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Utilization of GIS/GPS-Based Information Technology in Commercial Crop Decision Making in California, Washington, Oregon, Idaho, and Arizona

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Abstract: Ground-based weather, plant-stage measurements, and remote imagery were geo-referenced in geographic information system (GIS) software using an integrated approach to determine insect and disease risk and crop cultural requirements. Weather forecasts and disease weather forecasts for agricultural areas were constructed with elevation, weather, and satellite data. Models for 6 insect pests and 12 diseases of various crops were calculated and presented daily in georeferenced maps for agricultural areas in northern California and Washington. Grape harvest dates and yields also were predicted with high accuracy. The data generated from the GIS global positioning system (GPS) analyses were used to make management decisions over a large number of acres in California, Washington, Oregon, Idaho, and Arizona. Information was distributed daily over the Internet as regional weather, insect, and disease risk maps as industry-sponsored or subscription-based products. Use of GIS/GPS technology for semi-automated data analysis is discussed.

Key words: crop models, crop risk, degree days, disease forecast, disease modeling, disease risk, disease weather forecast, GIS, GPS, harvest forecast, insect risk, Internet, mapping, weather forecast.

The recent improvement of weather station technology facilitated the establishment of large, privately operated crop pest risk weather networks in the the western United States during the last 6 years. More than 2,000 weather stations now operate in California, Washington, Oregon, Idaho, and Arizona. Other advances in crop modeling and crop pest modeling, satellite imagery procurement and processing, and weather forecasting have increased our ability to obtain information from these networks for crop management recommendations. Data are geo-referenced using differential geographic positioning measurements (DGPS) and analyzed in geographic information system (GIS)-based software. The adaptation of the Internet into the mainstream agricultural community has facilitated the ability to provide a large number of people with near real-time crop risk information. These improvements in software, hardware, and Internet capabilities have been integrated into seamless automated and semi-automated systems that process information for near real-time management decisions. Growers and producers in commercial agricultural operations use this information to make disease and cultural practice decisions as standard operational practices for a number of crops covering millions of acres.

Ground-based weather and plant-growth measurements are integrated in different GIS global positioning system (GPS) software applications to determine disease and insect risks. GIS/GPS software applications are also used for site-specific weather forecasts, disease weather forecasts, regional risk maps, irrigation management, and harvest forecasts. Previously, manually operated data collection and analysis made real-time information distribution impractical.

Automated weather stations are used in weather networks for grape, melon, tomato, peppers, potato, strawberry, hops, apple, pear, and lettuce as well as other crops. Disease risk is estimated for late blight (potato, tomato, celery), *Botrytis cinerea* (flowers, tomato, grape, almond, strawberry), powdery mildew (grape, tomato, strawberry, lettuce, flowers, hop, apple, melon), and *Alternaria spp.* (carrot, almond, tomato, potato). For the purpose of this paper, the grape system is discussed because it is the oldest and the most advanced crop that uses these technologies in the western United States. The California lettuce system is discussed because it was the first to document the need for intense weather networks. The Washington apple system is discussed because it is the most extensive insect risk system.

Materials and Methods

Weather data collection: Ground-based temperature, relative humidity, leaf wetness, precipitation, wind speed, wind direction, and solar radiation were collected from more than 2,000 weather stations in California, Washington, Oregon, Idaho, and Arizona using Adcon Telemetry weather stations (Adcon Telemetry, Santa Rosa, CA). A weather station was established every 5 to 10 km in coastal hills and valleys and every 20 km in the inland agricultural areas and geo-referenced using DGPS. The weather data were automatically collected every 15 minutes by radio telemetry, sent by phone modem to central processing centers, and used to produce color-enhanced contour maps or bubble maps on a daily basis for distribution. These maps are distributed via the Internet (www.fieldwise.com;

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For the grape harvest projections, aerial imagery was collected from selected vineyards in the blue, green, red, and near infra-red (NIR) bands using an airborne, multispectral sensor and incorporated into a GIS software system.

