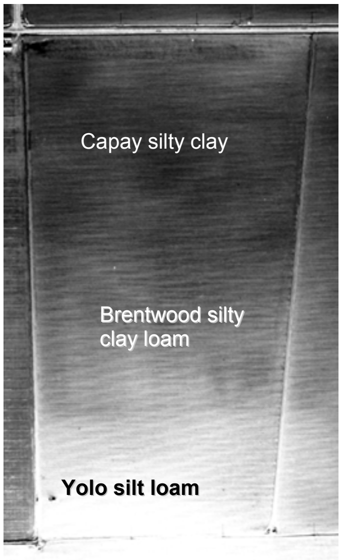
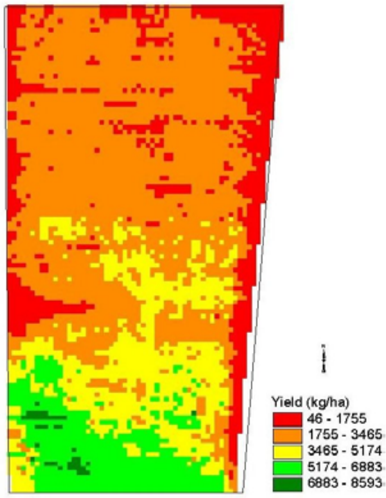
Site Specific Farming Information Systems in a Tomato-Based Rotation in the Sacramento Valley

January 1, 1996 – June 30, 1998



Bare soil 12/95



Wheat yield 6/96

Final Report
to the California Department Of Food & Agriculture
Fertilizer Research And Education Program

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Agreement 95-0518,

May 2000
University of California
One Shields Avenue
Davis CA 95616-8627

FINAL REPORT
TO THE CALIFORNIA DEPARTMENT OF FOOD & AGRICULTURE
FERTILIZER RESEARCH AND EDUCATION PROGRAM

PROJECT TITLE: Site-Specific Farming Information Systems in a Tomato-Based Rotation in the Sacramento Valley

PERIOD COVERED BY REPORT: January 1, 1996 – June 30, 1998

PROJECT AGREEMENT: Agreement 95-0518, University of California, One Shields Avenue, Davis CA 95616

PRINCIPLE INVESTIGATORS:

Stuart Pettygrove, Department of Land, Air and Water Resources, University of California, One Shields Avenue, Davis CA 95616-8627, phone 530-752-2533, gspettygrove@ucdavis.edu
Robert O. Miller, former Extension Specialist, Department of Land, Air & Water Resources, U.C. Davis
Richard E. Plant, Professor, Department of Agronomy & Range Science, U.C. Davis
R. Ford Denison, Associate Professor, Department of Agronomy & Range Science, U.C. Davis
Leland F. Jackson, Extension Specialist, Department of Agronomy & Range Science, U.C. Davis
Shrini K. Upadhyaya, Professor, Department of Biological and Agricultural Engineering, U.C. Davis
Thomas E. Kearney, Farm Advisor, U.C. Cooperative Extension, Woodland
Michael D. Cahn, Farm Advisor, U.C. Cooperative Extension, Yuba City

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EXECUTIVE SUMMARY

The objectives of this project were

1. Explore and demonstrate the potential for relating in-field variations in crop yield with normalized difference vegetation index (NDVI) derived from color infrared aerial photographs.
2. Relate variations in wheat flag leaf nitrogen, grain head nitrogen and leaf chlorophyll content at anthesis to grain protein at maturity in wheat.
3. Relate variations in tomato canopy NDVI, leaf nitrogen and petiole nitrate at three dates to tomato fruit yields in farmer fields.
4. Explore and demonstrate the potential for relating in-field variations in one crop to variations in growth and yield in other crops in the rotation. Identify soil properties that may be related to crop yield variations.
5. Provide grower outreach information on the use of spatial yield information on the management of crops in the wheat/tomato rotations.

The research has been conducted over four cropping seasons at the Button & Turkovich farm near Winters, Yolo Co. Project fields include both Class I and Class II soils. The main management challenges are how to optimize irrigation, seedbed preparation, and fertilization where fields have areas with loamy texture and medium to high permeability and other areas with clay loam/silty clay textures and low permeability.

Data from the 1996 wheat crop and the 1997 processing tomato crop in three fields are presented in this report. Data include yield monitor/GPS records, color infrared aerial photography, and plant and soil samples.

Several findings have been made in this project based on analysis of the 1996 wheat and 1997 processing tomato crop.

1. Wheat yield in field 58 was most affected by the presence of grassy weeds. An economic analysis of this variable weed impact in field 58 was presented at the 1997 California Alfalfa Symposium. Soil texture variation was not a significant factor. Grain protein content within the field was correlated with chlorophyll meter and N analysis on the flag leaf at anthesis.
2. In field 5, which has large areas of slowly permeable, high clay soil, wheat yield was most closely correlated with clay content, i.e. low yield where clay content was highest. Secondarily, grassy weeds reduced wheat yield. This analysis was clearly shown with a statistical method, CART (Correlation and Regression Tree analysis) that has rarely been used in site-specific farming yield analysis.
3. In one field, a wheat yield pattern of stripes perpendicular to beds was shown to exist and is believed to be a result of non-uniformly applied N topdressing during the winter.
4. Even though average tomato fruit yields of the three fields were quite different and appeared to be limited by different factors, yield distributions were similar. The least productive 25% of the total area in each field yielded 71 to 75 percent of the field average and only 55 to 57 percent of the most productive 25% of the total area.
5. Tomato yield distribution in two fields (14 and 58) was unrelated to wheat yield variability one year earlier. In a sandier area of a third field (field 5) wheat yield in 1996 was highest, while 1997 tomato yield was relatively low compared to

areas with somewhat finer texture, probably due to inadequate irrigation frequency of the tomatoes in that part of the field.

