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Image-Based Decision Tools for Vineyard Management

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Abstract. *Vineyard managers in California's premium wine industry are concerned with canopy development, field uniformity, relative amounts of leaf and fruit production, and irrigation management strategy. The application of high-resolution satellite imagery to viticultural management in Napa Valley was examined with respect to each of these issues. Ikonos multispectral data were transformed to a spectral vegetation index and combined with ground measurements to map vineyard canopy density, expressed both as leaf area index (LAI) and leaf area per vine. Within-field variance was used to quantify field uniformity. Leaf area and yield data were combined to map end-*

of-season vine balance (leaf area to fruit weight ratio). A water balance model was developed to assist with irrigation planning. The model combines leaf area with weather and soils databases to predict soil moisture, vine stress, and water replacement needs. The simulation operates on a 24 hour timestep, and results can be temporally aggregated as needed. It is concluded that remote sensing can provide a basis for decision support in vineyard management.

Keywords. Remote sensing, multi-spectral image processing, leaf area, irrigation modeling, yield monitor, viticulture, decision making

Introduction

Premium wine production is an intricate fusion of viticulture and enology. The viticultural aspect is becoming increasingly knowledge-based as growers seek to maximize the potential of their lands. Winegrapes are a very high-value crop and investments, technology or otherwise, which boost crop quality or yield can be well rewarded. At the same time, the industry is highly competitive and, like other agricultural sectors, production efficiency is a key concern.

It is widely recognized that environmental differences within the vineyard, with respect to soils, microclimate, and topography, can influence grape characteristics and crop yields. Airborne imagery has been used to map these *relative* differences in canopy density within individual vineyard fields (Wildman et al., 1983; Johnson et al., 1996, 2001; Hall et al., 2002). An increasing number of commercial winegrape growers in California's North and Central Coast viticultural regions are using digital imagery for various purposes such as harvest preparation, vineyard re-development, and identification of problems related to irrigation, nutrition, disease, and pest infestation (Carothers, 2000). Based on ground measurement calibration, multispectral aircraft and high-resolution satellite imagery has more recently been used to map vineyard canopy density in *absolute* terms as leaf area index (LAI; leaf area per unit ground area) and related measures (Johnson et al., 2001, 2003a; Dobrowski et al., 2002).

Some important factors relating to wine quality and yield include: 1) field uniformity, 2) leaf to fruit balance, and 3) timing of water stress onset. Remote sensing and related geospatial technologies can help growers manage each of these aspects. This paper describes some higher level prototype image-based products intended for decision support in the premium winegrowing industry.

Image-Based Products

The products described in this paper are based on Ikonos multispectral satellite imagery (Space Imaging, Inc.) from various acquisitions dates. Digital counts in each spectral channel were converted to at-sensor radiance units by applying radiometric calibration coefficients of Peterson (2001). The images were registered to the California State Plane Coordinate System (Zone II-3301, North American Datum 1983, GRS 80) by image-to-image registration with a U.S.G.S. Digital Ortho Quarter Quad. The radiance values were converted to normalized difference vegetation index (NDVI), formulated as (NIR-red)/(NIR+red), on a per pixel basis. NDVI maps were converted to LAI based on supporting ground measurements; field planting density (row and vine spacing) was used convert LAI to leaf area on a per-vine or per-meter-of-row basis (Johnson et al., 2003a). Additional research has shown that the relationship between NDVI and LAI has a high degree of temporal stability (Johnson, 2003b).

Field Uniformity Map

Growers tend to regard individual fields as separate management units for cultivation and harvest. However, within-field differences in plant vigor can cause differences in ripening rate and fruit characteristics. This can result in the mixing of grapes of differing flavor and color within a single fermentation batch or wine "lot," which is considered undesirable from a winemaking standpoint. Hence, growers generally strive for within-field uniformity.

