Report from the Field:
Results from an Agricultural Wireless Sensor Network

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Abstract

This paper reports the results of a 6-month deployment of a 65-node multi-hop network in a vineyard setting. This deployment specifically looked to discover ways in which a farm setting could find a return on investment for deploying such a network. Our ongoing collaborations of over two years ultimately have included everyone from the vineyard owners to the technology developers. We have been able to find several areas where wireless sensor networks deliver valuable information and provide a return on investment.

1. Introduction

This paper reports the results from an operational sensor network. We will cover learnings not only on the networking side but also for the content area (agriculture), specifically looking at areas where the sensor network provides valuable (and previously unobtainable) information to the agriculturist.

This network is large (65-node), dense (the 65 nodes are distributed over just two acres), and deep (up to 8 hops). Our goals included trying to show what the return on investment might be for someone deploying such a network. To that end, we collected, and will report here, data that have particular agricultural significance. Although the data we have collected were exclusively in a wine grape vineyard, these data do extend to many other agricultural crops.

Another way to think of this report is that this is a study of a little known law called "Segal's Law" which states that: "A man with a watch knows what time it is. A man with two watches is never sure." In fact, what we show in this paper is that climatic conditions are unlike Segal's time. A man with one sensor may act as though he knows about his domain but, in fact, a large number of sensors is required.

2. Field work

We began this project with an ethnographic study of the denizens of vineyards. We worked with vineyard owners and managers, wine retailers and wholesalers; we did participant observation (during harvest and crush) to better understand the field work [1]. We quickly came to the realization that we had to consider the needs of users in developing a useful system. To that end, we have engaged with a variety of types of potential users, the most significant for this paper are the agricultural researchers who undertake research for the benefit of working farmers. Intel Research collaborated with a lab at AgCanada's Pacific Agri-Business Research Centre (PARC) and has been involved in joint research in the Okanagan Valley in British Columbia. With this research we hope to determine, in this early stage of development, which sets of measurements are likely to have the most significance for farmers.

For this collaboration, we have been measuring temperature with dense deployments of sensors in vineyards. By placing these sensors in a dense grid, we can characterize the temperature variation across the surface of a vineyard. Dense, here, is being used in a relative sense. Most vineyards in the past used a single sensor at one point and then would assume that temperature (or a simple extrapolation of it) could be used to characterize the temperature profile of the vineyard. We are working to understand the value of such data.

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2.1 Background

We have been exploring the ways in which sensornet technologies could find a place in agriculture. Specifically, we have been doing research on a particular crop within agriculture: wine grapes. We believe, and our research has demonstrated, that interesting ubicomp solutions will require a relatively deep knowledge of a domain and that these domains are domains writ small. A system designer cannot simply design for agriculture in general, both crop and environment will be significant. Crop will bring with it at least two idiosyncrasies. First, different crops have different agricultural needs. Second, crops have particular sets of management practices with which they are associated. In addition, we selected grape vineyards because they are an interesting crop for several reasons. Being a non-field crop (unlike, e.g., wheat), grapes allow simpler deployment of the relatively large and expensive prototypes with which we are now working. Also, wine grapes can be a high dollar crop with surprisingly tight margins. Reducing costs and/or increasing crop value are at the forefront of research into grape growing. This document outlines some of the issues that we are addressing at this phase in our research as well as describing some of the work being done by researchers in Canada.

2.1.1 Homogeneity. Much of the work on a farm is based on a unit sometimes called a management block. Sections of a farm are divided into blocks that will be worked on as units. A typical example is irrigation. The irrigation system will usually be able to irrigate a small section (one block) of the farm at any one time. Once one block is done, another block can then be irrigated and so on, until all areas requiring irrigation are completed. While this is true of irrigation at least in part because the pipes to deliver high volumes of water throughout a large area would have to be huge, it is also the case that different areas may have different watering needs. Blocks are established so that their needs are relatively homogeneous. The same is true with many other practices on the farm ranging from harvest to pest control. Work is done on a block-by-block basis. There is an assumption here that there are no significant differences within a block. This is an assumption of homogeneity.

