The Application of Earth Science Findings to the Practical Problems of Growing Winegrapes

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Abstract
Transforming science findings into practical applications is presented in the specific case of using remote sensing to detect the presence of an infestation of grapevines. The vines of Napa Valley were attacked by the root louse, *Phylloxera*, in the 1990's resulting in a very large loss of production. The spectral response of the vines can be causally linked to the disruption in the ecology of these agro-ecosystems. Borrowing from NASA's investments in ecological science and its use of remote sensing, an applied project was formed and conducted with Robert Mondavi Winery to experimentally determine if we could remotely sense changes in the vineyards linked to the actions of this louse. We found that changes in leaf development due to the destruction of the roots was strongly associated with presence of the louse. This result is consistent with the ecological science and remote sensing of natural ecosystems. We also examined changes in leaf biochemical composition, leaf temperature and chlorophyll content. The experience has helped to further the development of a service industry based on remote sensing in the grape-growing regions of California.

I. INTRODUCTION

After years of false starts, NASA has re-established a program of applications, called the Applications, Commercialization and Education (ACE) Program in the last few years. One of the stated goals of ACE is to find ways to apply the findings and associated remotely sensed data of the global change science programs to help solve practical everyday problems[12]. While the intention of the ACE program is wide in vision, it opens the question of just how much and what of the science and data have good potential for transformation into the specialized needs of end users. Unlike earlier applications programs of the 1970's and early 1980's, the ACE effort is burdened by a science endeavor focused almost exclusively on global scale issues with a data acquisition system driven by the needs of its science community. In addition, it must deal with a commercialization element aimed a getting as much as possible of the NASA remote sensing investment out of the private sector. Both of these realities have consequences, beneficial and detrimental, to the aims of an applications program. It is fair to ask how the findings of a globally oriented science can be brought to bear on practical problems of everyday end users. The science program developed over the past 20 years never fully considered the requirements of the practical parts of society, despite a number of years of previous useful experience, in formulating the strategy for the global science and data systems. This situation decreases the chances for applied successes, if the needs of the two communities are far apart. This could be a political problem for the global program, if the political system insists on more than science driven policy (the principal and worthy aim of the global effort) as justification for the program. It is also fair to ask if the business models being adopted by the commercial sector would encourage or discourage the investment in remote sensing and modeling technology of end users. This paper looks at the former questions, how can the science be brought to bear on an important practical problem and what does this tell us about the data system.

The example we will discuss is the real problem of a severe infestation of the grape growing regions of California by a root louse. We will show how previous science investments in terrestrial ecology, remote sensing of ecologically important variables, and in the development of sensor technology was used to analyze and to monitor this crop pathology.

II. THE PROGRAMMATIC CONTEXT OF ACE

NASA is making three major investments in Earth science. In support of the international global change science program, called the International Geosphere-Biosphere Program (IGBP), NASA funds a large interdisciplinary research program in conjunction with the IGBP international partners and the U.S.

1082-4006/00/0602-181$5.00

Global Change Research Program [14]. The goal of these programs is to achieve an integrated and predictive understanding of the interactive global processes of the entire Earth system (see www.earth.nasa,gov). This is science at a truly planetary scale. The principal purpose is to inform the public debate on policy based on sound scientific analyses and judgments. While the IGBP/USGCRP encompass the entire Earth system, NASA's emphasis has focused a bit more narrowly on the climate system [8]. This includes those processes in the biological domain that affect changes in climate, such as the feedback between the biosphere to the atmosphere in terms of biogenic trace gas production, momentum, energy and water exchange, and radiative transport. One of the most highly visible products of this research is the development of many mechanistic models of Earth processes, models the science community eventually hope to integrate and operate on a truly interactive and predictive level. Thousands of scientists and graduate students are actively engaged in this science program, both within NASA and all of its partners [12](and at www.earth.nasa.gov)