Field uniformity can be expressed as the coefficient of variation (standard deviation / mean * 100) of the NDVI or leaf area maps. The uniformity maps can assist managers in identifying fields where new or revised management practices might need to be implemented. When the CV is monitored over consecutive seasons, a change map can be developed to quantify the increase or decrease in uniformity. Managers can then determine the effectiveness of mitigation practices. In the given example (Fig. 1), fields coded as red, orange, and perhaps green throughout a 400 ha property have relatively high CV and might require intervention. It is notable that fallow or young fields routinely tend to have a high CV, and this is not considered a problem. Accurate conclusions thus require map interpretation by a cognizant vineyard manager.

Vine Balance Map

The balance between leaf and fruit production affects yield and quality (Iland et al. 1995, Smart 1995, 2001). Canopy size should provide sufficient photosynthetic capacity to support fruit ripening, while avoiding excess shading that can retard ripening and increase disease pressures. Viticultural research has suggested an optimal value of 1 m^2 leaf per 1 kg fruit for cooler climate regions such as the Napa Valley (Smart, 2001). Grower experience ultimately provides the best gauge for a given property.

Low Resolution (Per-Field)

Mean leaf area values were calculated per-field. Mean yield in terms of kg $vine^{-1}$ was calculated from harvest data, which were aggregated at field level. The resulting map shows average vine balance on each field of a 400 ha property (Fig. 2). According to the general guideline provided above, fields coded as dark and light blue might be considered out of balance (excess leaf canopy), as might those in red (insufficient canopy).

High Resolution

A higher-resolution vine balance product was produced on the basis of mechanical yield monitor data collected during the 2002 harvest. Map projected yield data in Arc/Info grid format (0.75 m resolution) were generated by inverse distance weighted interpolation of point samples. ArcGIS v8.3 was used to convert the yield grid from tons $acre^{-1}$ to kg $vine^{-1}$, based upon planting density. The grid was then imported to ERDAS/Imagine and registered to an image-based leaf area map collected also during the 2002 harvest. The yield grid was resampled to 3 m spatial resolution, and high frequency noise was further suppressed by applying a low-pass filter with a 5x5 averaging window (after Lillesand and Kiefer, 1994). The leaf area grid (Fig. 3, top) was divided by the yield grid (Fig. 3, middle), to produce a map showing differences in vine balance within a single 1 ha field (Fig. 3, bottom). Large within-field differences in yield and balance are evident within this field. Overall, the northern portion appears to be in reasonable shape, but the southern portion might require management intervention to curtail vegetative growth or promote fruit production.

Water Balance Map

Irrigation is generally required for California grape production. Many winegrowers use deficit irrigation, which imposes mild-to-moderate levels of plant water stress, at certain times during the season for canopy management and grape quality manipulation (Goodwin, 1995). A simple water balance model (Vineyard Soil Irrigation Model, VSIM) was developed to facilitate irrigation strategic planning. The model simulates vineyard daily and seasonal water balance as a function of LAI, weather, soil type, soil depth, gravel fraction, and rooting depth (Fig. 4). VSIM was adapted from the Forest-BGC process model (Running and Coughlan, 1988), and takes advantage of weather and evaporation data measured and archived by the California Irrigation Management Information System (CIMIS, 2002). The user can manipulate LAI, weather, soil water holding capacity, and cover crop to examine effects on soil moisture and vine water stress. Water gains (rainfall, irrigation) and losses (evapotranspiration, runoff) are used to revise soil moisture and plant stress (leaf water potential) on a daily basis. Crop ET is calculated as a proportion of potential ET measured by the CIMIS network. The ET proportion is based on canopy LAI from remote sensing, and may be temporally interpolated or extrapolated based on growing-degree-day summation. A 1-d (point-based) version of the model was implemented in Microsoft Excel, and a 2-d (landscape) version in IDL (Research Systems, Inc.).

VSIM 1-d can be used to examine sensitivity of water demand and timing, in existing or planned vineyards, to any of the model input parameters. For example, Figure 5 shows demand curves for three months in early season as a function of planting density, soil type and rooting depth, with a goal of inducing water stress onset near veraison in mid-July.