2.1.2 Heterogeneity. Intra-block variation is common but often ignored. Measurements have historically been done at few locations (typically one) and this measurement is used to reflect the entire vineyard site. Berry measurements at the end of the season are done on berries sampled "randomly" from the blocks to account for heterogeneity but then this heterogeneity is thought to represent the entire vineyard (and the "random" sampling is thought to be the best that can be done rather than a sampling motivated by known variation in the vineyard). Dense wireless sensor networks will allow agriculturists to record and respond to intra-site variation.

2.2 Temperature

One of the most important books on viticulture [2] claims that "[t]he only factor of climate that proved to be of predominant importance [for wine quality] was temperature" (p.61). The difference, for example, between the Rhine region in Germany (one of the coolest wine growing regions) and Tuscany in Italy (one of the warmest) was that Tuscany had about 20% higher heat accumulation during the growing season. However, this study looked at temperature on a very gross scale, the temperature characteristics of entire valleys or wine growing regions.

Here, we are looking for significant variation in temperature over one management block. Vineyards are often on hillsides or other terrains that allow for air drainage. Standard practice is to have the measurement from a weather station apply to the entire vineyard. There are no data with which to manage the (very real) heterogeneity.

For the research reported here, we will consider in more detail two factors of paramount importance to agriculturists: heat summation and periods of freezing temperatures.

2.2.1 Heat Unit Requirements. Any site must have sufficient "Heat Summation Units" (HSUs) or "Growing Degree Days" for the selected crop. These two phrases are shorthand for one of the most significant characteristics of an agricultural site. Simply put, this characteristic is the temperature over a 10^{o}C baseline that a site accumulates over the growing season. (10^{o}C is the baseline for wine grapes because they see no real growth until the temperature goes above 10^{o}C. Each crop has its own characteristic baseline.) Different wine grapes have different requirements for heat units and, consequently, different sites will be able to support different grapes. Wine grapes require a long growing season, as long as practically possible, so the heat must accumulate slowly to develop the best flavor profile.

As can be seen in the Table 1, the heat unit requirements for Riesling are low, while those for Cabernet Sauvignon are high. This would suggest that in a cooler climate, even if there are not enough heat units for a Cabernet to mature, there might be enough for Riesling. This is significant since, also in Table 1, we can see that the per-ton price for Riesling is nearly half of what it is for Cabernet. If we can grow Cabernet, it would make financial sense to do so.

Table 1: Data for Various Vinifera Grapes

Heat Unit Requirements (cold hardiness) [average 2001 price per ton in WA State] [1]		
Low	Medium	High
Riesling (high) [600]	Chardonnay (high) [800]	Cabernet Sauvignon (moderate) [1100]
Gewurz (high) [650]	Syrah (low) [1225]	Cabernet Franc (moderate) [1000]
Pinot Noir (high) [700]	Merlot (low) 1000]	Sauvignon Blanc (moderate) [725]

2.2.2 Cold Hardiness. Cold hardiness is another variable to consider. If cropland is exposed to particularly low temperatures, crop damage can occur and more cold hardy plants make more sense. These data (to the extent that we had them available) are also in Table 1. The Okanagan Valley, where we did this work, is high, desert land and killing frosts commonly occur. These frosts can cause a grower to lose a year's growth (and profits) by killing the shoots of the new year in the spring or by killing the leaves (and cutting off the supply of energy) or buds at the end of the growing season. Worse yet, the low temperature can kill the entire plant causing the grower to lose at least three years in waiting for the plant to reach sufficient maturity to yield usable wine grapes.

Figure 2 shows the area where this research was carried out. The major lines on the map show grape variety boundaries. Chardonnay, to the right, is planted outside of a low area that gets enough frost to damage the plant. The hardier Auxerrois Blanc is planted in this pocket. Auxerrois is among the most cold-hardy of the vinifera (fine wine) grapes. However, there is a serious downside. The per ton price for Auxerrois is often as low as half that for Chardonnay so the vineyard owners are quite interested in knowing that the boundaries are as tight as possible. That is, it would be better to plant Chardonnay and finding the limits of range could greatly influence the value produced by that land.

When the viticulturists cited above talked about temperature, they meant growing-degree-days. Obviously, cold hardiness is just as important for bringing in a valuable crop.