The second major NASA investment is for an impressive series of satellite remote sensing missions to regularly compile a key global set of variables describing the Earth. The science community has identified 24 key variables for long term monitoring, some of which might clearly contribute to practical problem solutions. Other satellite and aircraft missions contribute additional data and variables. Over the next 20 years, numerous satellites will be launched to make these measurements regularly so as to build up a long term view of how Earth's environment is changing. The first in the major series (the Earth Observing System, EOS) was recently launched in 1999, called Terra [9]. The first large satellite bus carries several sensors including the Moderate Resolution Imaging Spectrometer, which can make nearly daily observations over much of the world. The Earth Observing System is coordinated with related and smaller missions and those of many countries as well as other US agencies. And, some data components of the system are expected to be obtained from commercial providers. Virtually the entire fleet of long term satellites are free flying and in polar orbit.

The third major investment is for a data archive, management and distribution system. NASA's part is the EOS Data and Information System (EOSDIS), conceived mostly to satisfy the needs of its science community. Through the efforts of many people, NASA has come to recognize the EOSDIS may not well serve the needs of the end user community. So, NASA recently initiated programs to establish a data federation (called the Earth Science Information Partnership), a highly distributed data access and distribution system designed to provide access not only to NASA data but to all kinds of other data relevant to the interests of the end user community. And, NASA has created regional applications efforts to begin to work with regional to local end users. ACE also initiated several focused application research programs, some in conjunction with other agencies. Efforts are proposed to expand this regional program nationwide to reach regional, state and local users.

For various political considerations and decisions, the private sector will provide some of the key data needed by both the science users as well as, potentially, the end users. Two significant examples are high spatial resolution multi-spectral imagery and hyperspectral imagery. The primary business model is for tight control on the distribution and re-use of any data acquired, through copyright restrictions. Given the experiences with Landsat in the commercial sector, and the need to recover costs, the unit cost of such data can be somewhat prohibitive to members of the end user community. And, not too surprisingly, NASA is subsidizing these operations with fairly large annual data buys. Though the user base continues to expand, the main buyer of data is the federal government. Will this business model succeed in establishing the large user community and service industry needed to make remote sensing an everyday product?

It is against this backdrop that we will illustrate one example of how ACE can work to bring science to bear on a practical problem. The example contains aspects which do not fully use much of the investment (EOSDIS, satellite data) but relied on data acquired from aircraft, even though the kinds of data employed may someday be available from spacecraft. Our main goal here is to illustrate how advancements in science were used to address a practical agricultural problem by forming deductive and testable hypotheses with both scientific and practical benefits.

III. THE NATURE OF THE PRACTICAL PROBLEM

In the early1980s, a new strain of the root louse, *Phylloxera*, found its way to the vineyards of Napa Valley, California. Napa Valley is one of the premier grape growing regions of the world, producing fine wines in large quantities. This root louse is particularly well adapted to feeding on the most popular grafted root stock. AxR#1, used on as much as 75% of the grapevines in the county. The difficulty with *Phylloxera* is the lack of an eradication treatment or a means to control its spread. This very small louse feeds on the fine roots of the grapevine and spreads by reproduction as well as by mechanical and other means. The infestation weakens the plant by reducing its access to adequate water and nutrients from the soil. As the plant attempts, with the growers help, to mitigate the injury, it reallocates photosynthate to the roots reducing the supply for growing leaves, extending the vines and producing sugars for the maturing grapes. Sometimes fertilization and irrigation can extend the life of the vine as production declines, but eventually the plant dies and must be removed. This removal generally involves entire fields once the grape grower determines it is not economically feasible to try to combat the infestation and it becomes economically more effective to replant an entire field. This creates a serious cash flow problem since the newly replanted field is years away from production. The new plant, grown on resistant root stock, must be nurtured for a number of years to get another crop. The break in the productive life of the vineyard, a perennial plant, must therefore be identified as early as possible and its spread monitored. Then a plan can be made to replant destroyed fields while maintaining the overall production of the fine wines for which Napa Valley is justly famous [5].

