June 2014 Final Report

Billing Period: April 1, 2014 to June 31, 2014
Submittal Date: June 12, 2014

Contract: 11-C0089
Project Name: "Citrus Ecoinformatics"
Principal Investigator: Jay Rosenheim

I certify under penalty of law that this document and any attachment was prepared by me of under my direction in accordance with the terms and conditions of the Alliance Grant Agreement. Based on my inquiry of the persons who manage the project, or those directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. All information submitted in this document and all attachments conform to and is in accordance with the state and federal laws and I so here certify with my signature. I am aware that there are significant penalties for submitting false or misleading information.

__Jay Rosenheim_____ June 12, 2014
Principal Investigator Signature Date
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Final report

Executive Summary: This contract supported a novel research approach to identifying opportunities for enhancing pest control and decreasing the burden of pesticides associated with commercial citrus production in California's San Joaquin Valley. We adopted an 'ecoinformatics' approach, which works exclusively with data directly from the commercial setting. All data were obtained from a network of collaborating citrus farmers and independent pest control consultants. Data were obtained describing pest densities for >1,000 commercial citrus harvests (one harvest = one year's harvest from a given citrus grove). Analyses showed that farmers face strong economic incentives to control both indirect pests (which decrease total citrus yield) and direct pests (which create cosmetic damage to citrus fruits that cause downgrading at the packinghouse). In almost all cases, because citrus is a high value crop, pests have the potential to generate economic losses that are far greater than the costs of applying pesticides for their control. For this reason, a primary avenue for decreasing the environmental burden of pesticides will be to encourage the adoption of low-risk, or environmentally benign materials, rather than attempts to eliminate pesticide use entirely. Complementary approaches may include: (1) research to identify clearly the beginning and end of windows of crop sensitivity to direct pest damage, which can allow us to eliminate unnecessary pesticide applications when the crop is not at risk, and (2) campaigns of public education designed to increase acceptance of citrus fruits that bear superficial cosmetic blemishes that have no effect on underlying fruit quality.

Overview: The citrus ecoinformatics project unfolded with a mixture of unexpectedly difficult challenges, encountered during the first 16 months of the project, succeeded by unexpectedly rich opportunities, during the second 16 months of the project. Our earliest efforts to build a network of collaborating citrus farmers and independent pest management consultant ran into a substantial roadblock, because citrus farmers proved, in many cases, to be quite reluctant to share data. Citrus farmers are in direct competition with their neighbors, and may wish to keep their production practices and outcomes (e.g., yield) hidden from them. Furthermore, packinghouses also compete for contracts with farmers, and may not wish to share information regarding details

of packout and fruit quality thresholds used in grading fruit, or especially information on prices charged for picking and packing operations, or prices paid for the packed harvest. Even our independent consultants, who were willing to share data on densities of pest and beneficial arthropods and pesticide use decisions, in some cases received 'push-back' from the farmers for whom they consulted, as some growers were reluctant even to release data on pest densities. This level of data sensitivity exceeded by far what we had encountered in our previous collaborative work on ecoinformatics conducted with California cotton farmers.

In response to these experiences, we overhauled our outreach approach to farmers. With major collaboration from Dr. Beth Grafton-Cardwell, a universally respected and trusted citrus research leader and primary liaison between the University of California and the citrus industry, we hosted a series of meetings with farmers, pest management consultants, and county farm advisors at the University of California Lindcove Research and Extension Center. We also travelled repeatedly to the citrus growing region of the San Joaquin Valley, conducting one-on-one meetings to build a network of collaborating farmers and consultants. These meetings were successful. Some farmers still preferred not to share data, but most came to see the potential benefits of our project, once they had a chance to discuss it with us in detail and have their questions and concerns addressed. In this way we developed a group of enthusiastic participants. We also gained access to unexpectedly large and detailed datasets. Some of these datasets were quite detailed, because of requirements of organizations that were certifying citrus production as 'sustainable'. This certification was associated with requirements to gather and archive detailed information on all aspects of pest management, which has proven to be a boon for our study.

The result is that we now have, in hand, a rich dataset describing over 1,000 unique citrus 'harvests' (where one harvest is a year's citrus production in a given block of citrus that is monitored, managed, and harvested as an independent unit). Not all records are complete, as (for example) some young citrus blocks are not yet bearing, other blocks are 'top-worked' and are not harvested for a few years afterwards, some harvests were lost to severe freeze damage. Furthermore, in some cases records were lost, especially when growers shifted between packinghouses across years. In this report, we present the analyses of the impact of pests on total citrus yield (total tons per acre) as well as citrus quality (the grade of the fruit achieved at the packinghouse, which is the primary determinant of the value of the crop). We then present economic analyses that allow us to translate the effects of pests on yield and citrus quality into new recommendations for pesticide use within citrus pest management.