Documentation of microclimates: In 1996–97 compiled comparisons were made of meteorological parameters between Adcon stations as part of a program conducted by the Iceberg Lettuce Integrated Pest Management Risk Assessment Group (ILIPMRAG) (Fox, 1998). The purpose of the study was to define the size of microclimatic regions within the lower Salinas Valley, a topographically uniform region in which lettuce diseases frequently occur. Once determined, the density of weather stations needed for microclimate representation could be determined. Two time periods were chosen for analysis: 0600–1000 to bracket the morning burn off of coastal stratus and 0600-1200 to bracket the entire morning risk period for growth of downy mildew spores. The Adcon temperature/humidity sensors were located 0.3 m above ground and were representative of the near-canopy environment for lettuce. Between-station correlation coefficients of leaf wetness, temperature, relative humidity, wind speed, and solar radiation were calculated during the late-spring through late-summer growing season in 1997.

Software: Adcon Telemetry's proprietary software, addVANTAGE, was used to collect and process the weather data. The Fox Weather, LCC Export rapidly downloaded weather data from addVANTAGE and integrated it into Fox Weather's disease weather prediction model. MapInfo (MapInfo Corporation, Troy, NY) was used with proprietary Terra Spase, Inc. GIS software, Terroir, to analyze the weather data, create the maps, and automatically post them to the Internet. These maps provide growers with a regional perspective on weather and disease risk-related parameters. ENVI (Resource Systems, Inc., Boulder, CO) and a custom processing application built on Research System's Interactive Data Language were used to process aerial imagery from the airborne multispectral sensor for grape harvest projections. The multi-spectral imagery was processed to various levels and used to gauge vine stress and estimate crop yield (Fig. 1).

Proprietary weather analysis software developed by Marta Systems, Inc. (Santa Paula, CA) was used to analyze infrared and visible imagery from the Geostationary Operational Environmental Satellite (GOES) and display maps from numerical weather prediction (NWP) models. These were used to create the weather forecasts. The weather-related disease pressure forecasts were developed from Fox Weather's proprietary disease weather forecast system (DWFS), which integrates forecasted information and real-time weather data from the weather network. Geographically oriented, it predicts wind speed, temperature, leaf wetness, relative humidity, and precipitation. The DWFS predicts site-specific disease weather conditions up to 5 days in the future. Regional 10-day agricultural weather forecasts are issued daily, and a 30-day outlook is issued weekly.

Models: Insect degree days have not been mapped for grapes but have been mapped extensively for six apple insect pests in Washington, including obliquebanded leafroller, codling moth, peach twig borer, *Laconobia,* western cherry fruit fly, and pandemis leafroller according to the criteria listed on the University of California Statewide IPM Web site (www.ipm.ucdavis.edu). These maps were used in conjunction with trap counts from more than 3,000 traps located in the mapped areas to determine treatment actions.

The powdery mildew model was developed in 1994 at University of California, Davis, Department of Plant Pathology and Cooperative Extension. It is based on temperature, leaf wetness, and humidity (Gubler et al., 1999). The model was first validated for wine grapes in Napa and Sonoma Counties and for table grapes in Kern County, California, in 1995–96. The first commercial applications of the model were in 1997 in Napa and Sonoma Counties by Terra Spase, Inc. and in Kern County by Western Farm Service, Inc. This model is now used in many vineyards throughout the world. It has a cleistothecial model for the primary inoculum stage and a conidial model for the secondary inoculum stage. Cleistothecial warnings follow periods of prolonged leaf wetness at various temperatures. The conidial model, which uses temperature, includes an index that ranges from 0 to 100. If the index is between 60 and 100, it is appropriate to spray via the minimum-labeled spray interval. If the index is between 0 and 30, it is appropriate to spray via the maximum-labeled spray interval. If the index is 40 to 50, it is appropriate to spray on an intermediate-spray interval. This strategy usually saves at least one spray per season as compared to a calendar program and improves crop quality and yield.