6. In addition, low tomato yield in field 5 was correlated to both high clay content and low soil test and early season petiole phosphate. The grower applied P fertilizer in the late summer of the preceding year during tomato bed preparation. This was likely too far ahead of the April transplanting to be effective.
7. Tomato yield variation did not match variation observed in the vegetation index map computed from the color infrared aerial photographs.
8. The low soil P level in field 5 offers an opportunity for a fertilizer field experiment. A strip trial was conducted in the 1999 sunflower crop; yield data have just been obtained and will be reported later.
9. Researchers and the grower agree that management of irrigation and related tillage (i.e., subsurface tillage) are key cultural practices and need to be monitored along with nutrient, pest, and other soil variables.
10. We have published five technical journal and international conference papers and made seven conference and workshop presentations based on the data collected in the first two years of the project. Other publications, including a technical manual are in preparation.

INTRODUCTION

This report covers work done under FREP funding during the 1996 and 1997 crop years and subsequent analysis and interpretation of data from those years. The California Department of Food & Agriculture Fertilizer Research and Education Program has provided two additional years of funding (July 1, 1998 – September 30, 2000) to continue the project.

OBJECTIVES

Site-specific farming, also known as Precision Agriculture, can be defined as the management of crop inputs on a smaller scale than the whole field. The assumptions behind site-specific farming are

- Agronomically significant variability in plant growth, yield, pest pressures, environmental conditions, etc. exists within fields;
- The variability can be measured;
- The causes of yield or plant growth variability can be determined;
- Knowledge of this relationship can be used to aid farm management decisions and increase production, crop quality, and profitability, and/or reduce unwanted environmental and societal impacts.

The focus of the 1996-1998 phase of the project was to test the first three of these assumptions. The fourth assumption, that management responses to variability can be identified and implemented, is partially addressed in the project's 1998-2000 phase and will be described in a future report. Specific objectives of the 1996-1998 project were the following:

1. Explore and demonstrate the potential for relating in-field variations in wheat yield with normalized difference vegetation index (NDVI) at three dates during growth.
2. Relate variations in wheat flag leaf nitrogen, grain head nitrogen and leaf chlorophyll content at anthesis to grain protein at maturity in wheat.
3. Relate variations in tomato canopy NDVI, leaf nitrogen and petiole nitrate at three dates to tomato fruit yields in farmer fields.
4. Explore and demonstrate the potential for relating in-field variations in wheat grain yield to subsequent tomato fruit yields in farmer/grower fields and research plots. Identify soil properties which may be related to crop yield variations.
5. Provide grower outreach information on the use of spatial yield information on the management of crops in the wheat/tomato rotations.

PROCEDURES

Site Description

The study site consisted of three commercial fields located at the Button & Turkovich ranch in Winters, CA, latitude 38°32′ N, longitude 121°58′ W. We identify the fields using the grower's numbering system as Fields 5, 14, and 58. They are 32, 44, and 31 ha in area respectively or 78, 106, and 77 acres. Soils are predominantly alluvial clay loams, silty clay loams, and silty clays. Mean annual precipitation is about 17 inches, but actual annual rainfall was 32.4 inches in 1995-96 and 26.6 inches in 1996-97. The fields, which had been laser leveled, were graded to a uniform slope for furrow irrigation.

Cropping Practices at Research Sites

Spring wheat (*Triticum aestivum* L. cv. 'Express') was drill seeded in December, 1995 into raised beds with furrows spaced 1.52 m (5 ft) apart. The furrows provided surface drainage during periods of heavy rain that occurred in January and were used for a single irrigation in April at anthesis. Normal commercial practices, including pest management and supplemental fertilization, were followed in producing the crop. The crop was harvested in June, 1996.

Following wheat harvest, the fields were disced, chiseled, then disced again. Beds were listed on a spacing of 1.52 m. Phosphate fertilizer was banded into the beds. In February 1997, two fields (designated field 14 and 58) were direct seeded to processing tomato (*Lycopersicon lycopersicum* L. Mill.). In a third field (designated field 5), tomatoes were transplanted in April. In all three fields, the tomatoes were planted in a single row on each bed. Tomatoes were irrigated with hand-move impact sprinklers during the establishment stage, then by furrow irrigation. Water run lengths in two of the tomato fields were reduced by the use of flexible ("lay-flat") gated plastic pipe in mid-field. The tomatoes were managed by the grower using standard practices for the area and harvested in late July or early August.

Data Collection – 1996 Wheat Crop

In the 1996 wheat crop, aerial photographs were taken on Dec 16, 1995, March 8, 1996, and May 4, 1996 from an altitude of approximately 1000 m using 70 mm Kodak Aerochrome II 2443 color infrared film. In the 1997 tomato crop, photographs were taken Dec 2, 1996, March 6, April 1, May 30, June 19, July 21, and August 5, 1997. Positive images were scanned using an Agfa Arcus II scanner at 600 dpi. This corresponds to a resolution of approximately 0.9 m (3 ft.).

Soil and plant tissue sampling were carried out on a 61-m (200 feet x 200 ft) square grid in each field. There were 86, 108, and 78 locations sampled in Fields 5, 14, and 58 respectively. At each sample point 7 soil cores (0-15 cm depth) were extracted prior to planting from the tops of the beds in a 25-m^2 area and composited. Sand, silt, and clay content were measured. Soil pH, nitrate, phosphorus, potassium, and organic carbon levels were determined using standard methods of the UC DANR Analytical Laboratory (Anonymous, 1998).

In the wheat crop at anthesis, visual determinations were made at each grid point of stand density and weed and disease infestation intensity, each of which were rated on a scale of 1 to 5. Locations of sample points were determined using a Trimble ProXL® GPS (Trimble Navigation, Sunnyvale, CA), which were corrected by post-processing. The typical rooting depth of wheat is about 1 m, so that shallow soil cores do not present a complete picture of the environment available to plant roots. To partially offset this problem, in Field 5 a set of 13 soil cores located along a transect running from the north to the south end of the field were extracted to a 1.5 m depth. Sand and clay content were measured at 0.3-meter (1-ft) intervals. Plant measurements were: Leaf nitrogen content and leaf greenness (estimated by the Minolta SPAD 502 chlorophyll meter) at boot stage and anthesis, head nitrogen content at anthesis, and grain protein content just before harvest.