Sensitivity to interannual climate variation can also be examined. VSIM 2-d was run with CIMIS daily weather data for the years 1997-2002; climax LAI was specified throughout with the same 2000 satellite map. VSIM produced the expected result that warm and dry conditions during winter and spring cause earlier onset of plant water stress (Fig. 6). This finding is especially obvious in the extreme years of 1997 (warm/dry) and 1998 (cool/wet). Cumulative water stress was calculated, by summing daily stress values, for the phenological period from veraison to harvest (Fig. 7). As expected, stress values were low during 1998. The greatest values were seen during 1999-2002. Somewhat lower values were seen for 1997, when weather led to accelerated phenological development and early harvest.

As the model is further developed and joined with an increasingly rich and accessible body of earth observational data and improved weather forecasts, it should form the basis for improved tactical decisions at local and regional scales, and reduced grower risk (Nemani et al., 2003).

Conclusion

High-resolution multispectral satellite imagery was used to develop viticultural decision support products related to monitoring of field uniformity, vine balance, and irrigation planning. Image-based products such as these may complement, and perhaps ultimately replace, conventional point-based ground measurements. Additional validation, demonstration, education, and technology transfer efforts are needed to move these products and tools from prototype to operational status.

Acknowledgements

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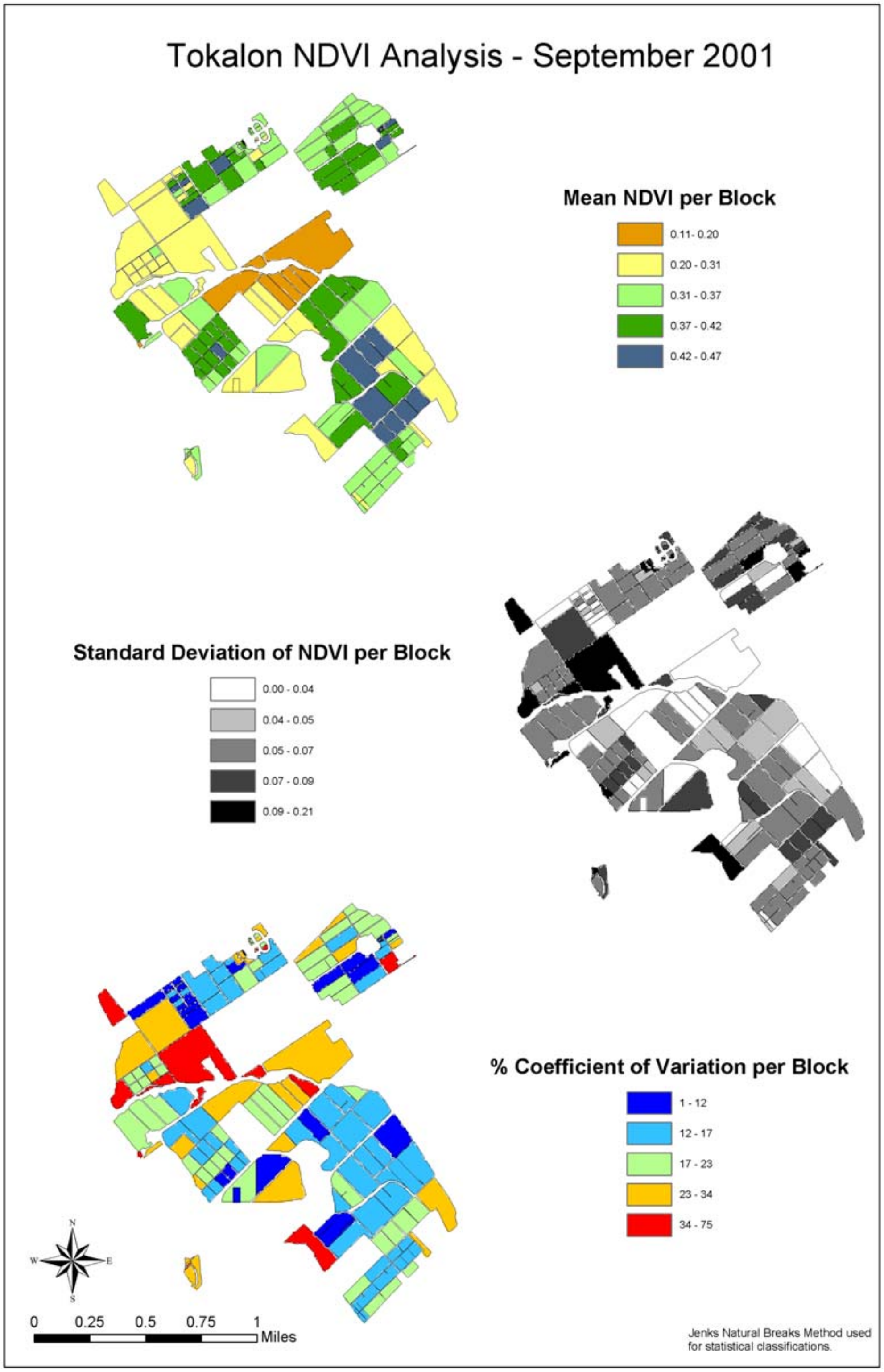