The Broome Botrytis model (Broome et al., 1995) was modified by Fox and Thomas (pers. comm.), validated in 1997, and commercialized in 1998 (unpubl.). The index is calculated at noon, based on temperature and leaf wetness duration. If the index is 0.5 or greater, it is appropriate to spray. Sprays are generally most effective if applied within 48 hours after a Botrytis event of 0.5 or more.

Harvest Forecaster, developed by Terra Spase, is a proprietary model that uses weather, ground, and aerial multispectral image data from the crop to predict harvest dates and yields in specific vineyard blocks. It was developed in 1996 and 1997 and implemented in 1998. It is now commercially available in the north coast of the California vineyard growing areas (Oltman, 1999).

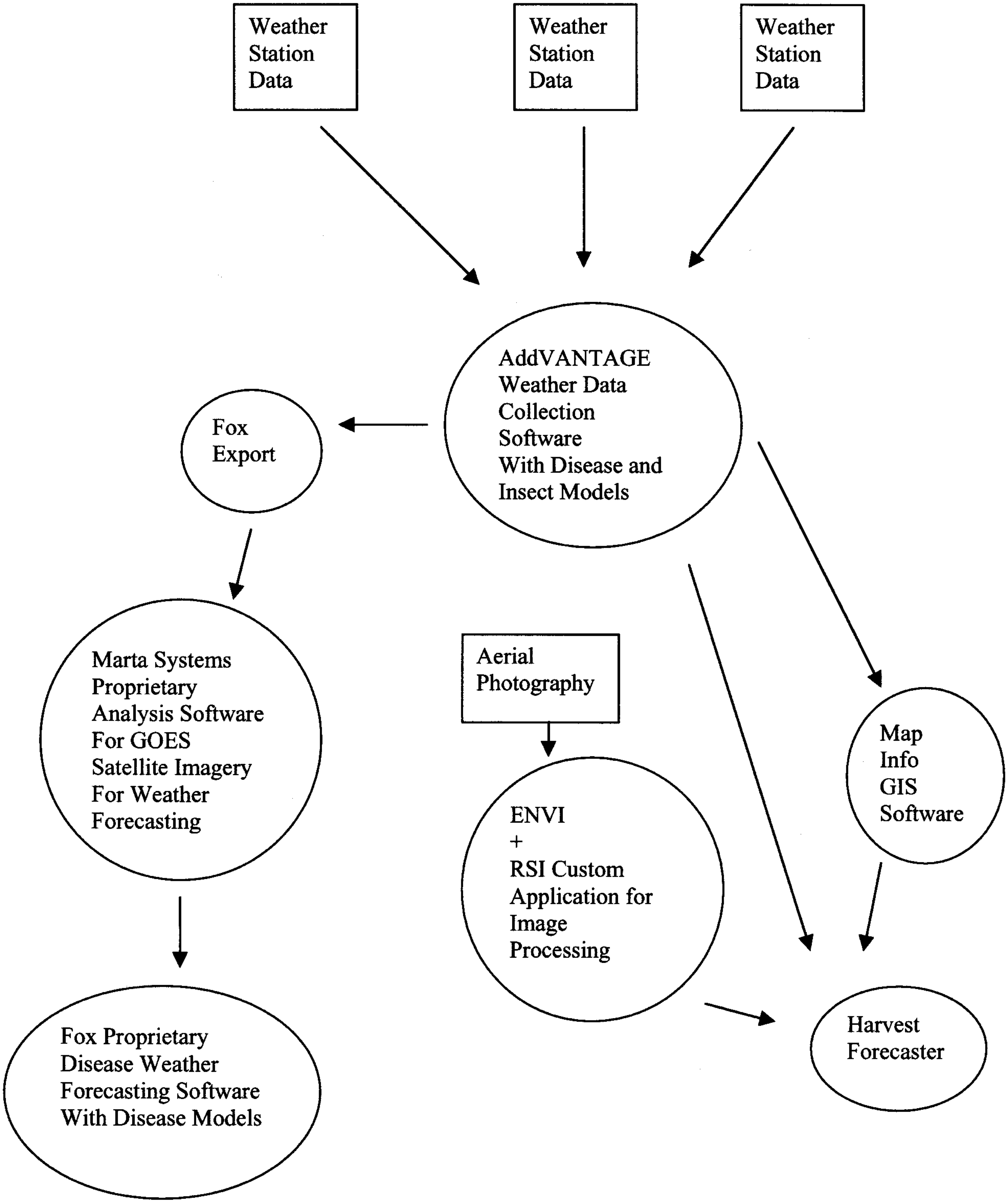

FIG. 1. Flow chart of GIS data processing and softwares.