At harvest, yield was measured using an Ag Leader®/GPS yield mapping system (Ag Leader Technology, Ames, IA). The yield monitor recorded grain flow rate, grain moisture, longitude, latitude, and distance traveled since last sample. Records were taken at a rate of one per second. At an average speed this represented a distance of about 1 m between samples. Nominal swath width was about 7.5 m. Yield data were differentially corrected and errors due to loss of GPS signal were rectified through spatial interpolation. Yield data were adjusted to 12% moisture content. Files of scanned images, point sample data, and yield monitoring data were imported into Arc/Info (ESRI, Redlands, CA) and georegistered to UTM coordinates.

Data Analysis and CART (Correlation and Regression Tree) Procedure –Wheat Crop

After georegistration, wheat yield data and remotely sensed data were resampled to a common grid with a cell size of 7.625 m (approximately the harvester swath width) on the ground. Data analysis was carried out using ArcView (ESRI, Redlands, CA), Excel (Microsoft, Redmond, WA), SAS (SAS Institute, Cary, NC), Minitab (Minitab, State College, PA), and CART (Salford Systems, Evanston, IL). Yield at sample points was estimated by aggregating yield monitor data over a 25-m^2 area centered at each sample point.

The CART methodology provides an objective means of generating management zones. Whereas linear regression produces a continuously varying regression surface, the regression tree is equivalent to a histogram estimate of a regression surface. In practice complete objectivity is difficult because classification and regression methods often do not produce zones that make sense from a crop management perspective, i.e. contiguous, reasonably large areas with a fairly simple shape. In our fields, however, the zones derived from CART were sufficiently close to a practical arrangement that we did not attempt any subjective modification. The zone structure was created from the CART groupings through the GIS operations of reclassification and map algebra.

Overfitting sample data is a danger for predictive methods such as CART. The problem occurs when a better fit of the sample data results in a lesser ability to correctly predict new sets of cases. To avoid overfitting CART first grows the maximal dichotomous tree and then prunes it back to an optimal tree based on the error rate with data that were not used to grow the maximal tree. Two approaches are used: (1) if the data set is large, the set is divided into separate learning and test subsamples; (2) if data set is small, CART uses cross-validation (usually ten-fold). In our analysis we employed ten-fold cross-validation.

Data Collection – 1997 Tomato Crop

In the tomato crop, petiole samples were collected at grid points (200 x 200-ft spacing) for nitrate, phosphate, and potassium content. Aerial CIR photographs were taken before planting, at early bloom (May 30), mid-bloom (June 19), and near harvest (July 21 for fields 14 and 58; Aug 5 for field 5). To analyze the tomato crop aerial photos: Color IR photos were taken at mid- to full-bloom stage from an altitude of 1200 meters above the site using 70 mm Kodak Aerochrome 2443 film, as described in the wheat data collection section. Transparencies were scanned using a slide scanner with a resulting spatial resolution of about 1.8 meters on the ground. Resulting 24-bit images in TIF format consisted of three colors corresponding approximately to the near-infrared, red, and green. These were analyzed using Image Pro for Windows (Media Cybernetics, Silver Springs, Maryland). The scanned images were ortho-corrected using GPS-determined locations of the field corners.

Tomato yield was measured with a prototype monitor mounted on one of the grower's harvest machines, which straddles a single bed of tomatoes. The yield monitor is described elsewhere by Pelletier and Upadhyaya (1999). Briefly, it consists of a load cell to measure the weight of the fruit as it passes over a conveyor on the boom elevator just before discharge into the receiving trailer. Red fruit is separated from clods, vines, and most off-grade fruit before the weighing point. Weights were recorded once per second, but due to limitations of the differential GPS receiver and data logger, latitude and longitude were only sporadically recorded. Neither time of day nor harvester speed was recorded. The load cell readings were calibrated by use of a mobile weigh cart. To compile the yield data set, a four-point running average of yield was written to each data location possessing an actual GPS reading. Spacing between adjacent yield points in the final data set generally ranged from 3 to 12 meters.

There were several inherent sources of error and smoothing in the yield monitoring procedure. Fruit followed a long, split flow path through the harvester before reaching the weighing point. Also at two locations in the harvester, a minimum mass of fruit was required to build up before any fruit was pushed beyond those points. Pelletier and Upadhyaya (1999) concluded that the yield monitor was not capable of detecting variability over a distance of less than nine meters. This is not greatly different from the resolution achieved by commercial grain yield monitors.

Commercial tomato fields are usually harvested with two or more machines operating at the same time. Because a machine harvests only one bed at a time, and there was only one yield monitor for our project, we were not able to obtain yield data on every bed. In two of the fields, the majority of the yield data were from every fifth bed. Due to the cooperation of the grower, on field 5, yield was measured on every bed in several large areas.

Data Analysis – Tomato Crop

Normalized Difference Vegetation Index (NDVI) was calculated as (IR-red)/(IR+red). NDVI values of <40 were removed, as these were mostly associated with field edges and irrigation pipelines.

To facilitate comparison of yields to aerial images, the tomato yield point data were converted in ArcView® (ESRI, Redlands, California) to a 9.15-m grid using inverse distance squared weighting of the 12 nearest neighbors. For geostatistical analysis, the original non-gridded data were used. Duplicate points and a small number (~ 5 per 1,000) of high yield points (>130 Mg ha^{-1}) were removed. To examine anisotropy, we produced variogram surfaces (Isaaks and Srivastava, 1989) using Variowin 2.2 software (Pannatier, 1996). Geostatistical analyses were limited by available computer memory to 1,400 yield points at a time, which represented areas ranging from 0.7 to 1.5 hectares.

RESULTS & DISCUSSION

Wheat grain yields and grain protein on the fields ranged from 0.5 to 3.0 US tons/acre and 10.7 to 15.2% protein. Wheat yield maps for the three fields are shown in Fig. 1. Flag leaf N, SPAD leaf greenness values and grain protein were spatially correlated within fields (Table 1). Fifty percent of the variability in grain protein could be accounted for by N content of the wheat flag leaf at anthesis. Grain phosphorus content was consistently negatively correlated with flag leaf N and grain protein content across fields. Grain yield and protein at maturity were affected by variation in weed intensity, which was mapped as a covariable.