IV. DEVELOPMENT OF THE REMOTE SENSING HYPOTHESES USING AN ECOSYSTEM APPROACH

When NASA first became engaged in global change science, the terrestrial ecosystem community began to develop predictive mechanistic ecosystem process models that could make explicit use of variables derived from remotely sensed data. Most of these models owed their heritage to the earlier International Biosphere Programme [18]. Those models were conceived from a lot of highly detailed and site specific information. Most of that information cannot to be obtained from remotely sensed data. So, the NASA goal was to simplify the models to operate on fewer and remotely sensible variables but still explain variation across regional to global scales. For example, net primary production in conifer forests can be estimated reasonably well if one can determine the leaf area index of the forests and combine that information with climate data [15]. Estimation of leaf area index (LAI), the surface area of leaves in a canopy per unit of ground area, had been investigated for crops and grasses for several years with some success using ratios of spectral reflectance observed in the red and near infrared (e.g.,[22]). The techniques were extended to conifer forests beginning in 1983 [17, 19]. Leaf area index is also related to the capacity to absorb photosynthetically active radiation (fPAR), a key variable to assess carbon assimilation [21]. The same techniques are often used for measuring both LAI and fPAR from remote sensing, and the measurement can be accomplished with broad band data such as AVHRR and Landsat TM [20].

The annual development of canopy leaf area is strongly tied to the availability of soil water [13] and the ability of the plants to take up this water. Any impairment of water transpiration by the loss of fine roots in the grapevines would suggest that canopy development would also be significantly impaired. Our first hypothesis (H_1), based on taking an ecosystem perspective, was that infested plants will display a reduced LAI, expressed as either shorter shoot lengths or smaller leaves or fewer leaves per unit of ground area.

Elucidating the biogeochemical cycling characteristics of ecosystems is more complex. Knowledge of the nitrogen content , protein and chlorophyll content in leaves can give some insight to the amount of nitrogen available for turnover as well as the capacity for absorbing PAR. Knowledge of the lignin content gives some indication, together with surface climatology and soil wetness, of the rates of leaf litter turnover or mineralization of organic nitrogen into inorganic and readily available forms for uptake by plants [1]. These biochemical components (protein and lignin) express themselves in leaves as absorption by organic bonds of O, N, H and C, harmonics and overtones of the fundamental stretching frequencies of the molecular bonds [4]. In the case of chlorophyll, the absorption is accomplished by electronic transitions. These properties may be sensible using high spectral resolution, or imaging spectroscopy, methods. And the new hyperspectral imaging spectrometers offer the first hope of doing this. We pioneered research in this area from the lab to the airborne sensors during the 1980's[16].

Once again, the loss of fine roots for taking up the soil mineral nutrients for transport to the leaves in the grapevines would suggest that biochemical changes might be related to the presence of the infestation. Since biochemical changes can occur even before visible symptoms appear, our goal was to determine if biochemical changes occur in a pre-visual state of infestation, i.e., very early, and how soon do these symptoms become prominent throughout the growing season? We hypothesized(H_2) that early and progressive biochemical changes would be sensible by high spectral resolution analyses at the leaf level, and hopefully the canopy level using remote sensing.

Finally, when plants experience loss of fine roots, their water transpiration capacity is impaired. Since a loss of evapotranspiration will fail to cool the broad leaves of grapevines, this should result in an elevated leaf surface temperature relative to the background soils. We hypothesized (H_3) that the leaf temperature of infested plants should be sensible as changes in thermal infrared emission and measurable with both hand held detectors in the field and should be reasonably well measured from an airborne sensor operating in the thermal infrared.

V. APPLICATION TO *PHYLLOXERA* PROBLEM BY HYPOTHESIS

As described above, by taking an ecosystem approach as informed by remote sensing research in natural ecosystems, we could develop a set of testable hypotheses for the study of the infestation of grape vineyards using remote sensing.

Research Team

This project was named GRAPES for Grapevine Remote sensing Analysis of *Phylloxera* Early Stress. The project team drew on the combined talents of personnel from the Robert Mondavi Winery, the University of California at Davis and its Cooperative Extension, the California State University at Chico and NASA Ames' Ecosystem Science and Technology Branch. This team not only wrote a successful proposal to fund the jointly sponsored research but also a detailed plan to implement and guide the study, including the naming of advisory and review panels. These two steps helped to assure the commitment of all the parties to the work.

