)**	**Acres in AOI**	**Percent of AOI**
2	Alderwood gravelly sandy loam, 8 to 15 percent slopes	9.00	0.0	0.8%
16	Harstine gravelly ashy sandy loam, 15 to 30 percent slopes	75.00	0.1	2.5%
22	Kapowsin gravelly ashy loam, 0 to 6 percent slopes	6.00	4.3	89.0%
23	Kapowsin gravelly ashy loam, 6 to 15 percent slopes	6.00	0.1	2.0%
37	Norma fine sandy loam	7.50	0.2	4.2%
64	Water		0.1	1.6%
Totals for Area of Interest			**4.8**	**100.0%**

Description

Organic matter is any material that is part of or originated from living organisms. Includes soil organic matter, plant residue, mulch, compost, and other materials.The stabilized material is the pool of soil organic matter that is resistant to biological degradation because it is either physically or chemically inaccessible to microbial activity. These compounds are created through a combination of biological activity and chemical reactions in the soil. Humus is usually a synonym for stabilized organic matter, but is sometimes used to refer to all soil organic matter. The active fraction is the highly dynamic or labile portion of soil organic matter that is readily available to soil organisms. May also include the living biomass. Particulate organic matter (POM) and light fraction (LF) are measurable indicators of the active fraction. POM particles are larger than other SOM and can be separated from soil by sieving. LF particles are lighter than other SOM and can be separated from soil by centrifugation.

Rating Options

Units of Measure: percent

Aggregation Method: Dominant Component

Component Percent Cutoff: *None Specified*

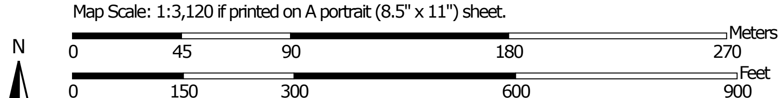
Tie-break Rule: Higher

Interpret Nulls as Zero: No

Layer Options (Horizon Aggregation Method): Surface Layer (Not applicable)

Soil Health - Organic Matter—Benton County Area, Washington
(Red Mountain Estate)

Map Scale: 1:3,120 if printed on A portrait (8.5" x 11") sheet.



Map projection: Web Mercator Corner coordinates: WGS84 Edge tics: UTM Zone 11N WGS84

MAP LEGEND

Area of Interest (AOI)

Area of Interest (AOI)

Soils

Soil Rating Polygons

<= 0.25

> 0.25 and <= 2.00

Not rated or not available

Soil Rating Lines

<= 0.25

> 0.25 and <= 2.00

Not rated or not available

Soil Rating Points

<= 0.25

> 0.25 and <= 2.00

Not rated or not available

Water Features

Streams and Canals

Transportation

Rails

Interstate Highways

US Routes

Major Roads

Local Roads

Background

Aerial Photography

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:20,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Benton County Area, Washington
Survey Area Data: Version 12, Sep 8, 2016

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Aug 6, 2010—Oct 17, 2010

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

Soil Health - Organic Matter

Soil Health - Organic Matter— Summary by Map Unit — Benton County Area, Washington (WA605)				
Map unit symbol	**Map unit name**	**Rating (percent)**	**Acres in AOI**	**Percent of AOI**
HeE	Hezel loamy fine sand, 0 to 30 percent slopes	0.25	25.3	61.7%
WdAB	Warden silt loam, 0 to 5 percent slopes	2.00	15.7	38.3%
Totals for Area of Interest			**41.1**	**100.0%**

Description

Organic matter is any material that is part of or originated from living organisms. Includes soil organic matter, plant residue, mulch, compost, and other materials.The stabilized material is the pool of soil organic matter that is resistant to biological degradation because it is either physically or chemically inaccessible to microbial activity. These compounds are created through a combination of biological activity and chemical reactions in the soil. Humus is usually a synonym for stabilized organic matter, but is sometimes used to refer to all soil organic matter. The active fraction is the highly dynamic or labile portion of soil organic matter that is readily available to soil organisms. May also include the living biomass. Particulate organic matter (POM) and light fraction (LF) are measurable indicators of the active fraction. POM particles are larger than other SOM and can be separated from soil by sieving. LF particles are lighter than other SOM and can be separated from soil by centrifugation.

