**Development of Economically Viable Variable Rate P Application Protocols for Desert Vegetable Production Systems**

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Funding Request

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## B. Executive Summary

Vegetable crops produced in the desert receive large annual applications of phosphorus (P) fertilizers. Amounts of P applied to vegetable production systems often approach and exceed 200 kg P/ha and crop recoveries of P fertilizers are generally less than 25%. While much of the added P is converted to insoluble forms in the calcareous soils of the region, some of it is carried in runoff and drainage water into receiving surface waters having adverse ecological effects. Further, erratic fertilizer pricing over the past several years has created incentives for improved efficiency. Approximately three years ago, the costs of mono-ammonium phosphate (MAP), a formulation widely used for desert vegetable production, exceeded $1,200.0 per ton. Although costs have since declined, rapid increases are anticipated as the world economy recovers and resource demand in the developing world regains momentum. In addition, world P reserves are rapidly declining and there is concern that a shortage of P fertilizers will ultimately result in large fertilizer P price increases and ultimately compromise world food production.

In studies we have shown most cool seasons vegetables produced in the desert will respond to P fertilizers up to a sodium bicarbonate P soil test level of 30 to 35 mg/kg. As pre-plant soil tests approach these critical soil test P levels, the probability of crop response to P fertilizer drops dramatically. However, P fertilization based on a composite soil sample from a production unit assumes relatively uniform fertility within the unit which is inconsistent with our findings. In high resolution sampling of vegetable production fields in the desert we have found large in-field variability in soil test P levels within production units (CVs from 18 to 90% usually exceeding 50%). Thus, if we made adjustments in pre-plant P recommendations to minimize economic losses due to under-fertilization, we would have to over-fertilize a large portion of the field. This not only has economic consequences, it can result in very high available P levels over part of the field and adverse consequences such as P induced micronutrient deficiency (particularly Zn).

The prospect of variable rate pre-plant P fertilizer application has not been extensively evaluated in desert vegetable cropping systems. The objective of this project is to 1. Develop economically viable and effective sampling protocols to generate prescription maps for the variable rate application of P, 2, Compare variable rate P application to current methods and evaluate alternative economic outcomes. In the first phase of the project we will test alternative sampling schemes. Sampling schemes evaluated will include grid sampling at various resolutions and sample schemes which seek to define management zones directed by other indices of in-field variability. In the second phase we will evaluate the efficacy and economic returns to variable rate P application. Project success will be the development of economically viable protocols for the implementation of variable rate P application technologies. The target audience will be crop advisors in the public and private sector that make fertilizer recommendations to producers, the fertilizer industry that can offer this as a value added service to producers, and growers that make production decisions on economic returns and, depending on their size may invest in infrastructure to implement this technology themselves.

## C. Justification

1. Problem

Phosphorus fertilizer added to agricultural soils is rapidly converted to forms less available to plants. Sorption and precipitation reactions are involved. The sorption of inorganic phosphorus from solution is related to the presence of iron and aluminum oxides and hydrous-oxide minerals (Fried and Dean, 1955; Fox and Kamprath, 1971; Cogger and Duxbury, 1984) and $CaCO_3$ (Cole et al., 1953; Griffin and Jurinak, 1973; Holford and Mattingly, 1975; Porter and Sanchez, 1992).

Phosphorus sorption is limited to relatively low initial phosphorus solution concentrations, and precipitation becomes a more important mechanism of phosphorus removal from the soil solution at higher phosphorus concentrations (Cole et al., 1953). The nature of the reactions products formed when phosphorus fertilizer is added to soil depends on the pH of the saturated solution, the coexisting cations, the quantity of phosphorus fertilizer added, and the chemical characteristics of the soil (Lindsay, 1979). In acid soils, iron and aluminum will generally precipitate the P. In calcareous soils, the acidic fertilizer solution would readily dissolve Ca and it is expected that most of the added phosphorous fertilizer would precipitate initially as dicalcium phosphate dihydrate (DCPD) and dicalcium phosphate (DCP) (Terman et al., 1958; Lindsay and Stphenson, 1959). These products are only meta-stable and undergo a slow conversion to compounds such as octacalcium phosphate, tricalcium phosphate, or one of the apatites. In calcareous soils, the reactions of added fertilizer P are often referred to as reversion because thermodynamics directs the added P toward mineral species similar to those found in mined phosphate, (Gowariker et al., 2009) forms typically not available to plants. Phosphorus availability to plants is optimal at soil pH levels of 6.5. The capacity of the soil labile fraction to replenish solution P is reduced by the formation of stable Fe and Al P minerals below pH 6.5 and by Ca minerals above a pH of 6.5 (Sanchez, 2006).