Field 5. Based on CART analysis, we determined that the factors exerting the most influence on yield were soil clay content, soil organic matter concentration, soil phosphorous content, and weed infestation level. It is likely that soil organic matter concentration is acting as a surrogate variable for clay content since the two are highly correlated. In choosing a means of representing the spatial distribution of clay content we evaluated the use of bare soil infrared photograph information. We rejected this approach, however, in favor of the first order inverse distance weighted interpolation of point sample data (Fig. 2). The two methods produced similar results, but the interpolation method generated a sharp boundary between regions while the infrared image method did not. In agricultural practice the reduced cost of the infrared image method would weigh strongly in its favor. In this situation a smoother relationship could be obtained through low pass filtering. We used first order inverse distance weighted interpolation to generate estimates of the spatial distribution of soil organic matter and phosphorous. Because of the excellent representation of weed areas in the May aerial photograph we decided that this provided the most precise representation of the spatial distribution of weeds. Visual comparison of the digitized image with the yield map indicated that high weed density was correlated with pixels for which in the digitized May aerial image either the infrared band had a digital number (DN) value greater than 155 or a red band DN value less than 33. After binary reclassification of the four yield-determining quantities (Fig. 3), the field was divided into five zones based on the classification shown in Fig. 4.

Field 58. Although the CART analysis shown in Fig. 5 generated four yield classes based on three splits, in practice only the first split, between regions of high and low weed infestation, is significant for crop management. The split on soil P produces one region with only two data points (i.e., having a size of about 1 ha), which is too small to be practical as a management unit. (It should be noted, however, that these two data points had a considerably higher yield, possibly indicating low soil P throughout the field). The other secondary split, on sand content, produces two regions whose difference in mean yield is within one standard deviation of each other. Therefore we used only the first split of the CART algorithm and as a result generated a set of two management zones based on weed population density as indicated by the May aerial photograph (Fig. 6).

Tomato yield analysis

Tomato yield maps of the three fields are shown in Fig. 7, and yield distributions are shown in Fig. 8. Even though average fruit yields of the three fields differed, yield distributions were similar. The least productive 25% of the total area in each field yielded 71 to 75 percent of the field average and only 55 to 57 percent of the most productive 25% of the total area.

Both fields were harvested with more than one machine. Because there was more complete coverage by the harvester with the yield monitor in Field 5, in that field, we were able to examine yield spatial pattern in greater detail. Yields in Field 5 (Fig. 7a) were lowest in areas of the field with slowly permeable Capay silty clay soil located mainly in the northern half of the field and corresponding to the areas shown in Fig. 2 with higher clay content. Yields were generally higher in the better drained silt loams and loams in the southern half of the field. However, yield in the coarsest-textured southwest corner of the field was relatively low, probably due to under-irrigation.

Such irrigation-induced variability is difficult to avoid in gravity-irrigated systems. If the grower had used a longer set (i.e., left the water on longer) to accommodate the coarsest-textured soil, the crop would probably have suffered from prolonged saturated conditions in the areas of the field having finer-textured, less permeable soils. Some possible "Precision Ag" solutions to this would be (1) apply one or more extra irrigations to the portion of the field with coarser-textured soils, (2) convert the whole field to trickle irrigation, or (3) change to more closely spaced furrows and irrigate on a skip-furrow basis in the poorer-drained areas. Trickle irrigation systems are expensive to install and maintain and have not always worked well on the heavy "cracking clay" soils of this farm, and the other two solutions involve unknown, but likely significant labor and management costs.

In Field 14, soil test P levels were well above the critical level for tomatoes of 15 ppm (sodium bicarbonate extractable). In contrast, in Field 5, both plant tissue and soil analysis indicate that the grower's knifed application of 100 lb P_2O_5/acre in the fall seven months prior to transplanting of the tomatoes was not effective. Petiole phosphate at early- to mid-bloom in Field 5 ranged from very low to adequate and was related to yields (Fig. 9). Soil available P of samples collected the previous year (during the wheat crop) was not as well correlated with tomato yield (Table 2); however the mean value (7.7 ppm, sodium bicarbonate extractable) was well below the acceptable level for optimum yield. Both yield and petiole phosphate levels were related to soil texture (Table 2). Therefore, it is uncertain whether the direct cause of low yield was (1) low soil P, or (2) inadequate P uptake due to poor root development in areas with fine-textured soil where the crop was subjected to prolonged saturation.

CONCLUSIONS

Several findings have been made in this project based on analysis of the 1996 wheat and 1997 processing tomato crop in three commercial fields in Yolo Co. We caution that these conclusions will likely be modified with an additional two years of crop data on the same fields and as we refine our data analysis methods.

1. Wheat yield in field 58 was most affected by the presence of grassy weeds. An economic analysis of this variable weed impact in field 58 was presented at the 1997 California Alfalfa Symposium. Soil texture variation was not a significant factor.
2. Grain protein content within the field was correlated with SPAD meter and N analysis on the flag leaf at anthesis.