RESULTS AND DISCUSSION

Documentation of microclimates: The data were filtered with regard to time of day to coincide with the time of maximum effect of weather parameters on growth of downy mildew disease in lettuce. Table 1 shows correlation coefficients between Adcon stations for both the stratus burn-off period and the 0600-1200 period.

TABLE 1. Comparison of simple correlations (R^2) of meteorological parameters between pairs of weather stations in Salinas Valley and within 20 km of each other (8 stations total).

Weather parameter	Range of correlations 6 a.m. to 12 noon	Range of correlations 6 to 10 a.m.
Leaf wetness	0.83 to 0.45	0.75 to 0.10
Temperature	0.98 to 0.88	0.97 to 0.84
Dew point	0.94 to 0.78	0.96 to 0.73
Relative humidity	0.95 to 0.66	0.90 to 0.48
Wind speed	0.93 to 0.54	0.88 to 0.37
Solar radiation	0.94 to 0.54	0.96 to 0.78

Leaf wetness was generally uncorrelated between sites with an r^2 value as low as 0.45 between 6 a.m. and noon or as low as 0.1 between 6 and 10 a.m. Other parameters were more closely correlated between sites. Temperature and dew point were highly correlated between sites ($r^2 > 0.84$). Intermediate variability was observed for relative humidity and wind speed, especially between 6 and 10 a.m. This indicates that it is important to directly measure leaf wetness in microclimates to accurately forecast disease risk. It was also found that (i) the main microclimatic differences between the stations were related to differences in the time of burn off of marine stratus; (ii) leaf wetness (> 3 units) occurrence was dependent on leaf temperature, dew point, wind speed, and solar radiation; (iii) timing of rain and subsequent wind events was important to forecasting both downy mildew and Botrytis index and leaf wetness; and (iv) small errors in timing of rain and wind events could significantly affect the length of time of leaf wetness. Errors in the estimation of duration of leaf wetness could affect the index and the accuracy of the disease index forecast. As expected, locations with earlier burn off of stratus experienced higher wind speed, higher solar radiation, and lower mean leaf wetness values. The details of this study are reported elsewhere (Fox, 1998).

Risk maps: Daily weather maps are produced for observed maximum, minimum, and average temperatures; average relative humidity; and total rainfall (Fig. 2). These maps are posted by 9 a.m. the day after the values are recorded. Temperature and precipitation maps have been used to adjust pest management spray programs and irrigation schedules. For example, some fungicides and fertilizers will cause burn on the crop if applied when air temperatures are higher than 35 °C. Rainfall maps are used to (i) adjust irrigation applications; (ii) decide if pesticides have been washed off and need reapplication; and (iii) evaluate the occurrence of erosion damage, flood risk, and ground water recharge. Average relative humidity is helpful in determining water stress risks and adjusting irrigation needs.

Insect degree-day maps were useful tools when used in conjunction with trap counts to time sprays according to field-specific biofixes (Fig. 2B). The trap counts also were useful in documenting that the populations remained low following spray applications, giving growers greater confidence in waiting to apply sprays for the optimum efficacy based on insect phenology.

Nematode soil temperature maps could be provided but have not been, to date. The authors hope that entomological collaborators will soon be identified and such work will expand into the grape industry (it already exists in the apple and pear industries). University researchers have been invaluable in determining the core weather parameters for pest risk assessment and in collecting detailed disease progress curves and insect counts needed for creating and validating new models. Projects in which researchers and commercial agriculture information companies use the same system to collect field measurements tend to become validated and implemented more quickly.