Figure 1. Field uniformity map (bottom), derived from NDVI mean (top) and variance (middle). Greater coefficients of variation indicate less uniform canopy.

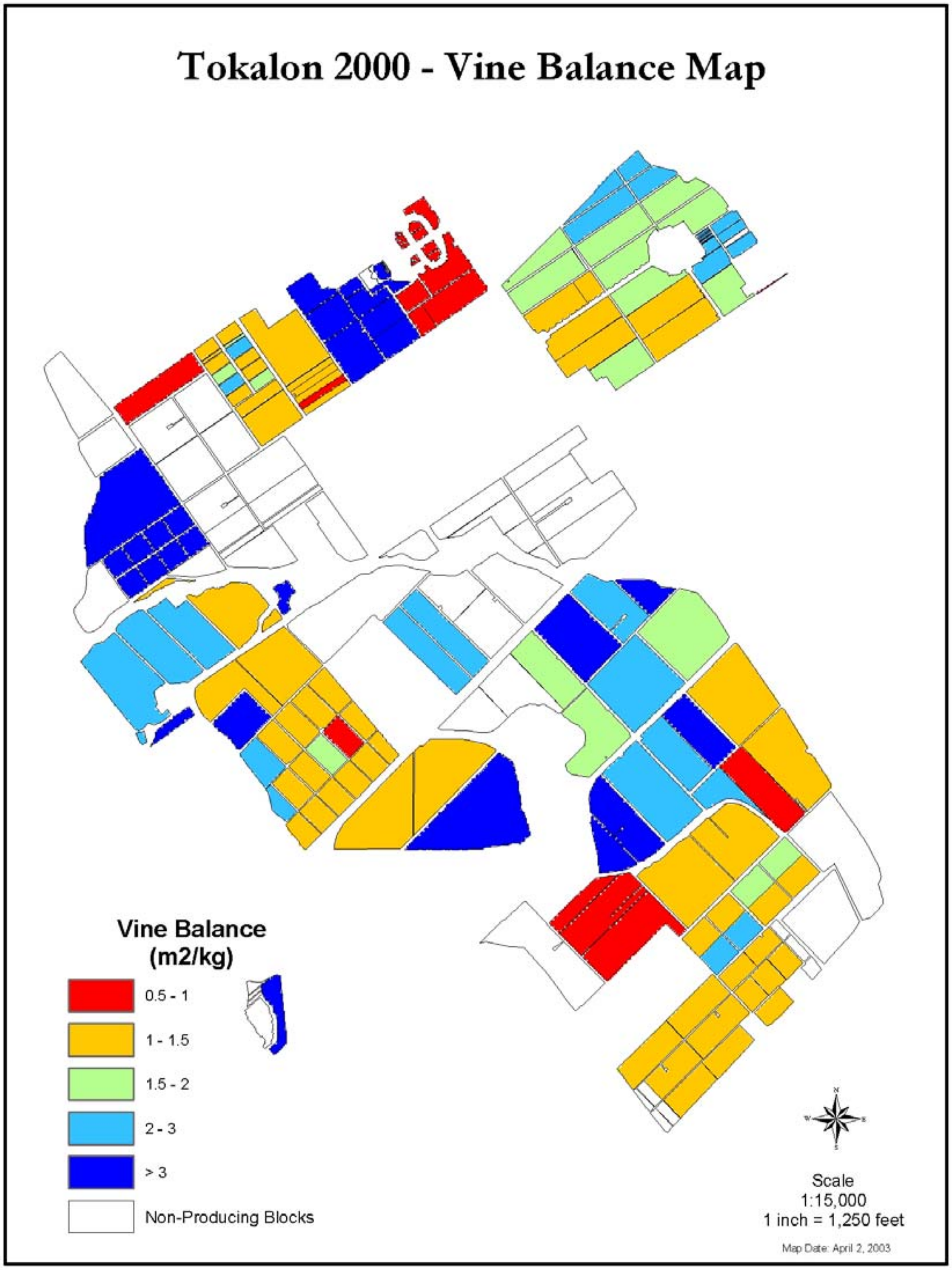

Figure 2. Vine balance map derived from leaf area (per-vine) image and per-field yields. Viticultural research suggests values in the range of 1-2 m^2 leaf area per kg fruit may be optimal for this climate. Blue fields may be able to support greater fruit production.