I. Goals

The overarching goal of the project is to improve citrus pest management by building and analyzing a large dataset 'mined' from records saved by farmers and independent pest management consultants engaged in commercial citrus farming in California's San Joaquin Valley. Approximately 75% of California's $2 billion citrus industry is located in the San Joaquin Valley, and that is the region in which we worked. Despite a long and proud tradition within the University of California of supporting the citrus industry with research-based pest management recommendations, major questions remain regarding optimal pest management practices. Conducting experiments on the impact of pests on citrus is exceptionally difficult, largely because of the perennial nature of the crop. As a result, for only one pest (citrus red mite) is there experimental support for the economic injury level that underlies the current control thresholds. Citrus is, however, host to at least six major pests (and a set of additional pests that can reach damaging levels more sporadically). Our goal was to generate data-driven pest control recommendations for as many of these pests as possible by quantifying effects of pest densities on yield and fruit quality. In the absence of such information, risk-averse growers

often use pesticide applications as a relatively cheap form of 'insurance'. Thus, our goal was to arm growers with more information, and thus help growers to restrict their use of pesticides to those cases where there was a real threat to crop value.

II. Objectives

Objective 1. Develop a database software application with an efficient interface that will allow Contractor to compile data from California citrus farmers (yield and crop quality), private pest control consultants (pest and beneficial insect densities; crop damage), and the California Department of Pesticide Regulation (CDPR) (pesticide use).

Objective 2: Collaborate with a group of approximately six leading private pest control consultants, the commercial citrus farmers for whom they consult, and CDPR staff to assemble, interpret, and enter citrus-related data into the database.

Objective 3: Analyze the resulting database using a variety of statistical tools that are designed to explore non-experimental (observational) data sets to develop recommendations for citrus pest management based on using pesticides when pest suppression is warranted to protect citrus crop yield.

III. Methodology

We collaborated with a private software firm to develop a customized database application, *Citrusformatics*. As expected, this was a highy iterative process, in which we began with an basic architecture, but then added features as new data streams became available and the nature of the analysis objectives were refined.

One methodological change in our project flowed from the realization that we needed a robust outreach effort if we were to succeed in building a team of collaborating farmers and consultants. The typical 'baseline' attitude within the citrus farming community proved to be one of strict secrecy regarding production practices and yield outcomes. We were able to push the project forward, but only by incorporating an effort to meet with farmers in both group and one-on-one meetings.

Once the farmers shared data with us, the data input process proceeded as expected. All data came in the form of hard-copy reports. Thus, we undertook the labor-intensive process of hand-entering all the data, requiring skilled research assistants who understood the nature of the sampling processes and were able to interpret data reports correctly.

Data analyses relied upon hierarchical models, using generalized additive mixed models (GAMM's) and generalized linear models implemented in R.

IV. Deliverables

Here is a complete list of our deliverables:

Deliverable 1.1: Semi-annual progress reports
Deliverable 1.2: Quarterly invoices
Deliverable 1.3: Informal update meetings as requested.

Deliverable 2.1: The *Citrusformatics* database software application will be available as open source code to any interested parties (other researchers, state or local government staff, or consultants). Code will be placed on a project web-site, administered through the Department of Entomology, University of California, Davis.

Deliverable 3.1: The *Citrusformatics* data set will be assembled over the course of the first 2.5 years of the project.

Deliverable 3.2: Contractor will develop means (non-linear regressions) of translating between qualitative pest density rating schemes used by cooperating consultants and absolute density estimates that Contractor will obtain from parallel sampling efforts. The primary focus will be on citrus red mite sampling estimates.

Deliverable 4.1: Conduct formal statistical evaluations of the individual and joint effects of major citrus pests on citrus yield and quality. Use these relationships to develop improved pest management recommendations for citrus growers.

Deliverable 5.1: Final report documenting goals, objectives, methodology, deliverables, conclusion, and discussion.

Task 1: Administration

Progress reports and quarterly invoices were submitted, and update meetings were held as planned.

Task 2: Database software development

The unexpectedly detailed data from our collaborating citrus farmers and consultants mandated expansions of the architecture of our database, *Citrusformatics* (Figure 1). The open-source database software files can be downloaded by pasting the web-site address below into your browser (the link imbedded in this file doesn't work if you attempt to access it directly from this MS Word file):

169.237.77.3/faculty/rosenheim/Jay_Rosenheim_files/Citrusformatics_DB_Stored_Procedures.zip

The database is now fully functional for data entry, error checking, and graphical and tabular data display, and has simple functionality for data reporting

Task 3: Collaborate with the citrus industry and CDPR to asemble the data set.

As described above, this task initially encountered significant difficulties, but with an enhanced outreach effort we were able to develop a successful approach for building a team of collaborators in the citrus community. PUR data on pesticide use were essential, as farmer records on pesticide applications were in many cases incomplete.

Citrus red mite is thought to be a key indirect pest, weakening citrus trees by damaging leaves and decreasing photosynthetic activity. Citrus red mites are also difficult for farmers and consultants to count, and thus sampling usually involves either a qualitative rating scheme or, in some cases, presence/absence sampling. Because of the perceived importance of citrus red mites as pests, we wanted to be able to translate consultant density ratings (Trace, Low, Medium, High) into absolute density estimates (e.g., the mean number of mites/leaf). We worked in the field with consultants to develop a small dataset addressing this question. We sampled citrus groves on the same day that the consultant completed estimates of citrus red mite population

density. We sampled one leaf from each of 100 trees. In the field, we recorded the total number of adult female citrus red mites per leaf by inspecting both the upper and lower leaf surfaces. We then bagged the leaves, preserved the mites in ethanol, and in the laboratory rinsed all mites all the leaves for counting under a stereoscope, where we could obtain full counts for mite eggs, larvae, deutonymphs, and adult males and females. Mite densities were almost universally low in the field during the year these data were gathered (2013), providing us with limited opportunities to contrast different quanlitative density classes; neverthless, consultant's qualitative density classes were clearly reflected in our field counts of adult female mites per leaf (F = 10.6, P = 0.0016).