Disease risk maps for powdery mildew and *Botrytis*, based on observed data from the weather stations, are posted daily (Figs. 2C; D). The color key allows growers to use the model more intuitively. Red areas are regions of high disease risk, green regions are areas of low disease risk, and yellow and orange regions have intermediate disease risk. Many of the crop disease models are calculated using differing methods and are not as standardized as insect degree days have become. The use of color-coded maps has greatly increased the speed at which growers and producers can learn how to use a new crop disease model. The colors are more intuitive—green is safe, red is danger, and yellow and orange are two levels of caution. With a large number of stations to evaluate, it is time consuming to do this one location at a time; but with a map, regional risk can be assessed quickly and accurately, making this a valuable operational tool for crop managers. Specific sites within high-risk areas can be evaluated more thoroughly using graphs of risk over the previous weeks. This approach has been especially useful for large crop management companies and processors, which must track conditions over many locations concurrently. Disease maps are combined with ''heads up'' scouting reports to let pest managers know what has been sited in each area and if inoculum is likely to be present.

Weather and disease weather forecasts: Weather forecasts and disease weather forecasts have been instrumental in removing the surprise factor of disease outbreaks. As new pesticide chemistry becomes less persistent in the environment, it is increasingly important to know the particular day-of-infection conditions early and apply preventive pesticides before the event. Disease weather forecasts have been 80% accurate. Growers can be informed of an impending disease infection event up to 5 days in advance. As the time of the forecasted event approaches, the timing and severity of the event forecasted become more accurate, approaching 80%. Growers can respond to the forecast by applying a spray

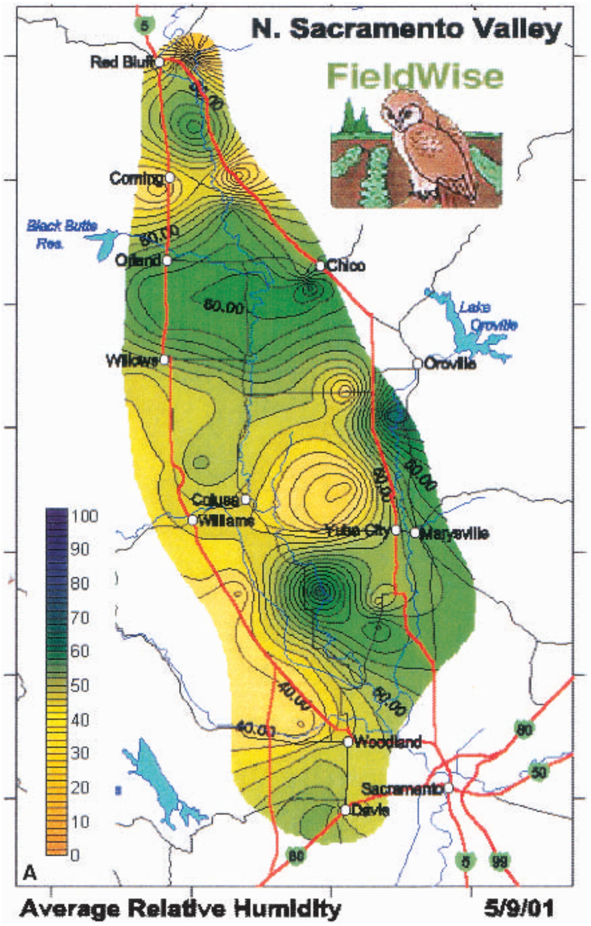

Fig. 2A. Example of a weather map, showing average relative humidity, generated using GIS /GPS technology from 50 weather stations (1 station per 20 km) in Sacramento Valley, California, which is a subset of the 2,000-weather-station system.