3. In field 5, which has large areas of slowly permeable, high clay soil, wheat yield was most closely correlated with clay content, i.e. low yield where clay content was highest. Secondarily, grassy weeds reduced wheat yield. This analysis was clearly shown with a statistical method, CART (Correlation and Regression Tree analysis) that has rarely been used in site-specific farming yield analysis. The low yield observed in high clay areas was due to heavy winter rains that kept the soil saturated.
4. In field 5, a wheat yield pattern of stripes perpendicular to beds was shown to exist and (based on interview with the grower and the aerial applicator) is believed to be a result of non-uniform N topdressing during the winter.
5. Tomato yield distribution in two fields (14 and 58) was unrelated to wheat yield variability one year earlier. In field 5, when wheat yields in high density weed areas were excluded from the data set, tomato yield was lowest in the high clay soil areas, just as the wheat was. However, in the highest sand area, wheat yield in 1996 was highest, while 1997 tomato yield was relatively low compared to areas with somewhat finer texture. While we have no direct information on the cause of this, a logical explanation was provided by the grower: It is likely that the irrigation frequency that was optimal for the more poorly drained areas was not frequent enough for the coarser-textured soils within the field.
6. Low tomato yield in field 5 was correlated to both high clay content and with low soil test and early season petiole phosphate. The grower applied P fertilizer in the late summer of the preceding year during tomato bed preparation. This was likely too far ahead of the April transplanting to be effective. A small area in the SW corner of field 5 also yielded low due to inadequate irrigation (conclusion #4 above).
7. Tomato yield variation did not match variation in the vegetation index computed from the color infrared aerial photographs.
8. The low soil P level in field 5 offered an opportunity for a fertilizer field experiment. A strip trial was conducted in the 1999 sunflower crop – data to be analyzed.
9. Researchers and the grower agree that irrigation management and related tillage management (i.e., subsurface tillage) are key cultural practices and need to be monitored along with nutrient, pest, and soil variables.

PUBLICATIONS AND PRESENTATIONS RESULTING FROM THIS PROJECT

Workshops/seminars

G.S. Pettygrove, Site-specific crop nutrient management, October 7-9, 1998, California Fertilizer Assoc. Nutrient Management Seminars, Sacramento, Fresno, and Salinas.

Publications, Reports, Abstracts

Pettygrove, S., L. Jackson et al. 1997. Site specific evaluation of soils as they affect crop yield and weed growth. Proceedings California Alfalfa Symposium (Visalia, Dec. 10-11, 1997)

Pettygrove, G.S., R.E. Plant et al. 1998. Developing site-specific information for cropping systems in California. Proceedings of California Plant and Soil Conference (Sacramento, Jan. 27, 1998). California Chapter Amer. Soc. Agronomy.

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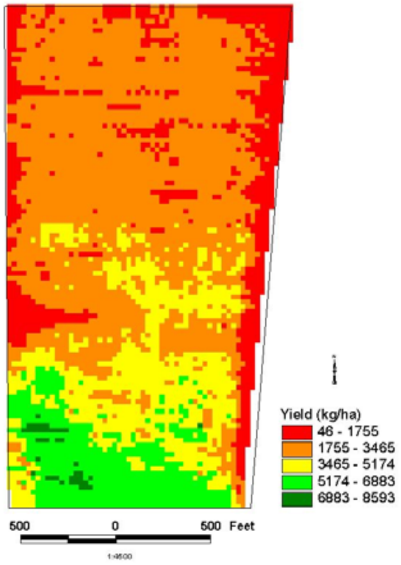
Miller, R.O., S. Pettygrove, R.F. Denison, L.F. Jackson, M.D. Cahn, R.E. Plant, T.E. Kearney. 1999. Site specific relationships between flag leaf nitrogen, SPAD meter values, and grain protein in irrigated wheat. p. 113-122. *In* P.C. Robert, R.H. Rust, and W.E. Larson, Proceedings of the Fourth International Conference in Precision Agriculture. 19-22 July, 1998, St. Paul Minnesota. American Society of Agronomy, Madison, Wisc.

Pelletier, M.G. and S.K. Upadhyaya, 1999. Development of a tomato yield monitor. p. 1119-1129. *In* P.C. Robert, R.H. Rust, and W.E. Larson, Proceedings of the Fourth International Conference in Precision Agriculture. 19-22 July, 1998, St. Paul Minnesota. American Society of Agronomy, Madison, Wisc. [*Development of the tomato yield monitor was not funded by FREP.*]

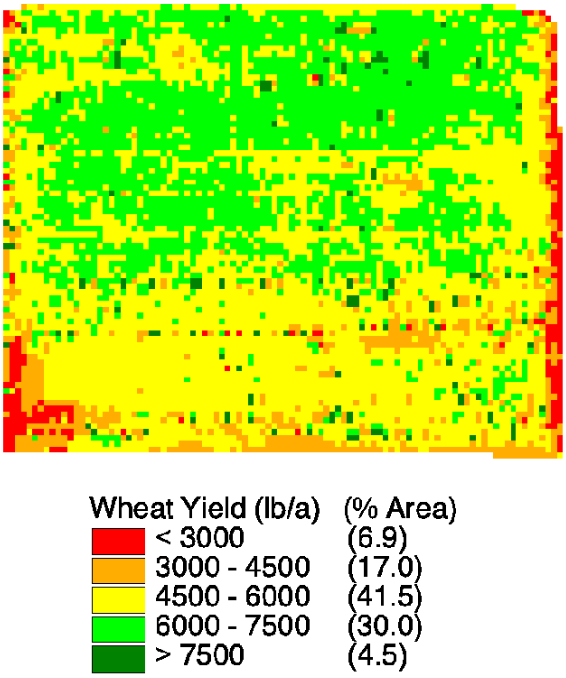
Pettygrove, G.S., S.K. Upadhyaya, J.A. Young, J.A. Young, E.M. Miyao, and M.G. Pelletier. 1999. Tomato yield variability related to soil texture and inadequate phosphorus supply. Better Crops with Plant Food. No. 2, p. 7-9. Potash & Phosphate Institute, Norcross, Georgia.

R.E. Plant, A. Mermer, G.S. Pettygrove, M.P. Vayssieres, J.A. Young, R.O. Miller, L.F. Jackson, R.F. Denison, and K. Phelps. 1999. Factors underlying grain yield spatial variability in three irrigated wheat fields. Trans Amer. Soc. Agric. Eng. 42(5):1187-1202.