Consultant rating	Sample size, N	Field count, adult female mites/leaf (mean ± SE)
'trace'	1	0.17
'trace-light'	14	0.67 ± 0.13
'light-moderate'	2	2.42 ± 0.71

<u>Task 4: Analyze the data set to quantify relationships between key insect and mite pests and citrus yield and quality; generate pest management recommendations for citrus growers.</u>

We present analyses for 744 harvests, involving 185 unique fields, and 12 unique years. Actual samples sizes vary significantly, depending on the particular analysis being conducted.

As a simple introduction to the dataset, we begin with an analysis that underscores the importance of recognizing that citrus is a perennial crop, and thus that tree age is of paramount importance as a covariate in analyses of yield effects. We examined the influence of tree age (years since planting) on total yield (tons of fruit harvested per acre). We fit a Generalized Additive Mixed Model (GAMM), using random effects for field, variety, and harvest year, and asked the model to produce a smoothed fit of the effect of tree age on yield. The effect is, not surprisingly, strong (N = 633, P < 0.0001; Figure 2). Mean yield also varied across citrus species, with greater mean yields observed for mandarins (ca. 40 tons/acre) than for the other dominant varieties (navel oranges or valencias, both of which had mean yields closer to 20 tons/acre). This analysis used a linear mixed model with random effects for field and harvest year and fixed effects for citrus type, N = 711). For these reasons, citrus type and tree age were included in the models of pest impact that we describe next.

<u>Effects of pest densities on total yield</u>

Some pest management consultants recorded estimates of pest densities using qualitative categories: either trace, low, medium, or high; or -, +, ++, +++. We converted these categories into a scale ranging from 1-4, and assigned intermediate values when consultants scored a particular citrus block as falling in-between two categories (e.g., "light-medium" was scored as 2.5). Three pests of citrus are strong candidates for generating yield losses; these are the "indirect pests" that reduce the overall tree vigor by feeding on leaves or stems, either damaging leaves (reducing photosynthesis; this applies to **California red scale** and to **citrus red mite**) or feed on phloem and stealing photosynthate (this applies to **citricola scale**). Other citrus herbivores are instead "direct pests," which we do <u>not</u> expect to decrease total yield, but which are candidates for decreasing crop value by decreasing the quality of the harvested fruit, since scarred or infested fruit are often downgraded at the packinghouse.

We built linear mixed models with random effects for harvest year, field, and variety; and fixed effects for age of tree and average pest density index over the full growing season prior to the focal harvest. The response variable was total yield (tons/acre). The tables reported below show 95% confidence intervals for the effect of pest density; the effect reported is change in yield (tons/acre) for an increase in density category of 1 step (e.g., low → medium).

Our initial analysis using the 1-4 qualitative density ranking data produced significant evidence of yield losses generated by only one of the indirect pests, California red scale (Figure 4).

Pest (indirect)	Mean effect on yield	Sample size	95% Confidence interval	Significant?
California red scale	**-5.56**	**436**	**-9.70 to -1.41**	**yes**
Citrus red mite	2.03	451	-1.38 to 5.44	no
Citricola scale	-2.86	392	-7.41 to 1.68	no

The direct pests, which are not candidates for generating yield losses, served as 'negative controls' in these analyses. As expected, we did not find any effects of the direct pests on total yield:

Pest (direct)	Mean effect on yield	Sample size	95% Confidence interval	Significant?
Citrus cutworm	-1.07	271	-7.83 to 5.70	no
Katydid	-2.32	271	-7.00 to 2.37	no
Citrus thrips	0.52	117	-3.54 to 4.58	no

Some of our consultants measured pest density using presence/absence sampling of fruits or leaves. Using these data, we can calculate mean percent infestation as a measure of pest density. We repeated our analyses of pest impact on yield using mean season-long percent infestation as an alternate measure; these analyses revealed that one of the indirect pests, citrus red mite, was associated with significant yield losses, but not the other two indirect pests (California red scale or citricola scale, although both exhibited clear trends towards reduced yield):

Pest (indirect)	Yield effect	*N*	95% Confidence interval	Significant?
California red scale	-1.35	95	-4.31 to 1.61	no
Citrus red mite	**-1.33**	**465**	**-2.39 to -0.30**	**yes**
Citricola scale	-1.28	201	-3.13 to 0.57	no

Again, consistent with our expectation that direct pests should serve as 'negative controls' in our analysis of effects on total yield, none of the direct pests was associated with significant yield declines:

Pest (direct)	Yield effect	*N*	95% Confidence interval	Significant?
Citrus cutworm	9.35	364	-0.40 to 19.10	no
Katydid	-2.81	473	-6.60 to 0.97	no
Citrus thrips	-4.89	604	-15.85 to 6.07	no

We also investigated if there might be delayed effects of herbivory on yield, by asking if pest density during year x was associated with a change of yield in year $x + 1$. No such association

was found for any pest, suggesting that yield effects were being expressed during the year the damage was incurred.