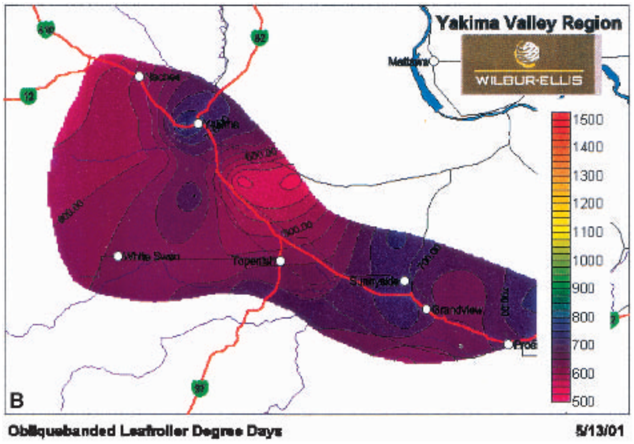

Fig. 2B. Example of a degree-day map generated using GIS/GPS technology from 25 weather stations (1 station per 20 km) in Yakima Valley, Washington.

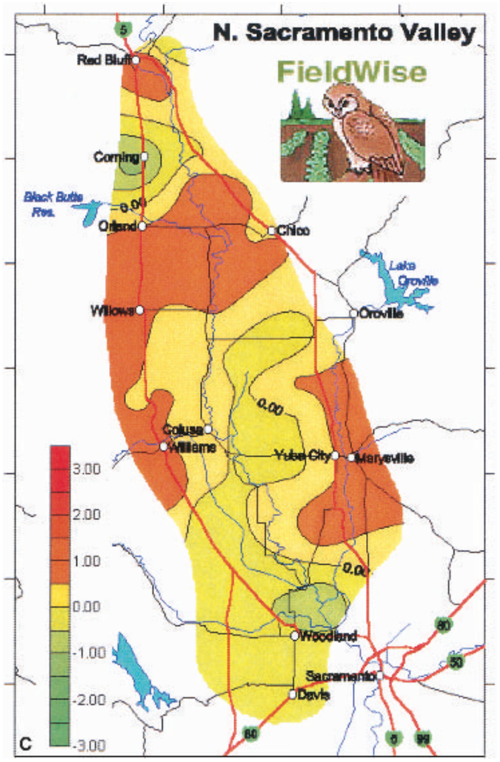

Fig. 2C. Example of a disease risk map, showing the Botrytis index generated using GIS/GPS technology from 50 weather stations (1 station per 20 km) in Sacramento Valley, California, which is a subset of the 2000-station system.

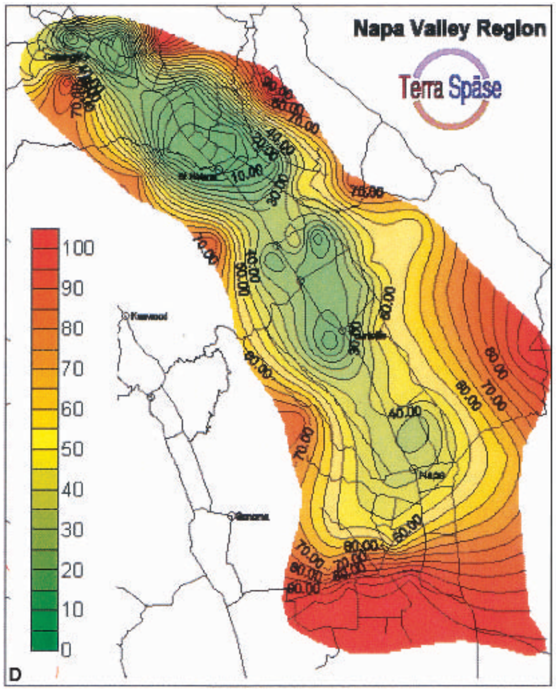

Fig. 2D. Example of a disease risk map, showing powdery mildew conidial index, generated using GIS/GPS technology from 50 weather stations (1 station per 7 km) in Napa Valley, California, which is a subset of the 2000-station system.

TABLE 2. Forecasted harvest dates made by Harvest Forecaster (Terra Spase, Inc.) at four dates compared to the actual harvest date in 1999 for wine grapes in California.