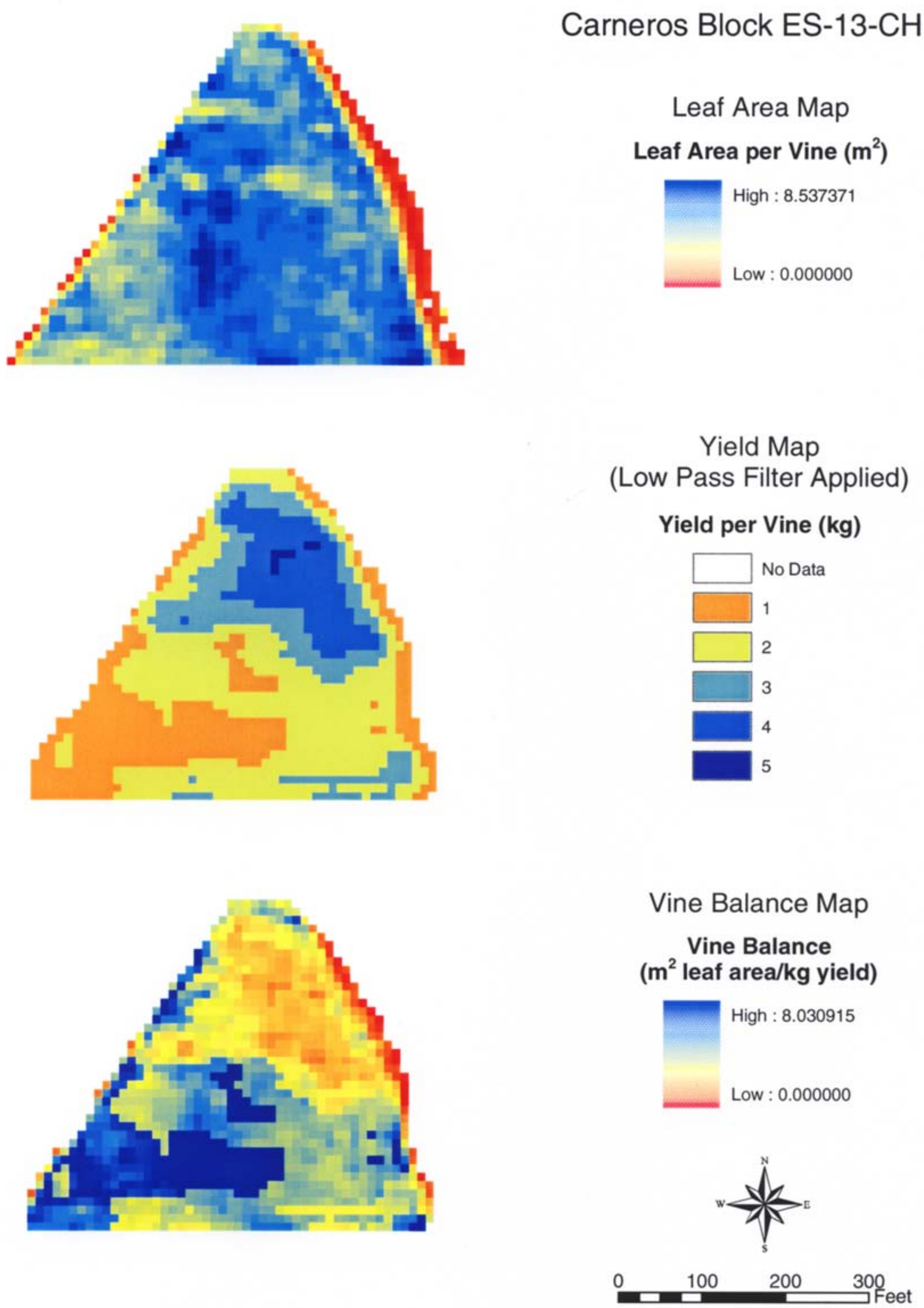

Figure 3. High-resolution vine balance map (bottom) derived from leaf area (per-vine) image (top) and yield monitor data (middle). Areas