Effects of pest densities on harvest quality

Fruit are graded into quality classes at the packinghouse, and these quality grades have major implications for the value of the crop. We looked for associations between pest densities and fruit quality grade, which we converted to a 1-4 point scale: Rot = 1 (this fruit has no value); Juice = 2 (this fruit is worth <10% of the value of a fresh-market fruit); Choice = 3 (this fruit is worth ca. 50% that of a fancy fruit); and Fancy/export = 4. Mean quality grade was calculated as a weighted average of these four categories, with weights determined by the proportion of the total harvest in each of the quality categories. The analyses asked how a 1-step increase in pest density influences the mean fruit quality grade. All other aspects of the analyses were as described above for the analyses of yield effects.

For these analyses, it could be hypothesized that both the direct and indirect pests might be associated with downgraded mean quality scores. We found significant evidence for such downgrades for several pests when density was measured on the trace-high density metric:

Pest (direct and indirect)	Mean effect on harvest quality index	*N*	95% Confidence interval	Significant?
California red scale	-0.04	425	-0.08 to 0.01	no
Citrus red mite	**-0.04**	**445**	**-0.06 to -0.01**	**yes**
Citricola scale	**-0.05**	**384**	**-0.10 to -0.01**	**yes**
Citrus cutworm	**-0.21**	**264**	**-0.27 to -0.16**	**yes**
Katydid	**-0.09**	**263**	**-0.18 to -0.01**	**yes**
Citrus thrips	0.07	109	-0.19 to 0.33	no

Somewhat enigmatically, these negative effects on fruit quality were not observed when pest density was estimated using presence-absence sampling, although several pests exhibited strong trends towards negative associations with quality:

Pest (direct and indirect)	Mean effect on harvest quality index	*N*	95% Confidence interval	Significant?
California red scale	-0.04	93	-0.12 to 0.03	no
Citrus red mite	0.00	464	-0.01 to 0.01	no
Citricola scale	0.01	201	-0.001 to 0.02	no
Citrus cutworm	-0.03	363	-0.07 to 0.01	no
Katydid	0.00	472	-0.01 to 0.02	no
Citrus thrips	-0.05	593	-0.14 to 0.04	no

Economics and new recommendations for pest control

A key question is whether or not the effects on yield quantity and quality revealed in our analyses are economically important for the farmer. In particular, how do the magnitudes of the economic losses compare with the costs of applying pesticides in citrus? The answer to this question is critical to understanding farmer motivations to use pesticides.

Citrus is a very high value crop. Oranges, which in this dataset showed total yields of about 20 tons per acre, receive an average price of ca. $13.00 per 40 pound carton in 2012 (USDA, Agricultural Statistics). This corresponds to gross returns of appoximately $13,000 per acre (see also University of California 2009. Cost and return study - oranges). For mandarins, crop value is still greater: the most recent cost and return study performed by UC Davis suggests a crop value of ca. $18,000 per acre (University of California, 2011. Cost and return study - mandarins). These high values mean that even small amounts of pest damage can generate large economic losses; this is a central challenge for efforts to reduce pesticide use in commercial agriculture. We can perform a basic economic analysis that a farmer might use as a guide to control decisions, using the effects of pests on citrus quality (trace to high density index). In this analysis, I quantify the loss of crop value from a single-step increase in pest density metric (e.g., low → medium), assuming that each decrease of quality class (e.g., fancy → choice, or choice → juice) causes a 50% loss of market value.

Monetary losses associated with a one-step increase in pest density

Pest	Loss of harvest quality (number of quality class downgrades)	Loss of cash value (%)	Total loss for oranges ($/acre)	Total loss for mandarins ($/acre)	Cost of insecticide application (material plus application cost)
California red scale	-0.04	2%	$260	$360	$230 (Esteem)
Citrus red mite	-0.04	2%	$260	$360	$40 (Abamectin)
Citricola scale	-0.05	2.5%	$325	$450	$120 (Oil)
Citrus cutworm	-0.21	10.5%	$1365	$1890	$64 (Dipel)
Katydid	-0.09	4.5%	$585	$810	$92 (Delegate + oil)

What emerges from this analysis is that each of these pests is capable of generating economic losses that far exceed the cost of their control (the only exception observed here was for California red scale; however, this pest also generates loss of total harvest quantity, further increasing its potential to decrease crop value). Thus, some of the farmers who contributed data to this analysis appear to be incurring substantial losses from pest attack.

With regards to pesticide use in California, this analysis suggests two primary conclusions. First, farmers face stiff incentives to use pesticides when faced with strict cosmetic criteria for fruit quality at the packinghouse. Many of the pests studied here (citrus thrips, katydids, citrus cutworm) generate cosmetic damage without changing in any way the quality of the consumed fruit. Thus, to decrease pesticide use, changes in consumer attitudes when purchasing citrus fruits will be necessary to decrease farmer incentives to maintain strict control of fruit-damaging pests. Second, given the intense financial incentives to maintain pest densities at very low levels, it becomes imperative to identify environmentally benign or lower-risk materials for farmers to use as replacements for compounds that pose the worst risks to environmental quality. Citrus is a good example where low-risk and high-risk materials continue to be used, side-by-side, to control the same pests. It should be a high priority to develop data demonstrating the efficacy of low-risk materials to encourage growers to switch to their use. This may be a highly effective

means of decreasing the environmental burden of pesticide use, and one that can be adopted by farmers without economic hardship.