2.3 Current Work

The technology we have been using for this project, and two previous trials [1] is well known in the ubicomp world - Berkeley motes. We have worked with several different topologies but in every case, we have deployed a number of mote-based sensors across a region of the vineyard and looked for variation or areas of discontinuity that would have been difficult to predict given standard measurement regimes.

2.3.1 Technology Overview. The key technology component for getting environmental data was the network of sensors. The network was based on the Berkeley mote, in particular the Mica II mote, and its associated sensor board. The mote is a 3V, low power microprocessor, with a 916MHz radio, flash memory, eeprom, and a multichannel A/D converter. The A/D converter provides a simple mechanism for easily integrating a variety of analog sensors.

In the experiment to be detailed in this paper, we used a customized version of the "Basic" sensor board and did a predeployment calibration [3] of the sensors in a temperature-controlled environment. Previous experience with the motes had shown us that there was substantial variation in the readings provided by the motes (reliably in excess of 3 degrees C). The customizations to the sensors represented an attempt to address this issue, as well as several others that we will now discuss. The customized sensor that we designed was a simple variation on the one built into the "Basic" sensor board. It uses the identical thermistor (YSI 44006) and a 1% 10K ohm metal film resistor in a simple voltage divider circuit. The precision resistor provided much closer mote-to-mote reliability. The other important change to the sensor design was remotely mounting the thermistor on a four-foot cable (see Fig.1. This was important for three reasons. The first reason relates to the close proximity of the standard sensor to the mass of the mote and its batteries. The batteries represent a large thermal mass coupled to the sensor. As a result this sensor tends to be a better indicator of the temperature of the mote, as opposed to the ambient air temperature (the true variable of interest). The other aspect of the large thermal mass is that it behaves like a low pass filter. So even relatively large fluctuations in temperature get smoothed over or ignored, and time shifted. All

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[1] These data are derived from "The Wine Grape Industry at Lake Chelan, Washington" a report prepared for the Chelan County Port District. Available on-line at: http://www.chelancounty.info/wine_pdf/full_verison/study.pdf.

classic behavior for low pass filters. The second reason is that the container itself can strongly influence the temperature of the mote, and as a result the temperature reported by the closely attached sensor. The color, the material, and the ventilation all play an important role in how the container affects the mote. The third reason is that agricultural researchers have a standard for measuring temperature. It is comprised of a simple sensor like the one that we designed and it is housed inside of a device referred to as a Stephenson screen. No one is arguing that a Stephenson screen represents perfection, but they have a known set of relevant characteristics including heat absorption and ventilation. In order for any results obtained from this experiment to be useful/comparable to other research in the field of agriculture this type of housing was a requirement (see Fig.1).

For our power supply, we decided to err on the side of safety and used a much larger power supply than that supplied with the mote. We used 6 Duracell Procell D Cell batteries (PC1300). Each of these batteries had 14 amp hours, giving our power supply 42 amp hours in total.

Fig. 1. PVC container for Mote hanging in a vineyard with Stephenson screen

The motes in their basic form are fairly fragile, relative to the environmental conditions that they were going to be exposed to, e.g., a wide range of temperatures ranging from -30C to +45C, rain, snow, high winds gusting to 140km/h, and general physical abuse that might result from being deployed in a working vineyard. So to protect the motes a PVC container was devised to house them. The container provided protection from moisture and physical abuse, while also providing sufficient ventilation so that the motes and power packs would not overheat. In addition to the PVC housing, the motes and power packs were inserted into a plastic bag with two packets of desiccant. The desiccant was included to prevent any moisture initially trapped in the bag from condensing on the motes and causing short circuits. The cable for the external sensor was routed out of the bottom of the bag, and then the bag was sealed with a wire twist-tie.

The network consisted of sixty-five motes distributed in a grid like pattern ten to twenty meters apart covering about two acres. The motes took approximately 1 person day to deploy. Much of this time was spent walking down rows and climbing through the wires that are used to support the plants. Since mote based networks can be self-configuring it simplified the process of planning the layout. The basic structure of vineyard also contributed to the ease of planning the layout and deployment. Vineyards by their very nature are simple grids composed of numbered rows and panels, originally done to facilitate the basic work and management in the field. The network layout had to satisfy two simple constraints. The first was that the sensors needed to be located in an area of viticultural interest, and secondly they needed to be within radio distance of some set of other motes in order to relay data back to the base station.