Rating Options

Units of Measure: percent

Aggregation Method: Dominant Component

Component Percent Cutoff: *None Specified*

Tie-break Rule: Higher

Interpret Nulls as Zero: No

Layer Options (Horizon Aggregation Method): Surface Layer (Not applicable)

4.4 Discussion

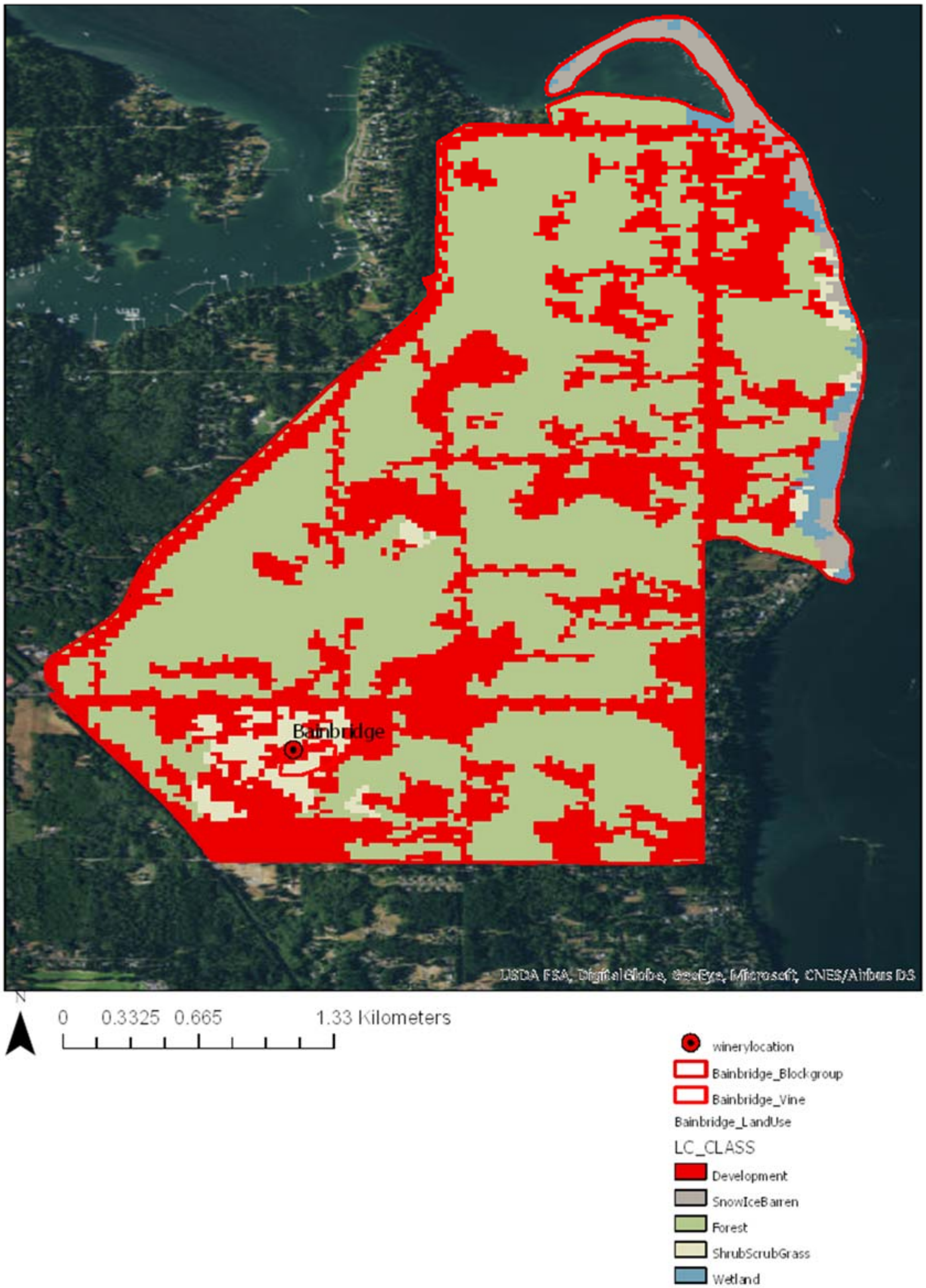


Figure 22: Land cover data for Bainbridge Vineyards

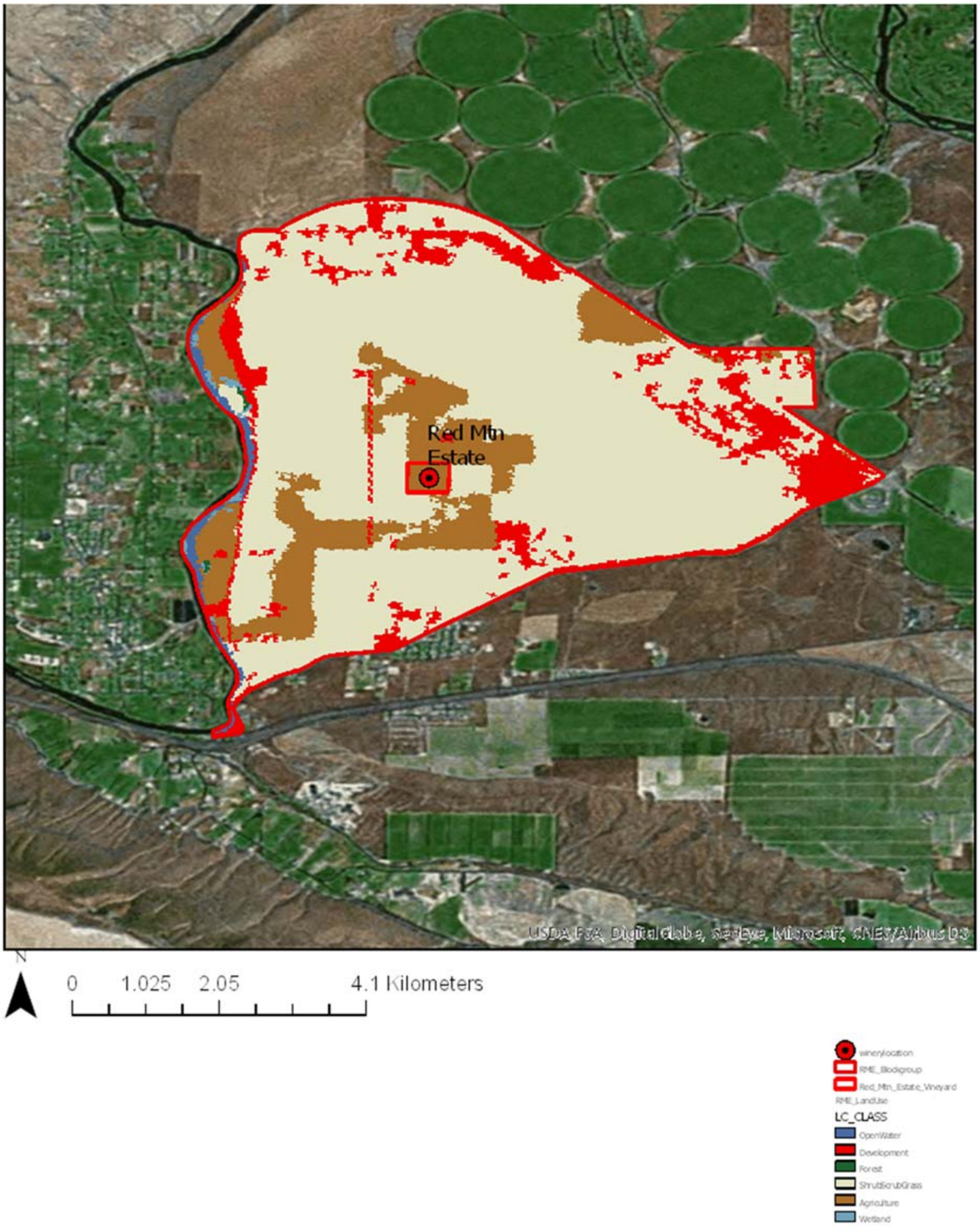


Figure 23: Land cover data for RME Vineyards