V. Conclusion

First, the indirect pests show some significant associations with yield, and these are always negative, as expected; in one set of analyses (density measured in qualitative classes), California red scale was associated with depressed yield, and in another set of analyses (density measured using presence-absence sampling), citrus red mite was associated with depressed yield. Citricola scale was not significantly associated with yield loss in either analysis, but both analyses showed a strong trend in that direction. Thus, our analysis reveals signals of yield loss associated with each of the three main indirect pests. None of the direct pests was associated with significant yield loss, as expected. Given the high values of citrus crops, these yield losses create significant economic incentives for growers to maintain low densities of all indirect pests.

Second, almost all the studied pests appear to be associated with reduced quality grades of fruit. This was true both for the pests that are viewed as direct pests, and therefore are expected to reduce quality grade (citrus cutworm, katydids, California red scale – which is both a direct and an indirect pest) and for pests that are viewed as indirect pests, and therefore might not be expected to reduce fruit grade (citrus red mite, citricola scale, although citricola scale can produce honeydew that supports sooty mold growth, which can reduce fruit quality). This is, to my knowledge, the first results to suggest that citrus red mite is depressing fruit quality. Thus, economic incentives for farmers to maintain strict control of these pests are strong.

It should also be noted that the direct pest that elicits the heaviest use of pesticides on citrus during the spring, citrus thrips, did not show any association with either total harvest quantity or with fruit quality grade (although a trend in this direction was suggested in the analysis that used presence/absence sampling to quantify thrips damage). Perhaps this is because growers are treating it too aggressively, a result that could allow us to recommend a more conservative approach.

VI. Discussion

This project is the first to apply ecoinformatics methods to studying interactions of pests with a perennial crop. The study has revealed that citrus farmers continue to experience strong economic incentives to maintain effective control of both indirect and direct citrus pests in their production of oranges and mandarins. Pest damage potential can create economic losses that are far greater than the costs of control. For CDPR and CalEPA, this result suggests a key pathway towards decreasing the environmental burden of pesticides generated by commercial agricultural production. Economic pressures faced by farmers are real. Some of these are generated by herbivory that weakens citrus trees, decreasing the total amount of fruit harvested. Equally if not more important, consumer preferences for cosmetically appealing fruit imposes stiff economic incentives to control those pests that generate superficial blemishes on citrus fruit rind, even if the underlying quality of the consumed portion of the fruit is unaffected ("direct pests"). Overcoming these economic incentives is a difficult task.

Perhaps a richer opportunity for decreasing the environmental burden of pesticides is in encouraging farmers to adopt environmentally benign or low-risk materials in place of materials

that have the greatest negative effects on water quality of human health. Citrus is a perfect example of a crop where most pests can, in principle, be controlled using either low-risk or high-risk materials. Different farmers make different choices. It is critical that evidence be collected from the real-world setting demonstrating that low-risk materials exhibit similar efficacy and cost-effectiveness as the higher-risk materials. High-risk materials are often older compounds, and thus may be more frequently prone to control failures due to resistance evolution in target pest populations. A broad-scale assessment of efficacy in the commercial setting that can incorporate control failures may be a strong pathway to developing strong recommedations for growers to increase their use of low-risk alternatives.

VII. Future goals

Our aim is to make the *Citrusformatics* database a 'living' resource for pest management research in California citrus. With the current invasion of California by the Asian citrus psyllid, pesticide use practices in citrus are changing rapidly. Decades of painstaking research to develop citrus IPM are at risk of being overturned by a pest that will elicit heavy applications of broad-spectrum insecticides. We are continuing to expand the database with support from CDPR, and are seeking USDA support to lengthen our time-series data to help growers adjust to the arrival of the Asian citrus psyllid in the San Joaquin Valley.

These results for yield effects will be refined considerably in ongoing analyses. We will continue to develop means of translating pest density ratings used by pest control consultants into traditional insect counts that are used by researchers; this will allow us to integrate our ecoinformatics approaches with experimental yield-impact studies to create the most robust foundation for data-driven pest control recommendations for farmers.

We will continue to develop the *Citrusformatics* database application, in particular to add analytics that will expand the range of data reporting options. In particular, we want to develop more 'digested' data reports, so that collaborating researchers will be able to obtain output files that are immediately ready for data exploration and formal analysis with minimal data manipulations. (The data analyses reported here were conducted after data manipulations, conducted with R routines, with the relatively 'raw' data report file that is the sole option currently available in *Citrusformatics*.)