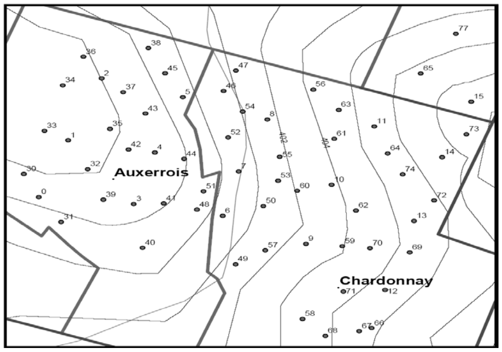


Fig. 2. Topographic map with two-meter elevation lines and mote locations.

Identifying the areas of viticultural interest was primarily the task of the agricultural researchers from PARC. This determination was based on a large number of parameters including grape variety, anecdotal data about locations of previous frost damage, and slope and aspect of the surrounding ground. Determining whether we were within radio distance of neighboring motes could be done based on heuristics from tests run in a laboratory setting (basically around 30 meters for reliable performance). However, a vineyard represents a fairly harsh radio environment. There are rolling hills, dense foliage, and miles of wire and metal posts supporting the vines, and as a result the heuristics do not always work. To simplify the process we designed a set of simple tools that we used to survey the vineyard during an earlier visit. The first set of tools simply sends and responds to a predetermined message similar to a network ping. This allows us to easily determine whether one location in the vineyard is in radio contact with another. In simple terms it behaves like a radio based measuring tape. This tool was designed to help laymen setup a network when the simple heuristics fail, or there is a known problem area. The second tool allowed us to test a network once it was deployed and characterize the connectivity and packet loss through a variety of network paths in the vineyard. In addition, this tool would instruct the motes to increment a hop counter, as well as add their own GUID to the packet, that way we could easily see the exact paths data was taking through the network as well as evaluate the performance relative to a variety of physical characteristics in the vineyard. Based on these original data we successfully deployed this larger scale network about as quickly as we could walk from one location to another.

As each mote was deployed it automatically joined the network upon hearing a synch signal (described in the next section), and began to relay data to the base station mote. In our case, the base station was attached via its serial port to a laptop computer in the vineyard owner's home, and was placed near a window facing the vineyard. The application on the laptop logged the data as it was coming in and provided a real-time display of the data. The motes reported the temperature every five minutes. This is three times more frequent than the convention in agricultural research. The five-minute interval allowed us to satisfy the agricultural research constraint as well as explore a closer approximation to real time monitoring. In addition to temperature data the motes reported telemetry data that was primarily of interest to the Intel researchers, including data relating to battery performance, packet loss, routing.

A more traditional set of sixteen sensors was also deployed in addition to the mote based sensor network. The loggers were used as an independent source of data to validate the mote based measurements. The contrasts in the effort required to deploy these sensors was quite remarkable. The data loggers were installed by a group of individuals experienced at the task, and it took them 6 person days to install and verify the data logger deployment (24 times the effort for the 65-node mote network). This in itself is significant, but what is even more important to consider is the total cost of ownership (TCO) of such data loggers. A person must physically visit the logger system and manually download the data by attaching a serial device. This process must be repeated at regular intervals throughout the growing season. The process is difficult, and expensive and precludes using the data to be used proactively for real-time applications like frost protection, precision irrigation and localization to guide and track work. In addition the data loggers give no feedback about their performance. So a failure is only identified at the end of a fairly long data collection cycle and can result in considerable lost data.

2.3.2 Software. The mote software was written using a prerelease version of TinyOS 1.1. The application was designed to record the temperature from the external sensor, an internal temperature sensor, as well as the power supply voltage every 5 minutes. The data for each mote was transmitted via the multihop network back to the base station. The base station mote would also broadcast a time synch signal at five-minute intervals, enabling the motes to stay synchronized. This signal was forwarded through the network. Synchronization is critical for this type of research since the goal is to characterize differences across a vineyard at each point in time. The synchronization signal also provided an easy mechanism to introduce new motes to the network, as well as provide a mechanism to easily replace motes in the network should they require maintenance. After synchronizing, the motes go to sleep, and reawaken at the appropriate time to take the next measurement. Since the motes are asleep (drawing 9uamps) the majority of the time, it results in significant power savings, and greatly extended battery life.