with vine balance shown as blue may be able to support greater fruit production.

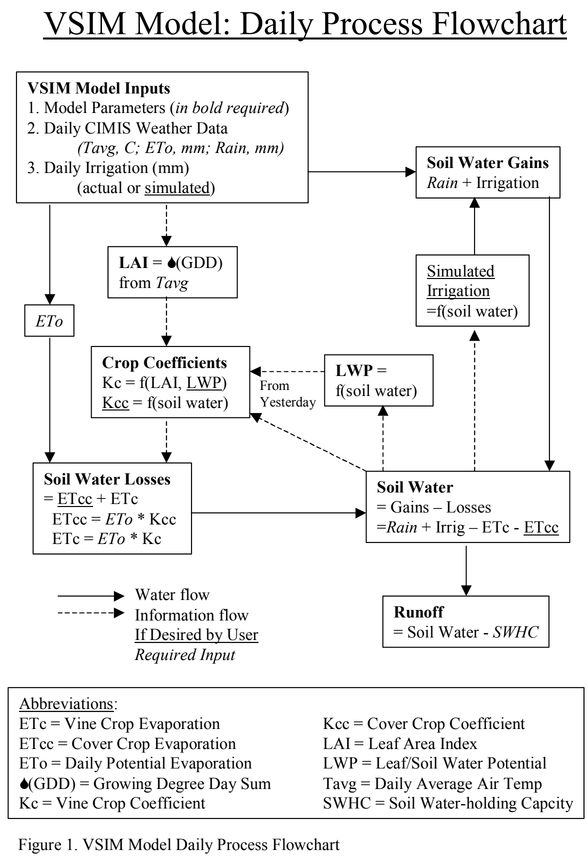

Figure 4. VSIM model daily process flowchart.