We anticipate ongoing work to conduct detailed analyses on pest-crop interactions, pest-pest interactions, interactions of herbivory with plant nutrient status, and the relative efficacy of lower-risk alternatives to insecticides like chlorpyrifos that have been identified as threats to water quality. A goal of ongoing analyses will be to explore both the within-year and between-year effects of herbivory. The analyses reported here all averaged pest densities across an entire growing season, but we are interested in exploring the possible importance of windows of greater crop sensitivity to damage. This is almost certainly the case for the direct pests, which can generate significant scars on fruit only when they feed on very small fruit. By identifying clearly when windows of crop sensitivity open and close, we hope to find opportunities to decrease total pesticide use. (Without clear knowledge of when a developing citrus fruit outgrows its sensitivity to pests like citrus thrips, growers may be motivated to continue with pesticide applications long after any risk of crop damage has actually passed.) We will also explore the possiblity that cumulative stresses imposed by herbivores across multiple seasons might generate effects that are not seen in a single season of damage.

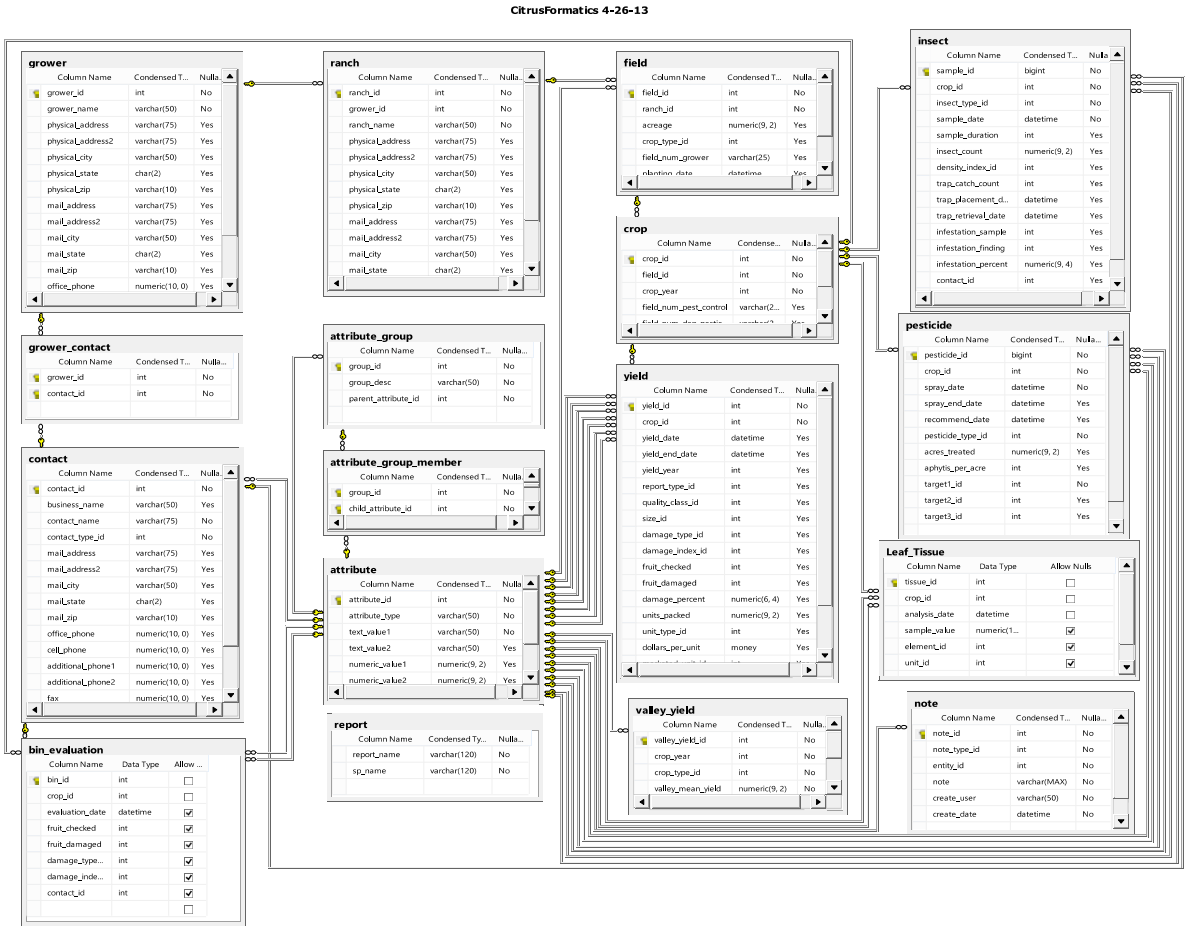

Figure 1: Architecture of the citrus ecoinformatics database, developed by Ten2Eleven Business Solutions, LLC.