The desktop application logged the data from the motes as well as providing a real-time display of the ambient conditions in the vineyard. The layout of the display reflected the simple grid layout of the vineyard itself. The primary purpose of this application was to provide long term measurement data for vineyard planning, to guide precision harvesting, and to develop new agricultural models. Our ongoing work on analyses and interfaces for these issues more fully addresses these questions. However, the logger and the real-time display are useful in their current form for applications like frost protection and heat unit summation. If the fruit is damaged by frost, the vineyard may lose the current year's crop. If the vines are damaged, they may need to be replanted, and will not yield a harvestable crop for several years. Current agricultural practice is to monitor the local weather reports and if there is a cold front moving into the area a worker may spend the night wandering the vineyard and taking measurements using a portable weather station. If the temperature gets cold enough, he/she will briefly turn on the irrigation system in that area to mist the plants which protects them from the frost. The measurement system we have developed can notify the vineyard owner of potential frost damage through a variety of mechanisms including: email, phone, and a warning presented in the GUI of the logging application. This is in itself a significant improvement, but we envisage a much more proactive system in the future, that could through the use of actuators be able to control the irrigation system, and automatically deal with the threat of frost and other problems in the vineyard.

2.3.4 Network Configuration. The mote network was based on a slightly different topology than typically described in the literature [4,5]. The main considerations in choosing this topology were practical and theoretical in nature. The network described in this paper was deployed prior to the current release of TinyOS 1.1 so many of the advanced features provided by the TinyOS Application Sensor Kit were not available (ad hoc routing with a variety of available algorithms, and advanced power management). This was a disappointment from one perspective since we wanted to try out the latest SDK and it required that we implement equivalent methods ourselves. However, it did give us the freedom to explore a slightly different approach to routing and network layout/deployment. The power management software we wrote was not theoretically interesting, and was derivative of the earlier snooze code implemented for the MICA mote. This module was primarily a port of the earlier code with some minor but useful modifications.

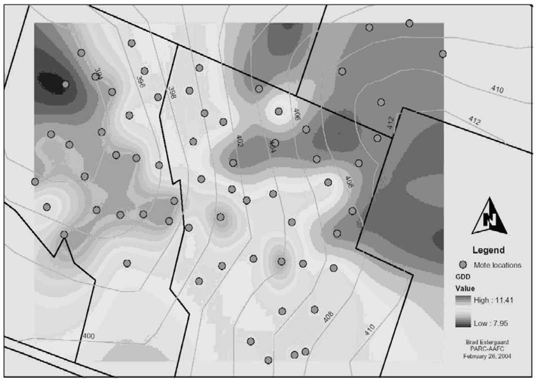
One of the distinguishing characteristics of this network compared to the canonical sensor network is that it is a planned network. As you will have noted there was no discussion of ad-hoc routing, which is commonly assumed to be part and parcel of a wireless sensor network. The current network layout was guided by the agricultural research interests rather than a purely mote centric perspective. As a result we knew *a priori* where the sensors were going to be placed with fairly high precision. So we did not use ad-hoc routing in a pure peer-to-peer network. Ad-hoc routing has two primary benefits, automatically configuring the routing pattern of data within the network, and being robust against failure of individual nodes. However, these benefits come at a cost: route discovery and maintenance consume bandwidth and battery power. Since the network was not random we could inject suggested routes into the network and/or hard code them. What is more important though is route maintenance, and what to do if motes failed to route data. We decided on a strategy of route diversity and repetition, basically each packet was sent multiple times (five times), using multiple routes. This is of particular concern in a large multihop network. A basic assumption on our part is that the radio is reliable but imperfect. When we test the motes in the lab we get consistently long ranges and high reliability in mote-to-mote connectivity in excess of 99%. Performance in the field tends to be lower, due to a wide variety of environmental factors, high temperatures, low temperatures, dense foliage, cabling, and radio interference. If one assumes that the performance of the radio is 99% reliable in the field, then the probability of a message surviving an eight-hop trip to the base station is approximately 92% (0.99^8). Since we had limited real world performance data we decided on the conservative approach of repeating the message to ensure it would be received at the base station. Therefore the probability of success is equal to 1 – p (all five failing) which is vanishingly small ($1- (1-.92)^5$).