Field 5: 1996 Wheat Yield



Field 14: 1996 wheat yield



Field 58: 1996 Wheat Yield

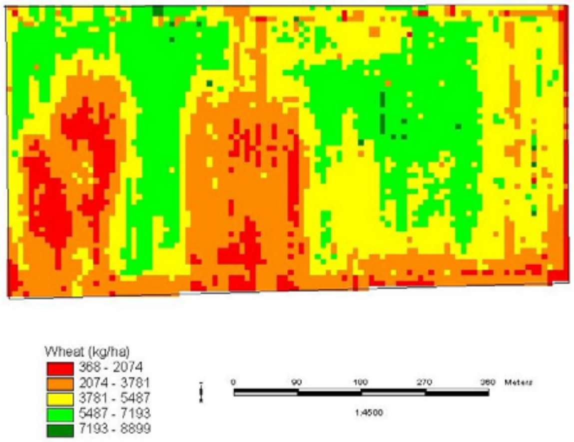


Fig. 1. 1996 wheat (cv. 'Express') grain yield in project fields.

Table 1a. Sample correlation coefficients for measured plant variables in Field 5 in 1996 wheat crop.

	Variable					
	Leaf N	Chl meter	Flag Leaf N	Head N	Grain Protein	Grain P
Chl meter	0.72					
Flag leaf N	0.47	0.74				
Head N	0.66	0.63	0.60			
Grain protein	0.45	0.51	0.56	0.60		
Grain P	-0.35	-0.59	-0.63	-0.49	-0.53	
Yield	0.83	0.59	0.27	0.61	0.52	-0.31

Table 1b. Sample correlation coefficients for measured plant variables in Field 14 in 1996 wheat crop.

	Variable					
	Leaf N	Chl meter	Flag Leaf N	Head N	Grain Protein	Grain P
Chl meter	0.78					
Flag leaf N	0.61	-				
Head N	0.61	-	0.65			
Grain protein	0.56	-	0.61	0.59		
Grain P	-	-	-	-	-	
Yield	0.83	-	0.07	0.16	0.22	-

Table 1c. Sample correlation coefficients for measured plant variables in Field 58 in 1996 wheat crop.

	Variable					
	Leaf N	Chl meter	Flag Leaf N	Head N	Grain Protein	Grain P
Chl meter	0.80					
Flag leaf N	0.72	0.79				
Head N	0.48	0.70	0.69			
Grain protein	0.56	0.56	0.56	0.53		
Grain P	-0.60	-0.53	-0.62	-0.40	-0.31	
Yield	0.32	0.00	-0.10	-0.30	0.06	-0.05

Chl meter = Leaf greenness measured by Minolta SPAD 502 chlorophyll meter.
Correlations >0.22 differ significantly ($P<0.05$) from zero. From Miller et al. 1996.

Figure 2. Surface soil (0-6 inches) clay content versus color IR aerial photograph image of bare, moist soil, December 1995. Clay content determined at 86 grid points on 200 x 200 ft spacing.

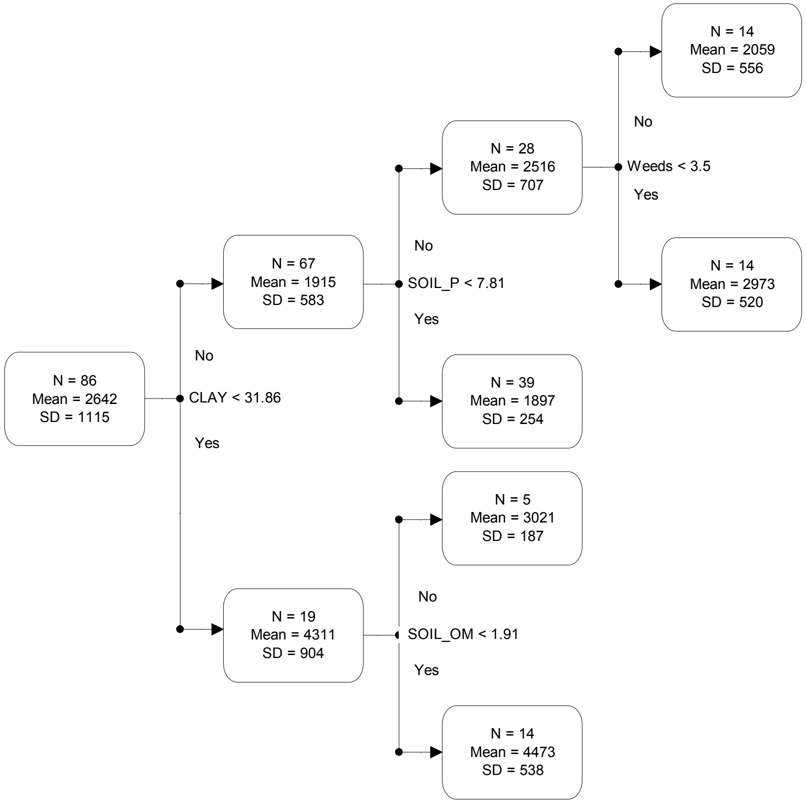


Fig. 3. Classification tree generated by the CART algorithm for yield determining variables in Field 5. Each branch indicates a split into subgroups made by CART. N=number of sample points in subgroup; Mean = mean yield (kg/ha) of points in the subgroup; SD= standard deviation of yield of points in subgroup (Plant et al., 1999).

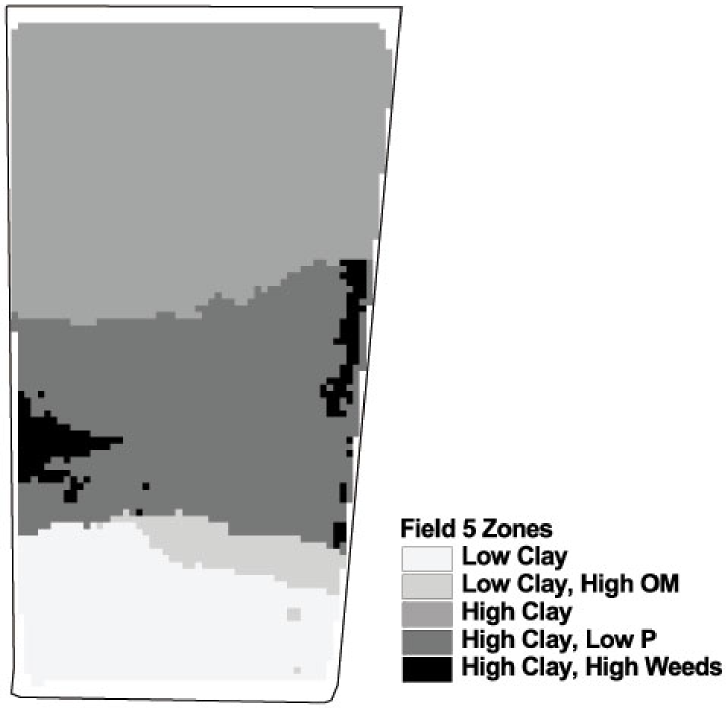


Fig. 4. Management zones for Field 5 generated by the CART algorithm as shown in Fig. 3 (Plant et al., 1999)