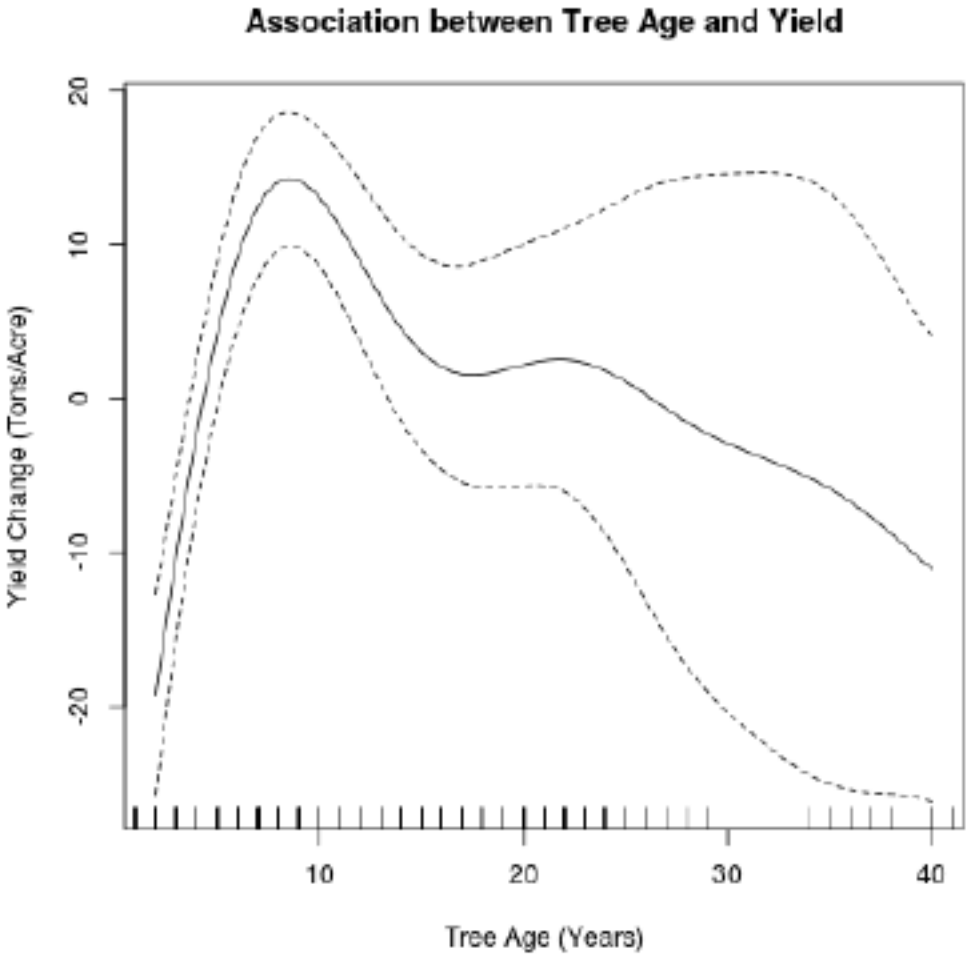

Figure 2. The influence of tree age on the total yield (tons of fruit/acre). Yield increases rapidly for young trees between 2-8 after planting, and thereafter declines.