Experiment

Shortly before the 1993 growing season (early May), a partially *phylloxera*-infested field of Cabernet Sauvignon vines grafted to AxR#1 rootstock was chosen as the study site. The 12 acre field, located near Oakville, CA (USA), was planted in 1981 in Clear Lake clay and Bale clay loams. The vines were trained on a standard two-wire trellis without shoot positioning. Rows were 3.65 meters apart, oriented northeast to southwest, with a vine spacing within-row of 2.43 meters. The site was clean cultivated to remove all vegetation except grapevines.

Nine study plots were established at the study site, with each plot containing 40 vines (4 rows, 10 vines per row). Three plots were established in each of three infestation categories: infested/visually symptomatic; infested/visually asymptomatic (pre-visual), and uninfested. The plots were delimited on the basis of grower knowledge, a 1992 aerial infrared photograph, and a *phylloxera* survey. The survey, performed in May 1993, involved excavation of several shallow roots from beneath drip irrigation emitters to a depth of 18-45 cm, and use of a magnifying lens for visual examination for *phylloxera* presence. Vines received a rating based on the highest population found among the root pieces examined. Eight values, four in each of the two middle rows of each plot, were designated as data vines for spectral analysis. To avoid damaging roots and possibly introducing additional stress on the "data" vines, *phylloxera* ratings were assigned as the mean rating of two immediately adjacent vines, one in the same row as the "data" vine and one in an adjoining row.

Remote sensing data

Given the fine scale at which the pattern of infestation presents itself and the support area for sampling the vines, a variety of airborne and satellite data were collected, recognizing that the former were the data most likely to discern the fine scale patterns provided the spectral information is adequate. Also, we chose to employ commercial airborne data in addition to data from NASA sensors in anticipation of future services to the wine industry if the project proved to be a commercial success. The airborne sensors included the Airborne Data Acquisition and Registration (ADAR), a commercial multi-spectral sensor; the Compact Airborne Spectrographic Imager (CASI) of Canada; the Digital Multi-spectral Video (DMSV), another commercial sensor; an experimental CCD camera from Ames called the EO Camera which operates from the NASA ER-2; the Real Time Digital Airborne Camera System (RDACS); and one of the airborne simulators for the Landsat Thematic Mapper, called the NS001 Thematic Mapper Simulator (TMS) flying aboard NASA Ames' C-130 aircraft. Only the CASI data have the performance characteristics to conduct spectroscopic analyses for testing hypothesis 2. The other sensors could be used to test hypothesis 1. And, test of the third hypothesis could be done with data from the TMS or from another Ames sensor specially designed for the thermal infrared, the Airborne Infrared Disaster Assessment System (AIRDAS) flying on the C-130. Most of the data were taken from the nadir direction except the CASI data at a 45 degree oblique view angle that tends to minimize the soil contribution. Table 1 lists some of the characteristics of these sensors [11]. A Landsat Thematic Mapper image was also acquired covering the entire area and used primarily for land cover mapping of the whole valley into broad classes but not for trying to detect patterns of infestation due the relatively coarse spatial resolution.

Table 1. Airborne sensors used in the GRAPES project. Spatial resolutions are based on the respective flight altitudes.

Sensor	Channel center (nm)	Spatial res. (m)	Source
ADAR	440, 515,650, 890	3	Positive Systems, Whitefish,MT
AIRDAS	645,1635, 4550, 9250	5	NASA ARC
CASI (4 ch)	550, 630, 680, 787	2	Borstad Associates, Sidney, BC, Canada
CASI (8 ch)	500, 550, 630, 680, 710, 737, 747, 788	resampled to 2	Borstad Associates, Sidney, BC, Canada
DMSV	450, 550, 650, 750	1	SpecTerra Systems, Pty., Ltd., Nedlands, Western Australia
EO Camera	680, 720, 735, 750, 775	5	NASA ARC
NS001 TMS	489, 566, 665, 839, 1240, 1640, 2240, 11300	3 to 5	NASA ARC
RDACS	548, 650, 821	1	NASA Stennis Space Center