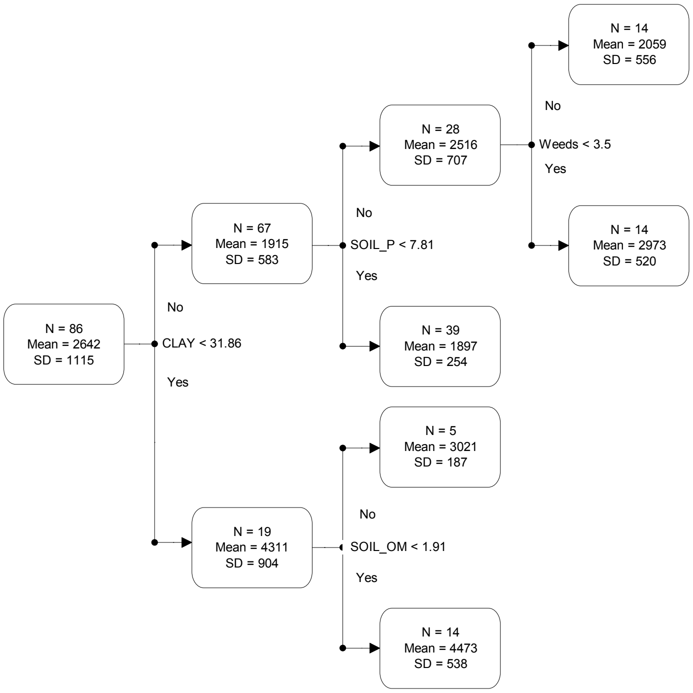
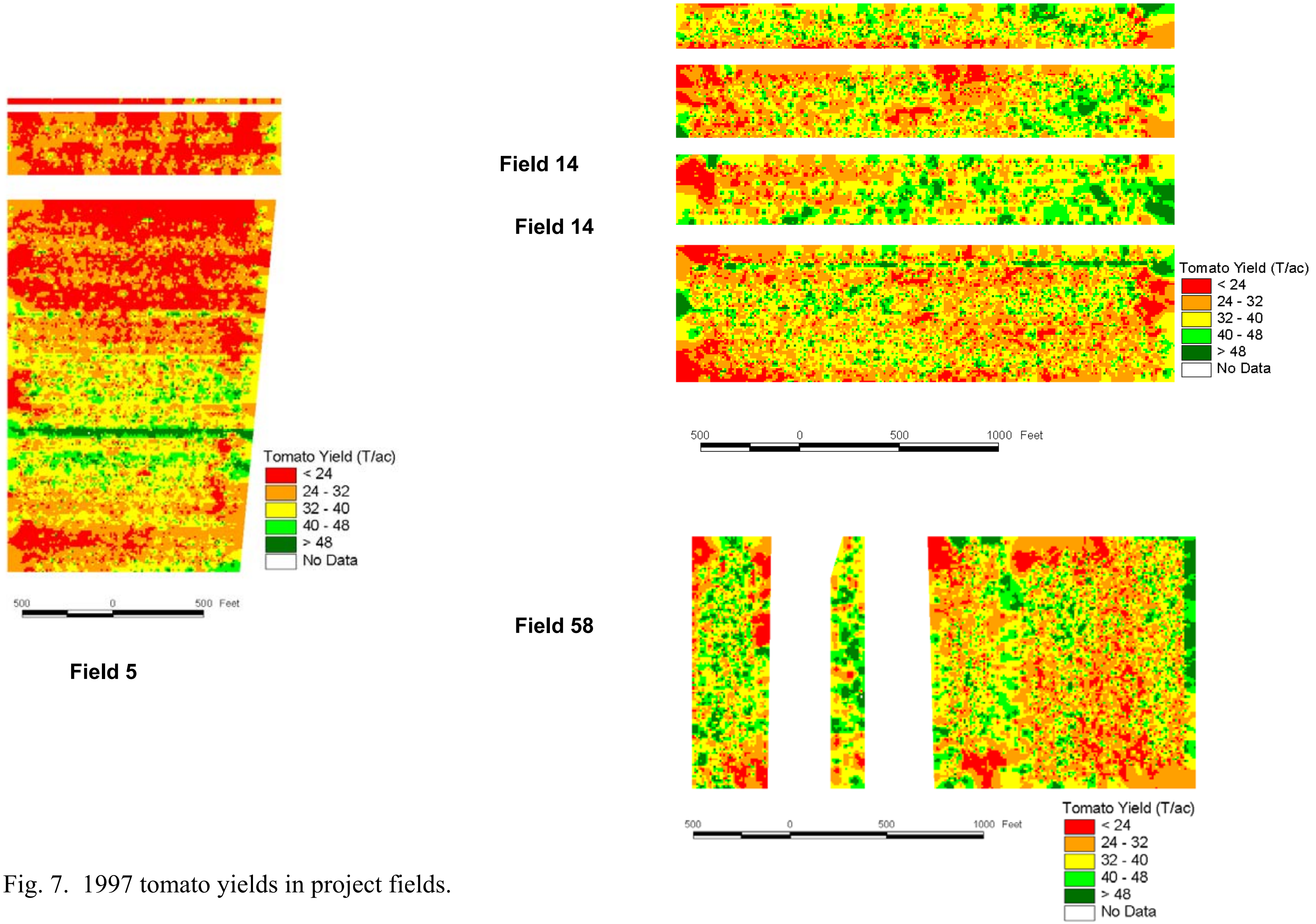


Fig. 5. Classification tree generated by the CART algorithm for yield-determining variables in Field 58. Symbols are as in Fig. 3. (Plant et al., 1999)

Fig. 6. Measure of weed population density in Field 58: Classification of DN (digital number) value of infrared band of the May 4 1996 aerial photograph.