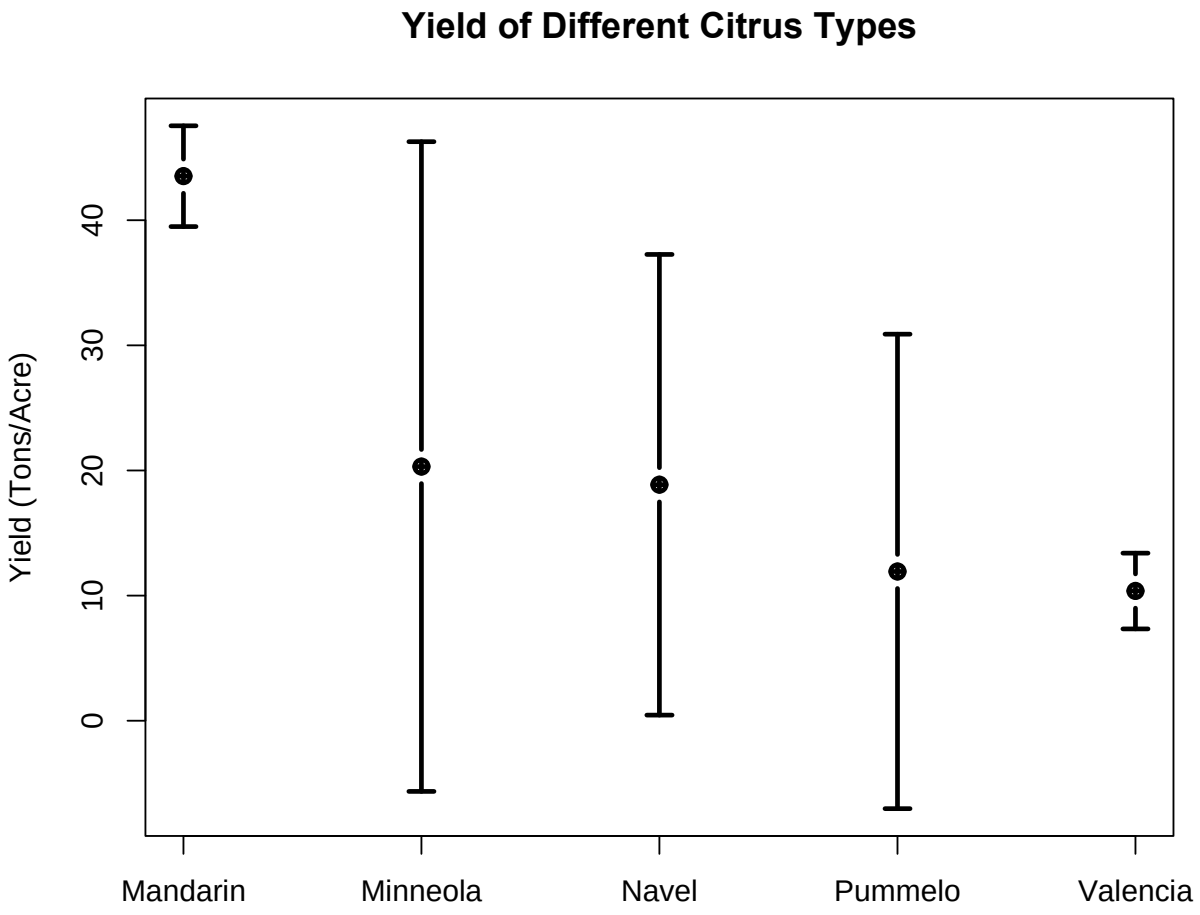

Figure 3. Yield for different citrus varieties grown in the San Joaquin Valley of California; shown are means ± SD.

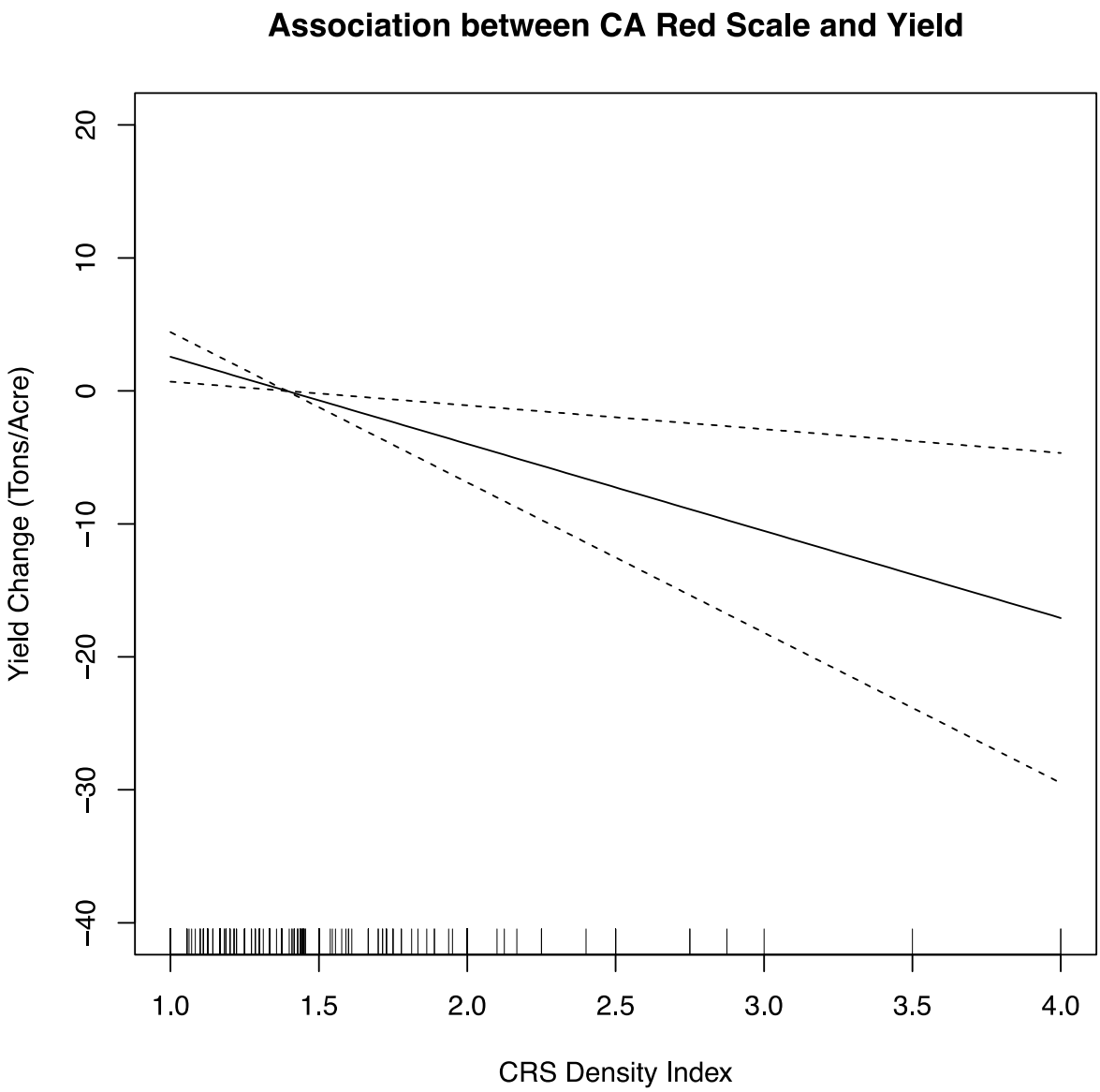

Figure 4. Association between California red scale density class (1 = trace; 2 = low; 3 = medium; 4 = high) and total citrus yield (tons/acre). Shown is the fitted linear relationship and the 95% confidence interval.

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