Hypothesis 1

In the dormant periods following the 1993 and 1994 growing seasons, pruning weights were obtained for each of the 40 vines within each plot. The pruning weight, which is generally highly correlated to leaf area, is the total weight of shoots per vine less a small amount of shoot retained to support the following season's new growth. Pruning weights (Table 2) were negatively correlated with mid-season *phylloxera* ratings in both 1993 (r2 = 0.71, n = 9) and 1994 (r2 = 0.72, n = 9), confirming that *phylloxera* stress reduced standing foliar biomass within the study site.

Spectral data from the high spatial resolution, airborne multispectral images were transformed to Normalized Difference Vegetation Index (NDVI = red – IR/red + IR). The NDVI is a commonly used transform related to the display of leaf area. NDVI generally ranges from near 0.0 for bare soil to near 1.0 for dense canopies. Due to the relatively large proportion of exposed soil found in the study site (typical of vineyards), the mean NDVI for the study plots occupied the low range: 0.19-0.38 in 1993 and 0.13-0.37 in 1994. For the combined 1993/1994 data set, the mean NDVI per plot was related to mean pruning weight per plot (Figure 1; NDVI = 0.15 + 0.24log(prun-wt), r^2 = 0.72, n = 18 [6]), suggesting that vegetation index is correlated to the reduction in leaf area related to the vine decline caused by *phylloxera*.

Table 2. Mean pruning weights per vine and mean Normalized Difference Vegetation index class values for pixels within plots.

	1993		1994	
Plot	*Pruning Weight (kg)*	*Class*	*Pruning Weight (kg)*	*Class*
1	1.39	1.648	0.92	0.023
2	0.70	1.129	0.45	0.186
3	0.95	2.581	0.58	0.795
4	2.25	5.835	1.57	2.000
5	2.94	6.626	2.50	3.907
6	1.13	4.851	0.54	0.020
7	1.60	7.301	2.45	8.375
8	2.51	6.699	3.36	7.488
9	2.95	6.720	3.95	9.085
	$R^2 = 0.60$		$R^2 = 0.88$	

The airborne data collected for this experiment is of somewhat higher spatial resolution but similar

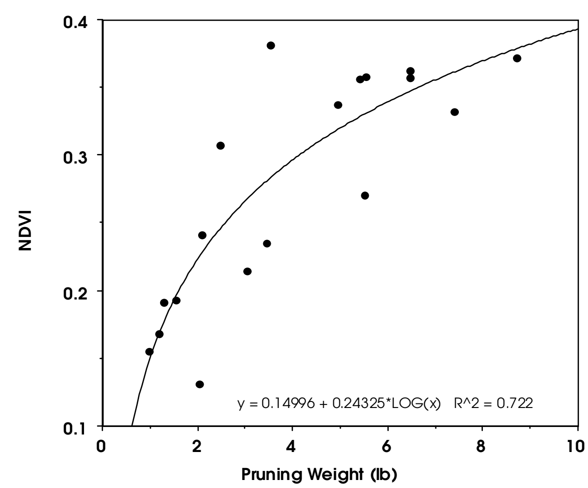

Figure 1. Mean per-vine pruning weight in each study plot vs. mean relative vegetation index assigned to each plot by processing of images acquired in 1993 and 1994. No significant difference was seen in the slope of the 1993 and 1994 regression lines. Strong goodness-of-fit (r^2 = 0.72) for the combined regression, shown above, underscores effectiveness of relative NDVI approach to monitoring canopy size over time (after Johnson et al., 1996 [6]).

spectral band configuration as the broad band satellites for terrestrial applications, Landsat and SPOT. As future multi-spectral cameras are launched with improved spatial resolution, we anticipate that satellite data might one day satisfy these kinds of applications and their data needs.