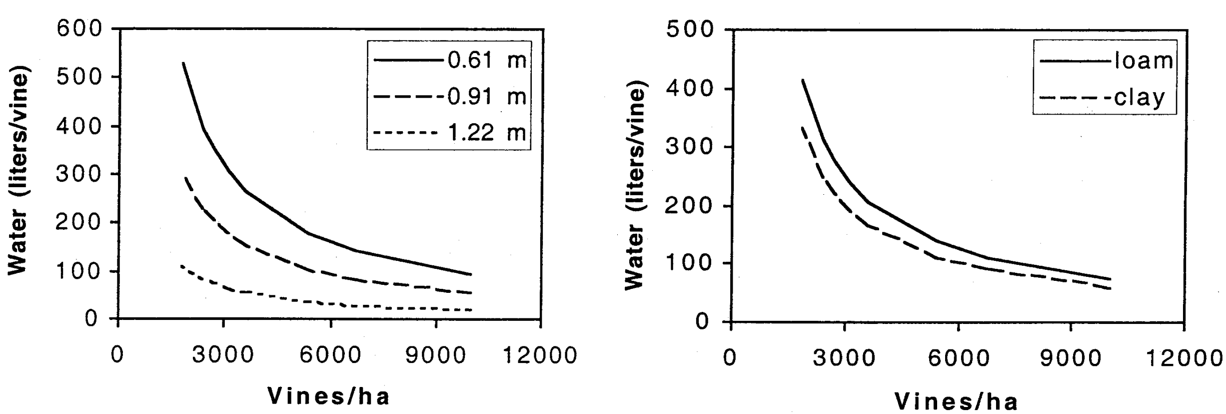

Figure 5. Simulated total water demand (rainfall + irrigation), cumulative for April-June, needed to evoke water stress onset (specified as -5 bars pre-dawn leaf water potential) in mid-July. Average weather and LAI of 1.7 m^2/m^2 were assumed in all cases. Left - sensitivity to rooting depth; clay-loam soil. Right - influence of soil type; root depth 0.61 m.

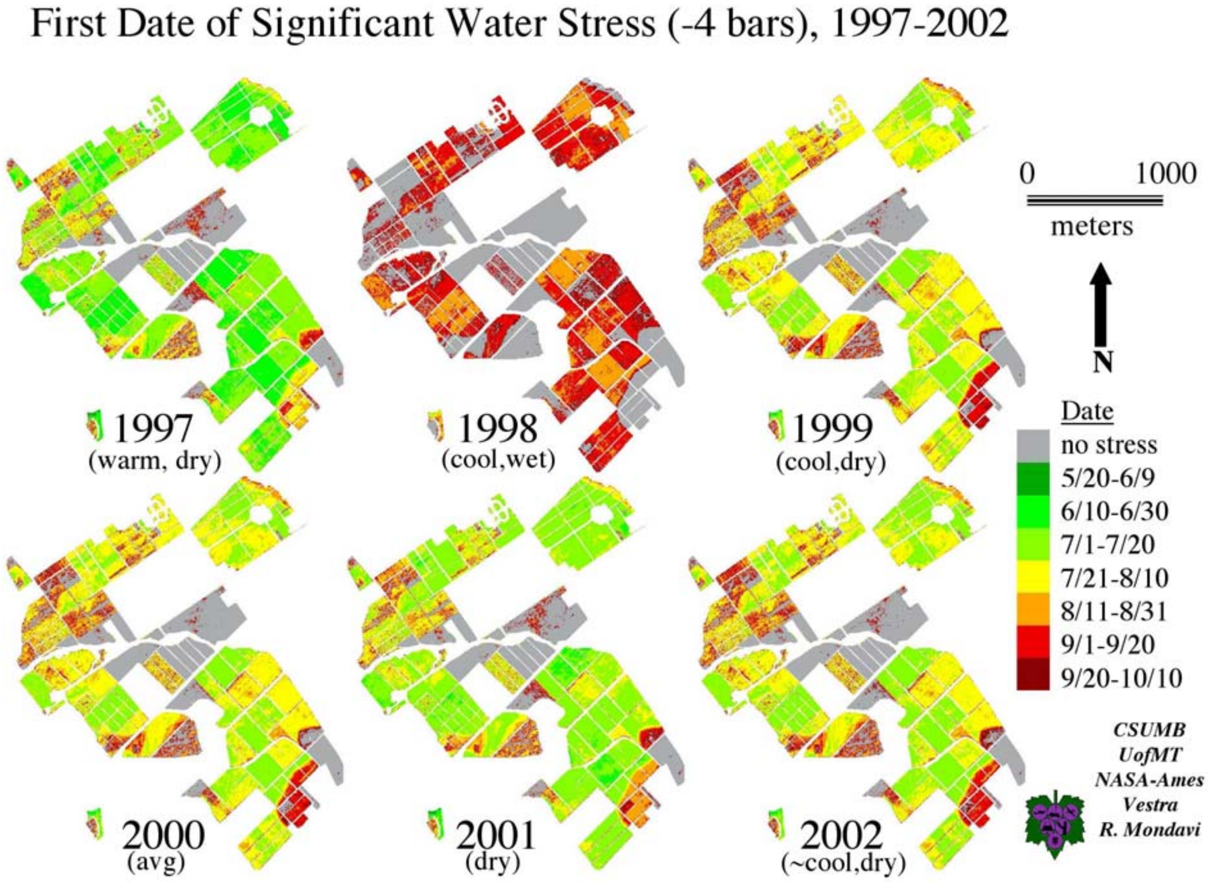

Figure 6. Simulation of water stress onset date for 1997-2002. Qualitative descriptor of temperature and precipitation, relative to decadal average, as shown.