The network was configured as a two tiered, multihop network with a maximum of 8 hops. The number of hops was determined by the fact that the optimal deployment of the motes from a perspective of viticultural interest tended to place the motes just at the edge of radio connectivity in the context of the vineyard (20 – 25 meters separation) using the simple ¼ wave omni directional antenna that shipped with the motes (i.e., a length of wire). The first tier was composed of 16 motes that were 20% duty cycle and served as sensing motes, and as primary routers for the network. The second tier was 3% duty cycle, and served as sensors only. This design provided a variety of benefits, the first of which was ease of layout, the second of which was good power efficiency combined with the ability to report the status of the entire network in real-time at five-minute intervals, and the third was ease of maintenance. The maintenance issue can be a significant factor when discussing networks that can be composed of hundred or thousands of nodes (near term expectations based on price and scalability). Our estimate based on experiments in the lab was that the low duty cycle motes would last longer than the growing season and the winter combined. In practice, our telemetry data from the live network shows that the battery life of the low duty cycle motes will approach the shelf life of the batteries that we used (approximately three years). However, the higher duty cycle motes generated a much greater drain on the power supply. Our estimates were that the batteries would likely last three months. In practice we did not wait until the batteries were completely drained before replacing them. Since they represented only a small subset of the motes, the process was fairly quick and painless, but does suggest design considerations for the packaging of the motes as well as the power supplies. For example an ideal container would have a sub compartment for the mote and some desiccant supply to prevent trapped moisture from condensing on the electronics. In addition, you would want a separate sub enclosure for the battery that opened to the outside and would allow the batteries to be easily changed. A nice addition would be to have two battery slots so that new batteries could be installed before the old ones were removed to allow uninterrupted operation even during maintenance. Our current design was guided by our knowledge of the work practices of the vineyard, in contrast to mote deployments in sensitive habitat [5]. We knew that vineyard owners/workers/researchers are constantly moving about the vineyard, and that occasional maintenance activity would be permissible. In addition, based on the power consumption estimates, we knew that the frequency of maintenance would be minimal.

3. Results

First, the network was up and reliable for the period from the onset of grape maturity through the second major arctic outflow (i.e., cold front) in the region. Consequently, we were able to collect data to address both the question of growing degree day differences and areas of potential frost damage. The data to be presented here are from (a) a one-month period during the end of the growing season and (b) the first arctic outflow. Furthermore, we were able to collect data to determine whether the temperature data co-varied with known agriculturally significant data.

3.1 Growing Degree Days



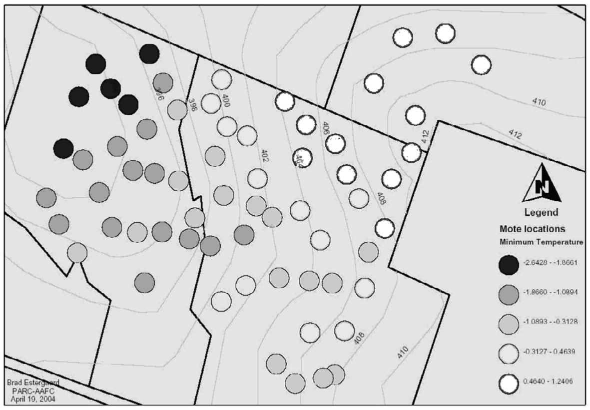
Brad Estergaard
PARC-AAFC
February 26, 2004

Fig. 3. Heat Unit Accumulation Differences Over a One-Month Period

Figure 3 presents the mean growing degree day data for August 15th through September 15th 2003. The mean data allows one to easily observe the relative differences for heat unit accumulation during that period. One can see from the legend that the means range from 7.95 to 11.94. The cooler areas, therefore, accumulate two-thirds the heat units of the warmest areas.