Field 14

Field 14

Field 58

Field 5

Fig. 7. 1997 tomato yields in project fields.

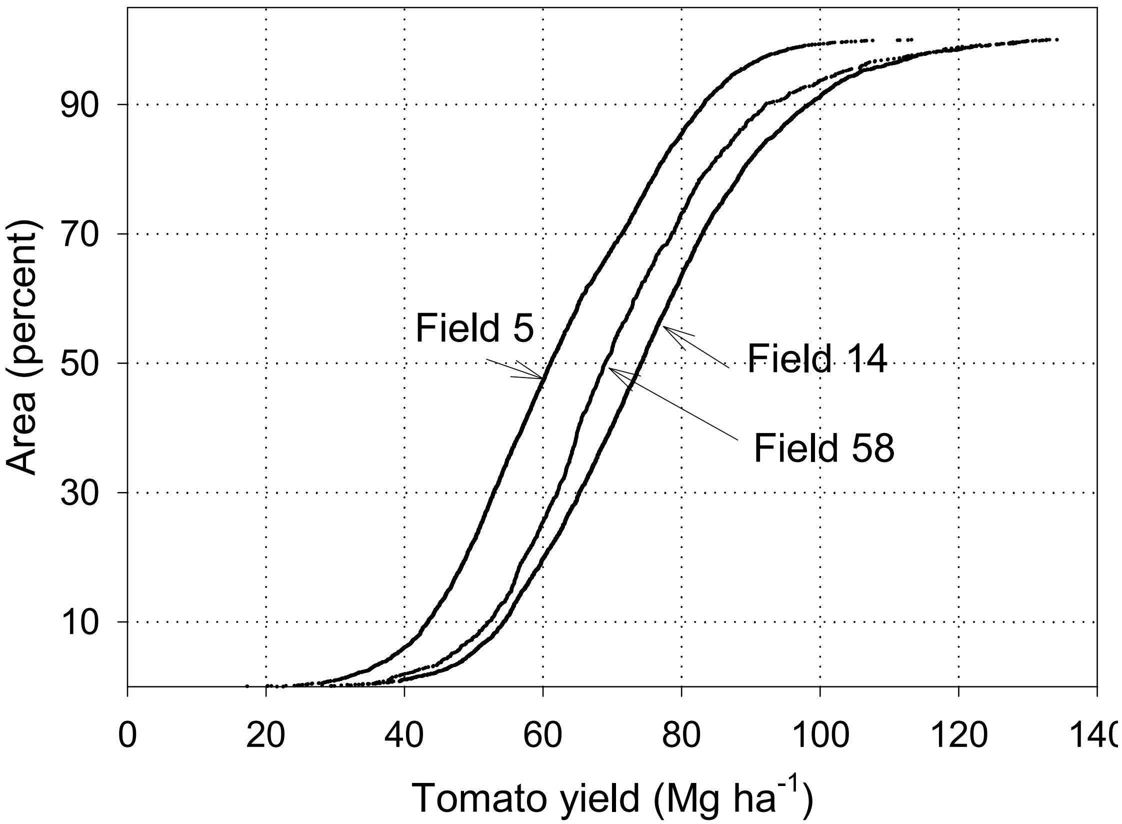


Fig. 8. Tomato yield distribution in three project fields.

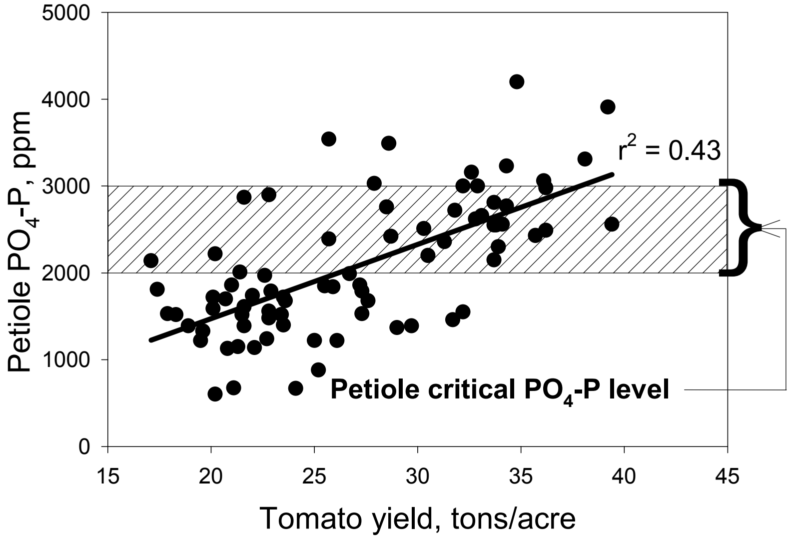


Fig. 9. Tomato petiole phosphate level at early bloom vs. fruit yield in Field 5. Fertilizer P (100 lb P_2O_5/A) was knifed into beds in the fall seven months before tomatoes were transplanted in April 1997.

Table 2. Relationship between tomato fruit yield and soil and plant characteristics in Field 2. Data was collected from 79 grid points on a 200 x 200-ft spacing.

	Yield	Midbloom petiole PO_4
	------------------- *r*	-----------------
Midbloom petiole PO_4	0.66	--
Late bloom petiole PO_4	NS	NS
Mid-bloom petiole NO_3	NS	0.53
Sand content	0.43	0.56
Clay content	-0.55	-0.65
Soil P, Na bicarb. extractable	0.49	0.41
Soil organic matter	NS	NS
Soil pH	NS	NS

r = coefficient of correlation. All significant at 1% level except where NS appears.