Hypothesis 2

During 1993, early-, mid-, and late-season field measurements were made on all "data" vines with a Minolta SPAD-502 chlorophyll meter (Minolta Corp., Ramsey, NJ). The meter operates by in vivo measurement of light transmittance through the leaf in two spectral channels centered at 650 nm and 940 nm, and has been used by others [10] to evaluate leaf chlorophyll concentration in several plant species. The measurements were made on one leaf per "data" vine, located two nodes above the second grape cluster on a vigorous shoot on the southeast side of the vine. Six Soil Plant Analysis Development (SPAD) readings were taken at various locations on the leaf surface and then averaged to represent the value of each "data" vine. Each average SPAD reading was then converted to in vivo chlorophyll concentration (mg/cm2) based upon a regression relationship for grape leaves ($R2 = 0.91$) reported by [3].

Immediately after acquiring the SPAD readings, each sample leaf was clipped, placed in a freezer bag, and stored in a dark, chilled cooler chest for transport to the laboratory. Within 12 hours, spectral measurements were made on the leaves with an NIRSystems Model 6500 spectrophotometer (Silver Springs, MD). The NIRS6500 measured leaf bidirectional reflectance (%) throughout the 400-2500 nm region (bandwidth = 10 nm, sampling interval = 2 nm). Measurements were made of single leaf thickness against a white background. Two variables were extracted from the spectral dataset: (1) green peak (GP), defined as the reflectance amplitude (%) of green light (550 nm), and (2) red edge inflection point (REIP), defined as the wavelength of maximum slope in the "red edge" spectral region, transitional between visible and reflected infrared light.

Mean chlorophyll concentrations in May 1993 were 0.043, 0.051 and 0.055 mg/cm2 for symptomatic, asymptomatic, and uninfested vines, respectively. Single factor analysis of variance (ANOVA) showed that chlorophyll concentration varied significantly (0.01 level) among the May 1993 infestation categories. A means comparison showed that the uninfested and asymptomatic categories differed significantly at the 0.025 level. These results suggest leaf chlorosis as a symptom of *phylloxera*-induced stress. This reduction was also correlated with a loss of yield [3].

Chlorophyll reduction was associated with increased reflectance of green light ($R2 = 0.72$, 0.49, 0.64 for the 3 dates) and also by shifts toward shorter wavelengths of the red-edge inflection point ($R2 = 0.74$, 0.50, and 0.74). Notably, however, neither of these expressions of leaf reflectance provided a statistically significant basis for discriminating asymptomatic vines from uninfested vines [7].

The NIRS6500 obtains high spectral resolution data that goes somewhat beyond the capabilities of any airborne imaging spectrometer. However, the anticipation is that future studies will be able to find comparable relationships in such airborne data at the whole plant level. The utility of spaceborne hyperspectral sensor data may still be dependent upon a suitable spatial resolution for this application.

Hypothesis 3

A small effort was made to determine if canopy temperature varied by category by obtaining thermal infrared imagery for the test plot. Data were obtained using the Airborne Disaster Assessment System (AIRDAS [2]) flown in a light aircraft. The qualitative findings were that thermal emittance of infected plots was higher than for uninfested plots. However, the readings included contributions of both the canopy and the underlying soils, much of which was exposed due to the incomplete canopy closure. These results were thus inconclusive.

VI. CONCLUSION

Methods developed for research in global change science can be adapted to the sensing requirements of this particular practical problem. In the present case, the problem was the infestation of vineyards by the root louse, *Phylloxera*, occurring in Napa Valley in the 1990s. Generalizing from this experience to the entire research base of the OES science program is not reasonable. The key in this case was to have the in-depth knowledge of the ecosystem approach as informed by concomitant remote sensing research, and to work with a highly motivated and skilled team of practitioners in the field. In this case, a knowledge of ecosystem properties and how they relate to variables one can obtain reasonably well from various remotely sensed data was essential. The translation of the science to the practical problem was improved by gaining familiarity among the team members by team planning and developing an ease with the scientific and the practical aspects of the problem and discovering the relationship between these two through careful discussions and trials.

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