Vineyard district	Variety	Harvest date forecasted on July 1	Harvest date	% Error
Carneros	Pinot Noir	Sept. 13	Sept. 13	0
Monterey	Merlot	Oct. 20	Oct. 20	0
Sonoma	Viognier	Oct. 1	Oct. 4	1.4
St. Helena	Cabernet	Oct. 11	Oct. 12	0.9
Stag's Leap	Cabernet	Oct. 16	Oct. 17	0.9

a day or two before the event to ensure that sufficient residue is present to protect the crop during the maximum-risk period.

The 30-day forecasts allow managers to make long-range plans. Later, managers check the 10-day agricultural weather forecast to see if the event is still likely. Finally, as the event approaches, they check the 5-day disease forecast and decide whether or not to apply a spray. The maps of observed risk are used to monitor the accuracy of the forecast and verify that the forecasted event actually occurred. If there is an error in the forecast, managers have immediate feedback to take corrective measures, usually within 24 hours. Forecasts are presented as maps or text, but are the result of geographically integrated and analyzed data from weather prediction and disease weather forecast models, satellites, and weather station observations.

Harvest date and yield forecasts: Harvest date was predicted in eight Cabernet Sauvignon vineyards in the Napa Valley using the Harvest Forecaster model in 1998 (Oltman, 1999). In 1999, additional varieties and growing districts in California were evaluated (Table 2). The actual harvest date in five vineyards was predicted on July 1, with less than 2% error. Results from yield estimation practices, which were based on data vines, and those produced by Harvest Forecaster are shown in Table 3. A 5% to 10% improvement in yield estimates was achieved using the Harvest Forecaster model in Cabernet Sauvignon and Pinot Noir vineyards, respectively.

Operations: GIS/GPS technology and software applications are effective tools to integrate and analyze complex datasets from various sources to create real-time and near real-time information products for crop decision support. Furthermore, these products can be more easily understood and are less likely to be misused because color is used in map presentation. Automation of data collection, analysis, presentation, and distribution is an essential component for large risk systems that service many areas and many crops.

Validation is conducted on interpolated mapped weather conditions using other weather stations that are located within the geographic area, but are not used to create the maps. If a new microclimate is identified, a weather station is placed within that microclimate. Weather data mapping has added the benefit of improving quality control efforts to network operators so they can more quickly identify sensor malfunction and correct it by replacing the sensor. Disease risk maps are validated by collecting scouting observations on a region-wide basis. Differences in mapped risk and observed risk have been due to sensor malfunction (which was quickly corrected), or lack of inoculum, or lack of site-specific data for a unique field condition, such as irrigation.

Distribution of information over the Internet has greatly increased the number of individuals who can access the same information concurrently. It is only recently that many growers have started using the Internet to obtain information, especially growers who are not located near university centers or large cities. The Internet has become a powerful information-gathering tool for them. The 24-hour-per-day/7-day-per-week availability is also helpful during busy operational periods.

As satellite imagery libraries, weather satellite, and weather network data become more expansive, the use of GIS/GPS technology to integrate these data will become increasingly powerful. Our ability to measure current conditions and predict future conditions, and then to re-measure current conditions and update forecasts can result in important resource allocation decisions for growers as they try to reduce inputs while optimizing quality, increasing profit, and facilitating the daily work of the operational field or vineyard managers.

The challenge of technology is to measure these conditions more efficiently and effectively. The challenge of science is to understand the significance of these measurements and their economic consequences. The challenge to growers is to make use of these approaches to produce a crop that is higher in yield, quality and (or) profitability. The more effectively current and fu-

TABLE 3. Comparison of forecasted yield predictions using traditional field estimation techniques and yield predictions using Harvest Forecaster (Terra Spase, Inc.) model in 1999.

Variety	Method of prediction	Predicted yield (tons)	Actual yield (tons)	Error (%)
Cabernet Sauvignon	Field estimation	45.9	50.6	9.3
Cabernet Sauvignon	Harvest forecaster	52.6	50.6	4.0
Pinot Noir	Field estimation	96.7	112.1	14.2
Pinot Noir	Harvest forecaster	108.1	112.1	3.5

ture conditions can be presented to growers, the more likely they are to make the best decisions for their business to remain profitable year after year with as few surprises as possible.

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