Since the temperature data are overlaid onto a topological map, one can also easily see that while temperature does co-vary somewhat with elevation and aspect, these do not predict temperature value overly well. In fact, attempts to fit these data with a neural net accepting slope, aspect, and elevation as inputs were not successful.

3.2 Frost Pocket and Cold Patterns



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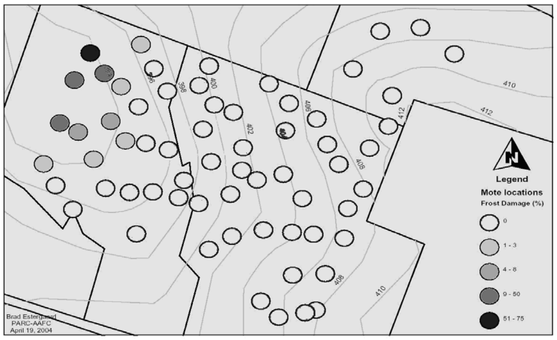
April 10, 2004

Fig. 4. Temperature below freezing during 10/14/04 arctic outflow

Figure 4 shows the minimum temperature recorded by each of the nodes during the first arctic outflow of the season. The first thing to note is, as in Figure 3, elevation does co-vary with temperature but not perfectly. The low-lying area planted in Auxerrois Blanc does see the coldest temperatures. However, some of the area planted in Auxerrois seems as if it could be warm enough for Chardonnay. This pattern will need to be followed over a few arctic outflows to see if it is consistent.



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April 19, 2004

Fig. 5. Bud damage caused by 10/14/03 arctic outflow

Figure 5 shows the damage to buds for these plants. The vineyard owner chose not to use the irrigation system to protect the plants and so we were able to collect data demonstrating the extent of damage from he arctic outflow and then compare it to the measured differences. Only one plant saw serious damage and it was in the coolest area of that section of the vineyard. It should be noted at this point that further data are available (length of exposure to below zero temperatures) and analyses are continuing on this and other outflows.

3.3 Network data

3.3.1 Network Performance. Radio performance in the field was substantially less than the 99% we saw in the lab. On average, data were received in 77% of cases (mean = 71320, s.d. = 15415). Our strategy of resending each piece of data 5 times, then, was significant and in many cases meant that we had complete data reports from each epoch. However, there were a few days where the network was unstable and many data points were lost. Resetting the network was necessary in this case.

3.3.2 Power consumption. The two tiers of the network had quite different performance. The high cycle backbone required two battery changes during the course of data collection. Voltage went from 3.2v to 2.8v in these nodes. The low duty cycle nodes showed no significant decline in power over the course of the study.

4. Discussion

This research has demonstrated some of the value that a wireless sensor network might bring to an agricultural setting. In addition to demonstrating (as a side effect) that the total cost of ownership of a wireless network is lower than a wired network, we were also able to show at least one example -- frost prevention -- where a live network is more valuable than a standard data logger.

More importantly, the extent of variation in this vineyard resulted in a measured difference of over 35% of heat summation units (HSUs) in as little as 100 meters. This is greater than the 20% difference between Tuscany in Italy and The Rhine in Germany. Over the course of a growing season, this could result in the difference in being able to mature a Sangiovese (typically grown in Italy) and a Reisling (typically grown in Germany).

If you want a quality wine, you need to manage for the diversity of the climate that you are working within. With a single source of data, typically you make an assumption of homogeneity. This is a simplifying assumption and it can make much of the work on a farm more manageable. However, if we can increase the value of a crop, additional complexity is warranted. Further, we have (elsewhere) described ways in which the use of a wireless sensor network can simplify the work on a farm or can balance the new requirements imposed by this new data and can be a work load neutral effect [1].

4.1 Back to Segal's Law

"Segal's Law" states that: "A man with a watch knows what time it is. A man with two watches is never sure." Time has the remarkable property of not varying (in a real sense) over the space taken up by a vineyard. It is likely that one watch would suit Segal just fine. Climate, in this case temperature, is quite unlike time in that it can and does vary significantly over the space taken up by a vineyard. Simply put, a man with one sensor may act as though he knows about his domain but, in fact, a large number of sensors **is** required.

5. References

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