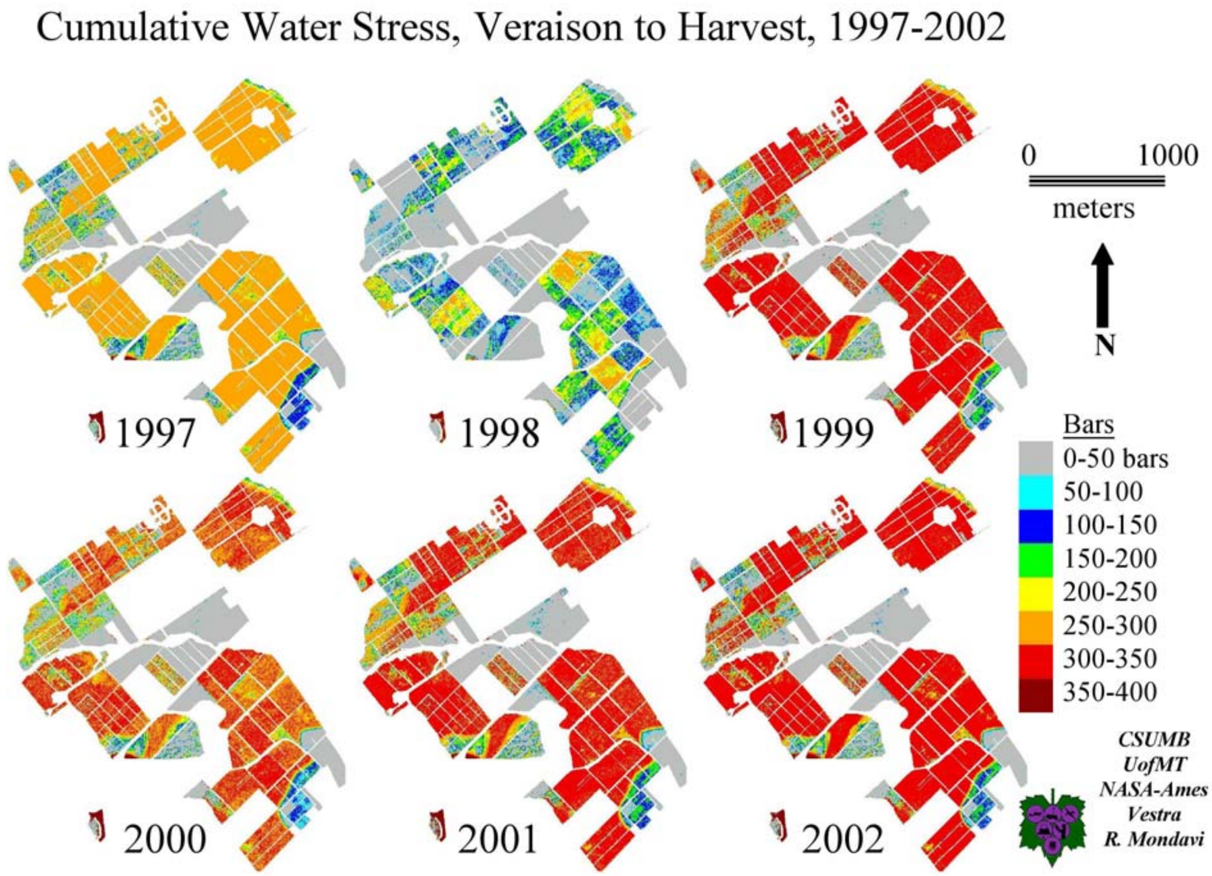

Figure 7. Simulation of cumulative water stress during late season (veraison to harvest), derived by summing daily values of leaf water potential. Weather descriptors as per Fig. 6.