Soil phosphorus transformations are complex and poorly defined for any given soil. Phosphorus availability is often characterized in general terms as solution P, readily available or labile P, and non-labile P. The labile fraction might include easily mineralizable organic P, low-energy sorbed P, and relatively soluble mineral P. The non-labile fraction might include resistant organic P, high-energy sorbed P, and relatively insoluble phosphorus minerals. As plants absorb phosphorus from the soil solution, it is fairly rapidly replenished from the labile fraction, which in turn is more slowly replenished by the non-labile fraction but often at rates insufficient to meet plant demand. The sodium bicarbonate soil test used in the western United States aims to characterize the soil labile fraction.

Phosphorus not used by crops or tied up by the soil is eventually transported downwind and downstream, entering streams, rivers, lakes, and oceans. Since P is limiting to production in aquatic ecosystems (Elser, 2007) as it is in agricultural land, this loading of P leads to eutrophication (Smith, 2006). In lakes and marine ecosystems, eutrophication outcomes include algal blooms that often involve toxic species that impair drinking water quality, and result in significant economic losses recreation, real estate values, and remediation and ecosystem restoration (Dodds er al., 2009; Diaz and Rosenberg, 2008; Hoagland, 2002).

A more recent concern is the long term supply of P mineral reserves. Cordell et al. (2009) considered patterns of overall global P use in relation to estimated P reserves (as of ~2005) and suggested a maximum global P extraction rate as early as 2035. This estimate attracted considerable attention given its correspondence with major price increases in 2007 and 2008 in the price of phosphate rock (>500%) and phosphate fertilizers (>250%). Also important in driving concerns is the fact that P reserves are geographically confined to just a few countries (Morocco, China, USA, Jordan, and South Africa contained >85% of the 2005 reserve estimates). Van Kauwenberg (2010) re-analyzed available information about global P deposits and released new estimates. The change came largely from estimates for Moroccan P reserves, which were revised upwards by 10-fold based largely on an over-looked geological report from the 1980's. This revised estimate was endorsed by the United States Geological Survey, increasing global P reserve estimates by 4-fold. However, Cordell et al. (2011) noted that this revision awaits independent verification and, even if accurate, only shifts the estimated date for maximum extraction back by several decades. Meanwhile, Elser and Bennett (2011) note that the new information highlights the importance of the geopolitical, rather than the geological, dimensions of P. The extreme stratification of P reserves in a single country sets the stage for future monopoly pricing, a highly problematic situation given our dependence on P fertilizers for food production.

The need to improve P use efficiency in agriculture production systems is urgent. This is especially true for high value vegetables which receive large amounts of P fertilizer for optimal yield and quality. Soil testing remains one of the most promising tools for improving efficient P use in that rates applied take into consideration available residual P. In studies we have shown most cool seasons vegetables produced in the desert will respond to P fertilizers up to a sodium bicarbonate P soil test level of 30 to 35 mg/kg (See Figure 1). As pre-plant soil tests approach these critical soil test P levels, the probability of crop response to P fertilizer drops dramatically. However, P fertilization based on a composite soil sample from a production unit assumes relatively uniform fertility within the unit which is inconsistent with our findings. In high resolution sampling of vegetable production fields in the desert we have found large in-field variability in soil test P levels within production units (CVs from 18 to 90% usually exceeding 50%; see Figure 2 for one example). Thus, if we made adjustments in pre-plant P recommendations to minimize economic losses due to under-fertilization, we would have to over-fertilize a large portion of the field. This not only has economic consequences, it can result in very high available P levels over part of the field and adverse consequences such as P induced micronutrient deficiency (particularly Zn). It should be noted that although much the data shown

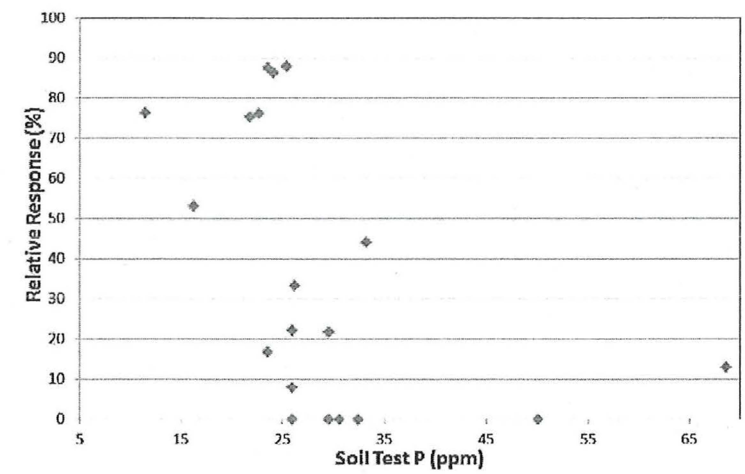


Figure 1. Relationship between P soil test and relative response of lettuce to P fertilizer. (unpublished data of Sanchez)

in Figure 1 was collected in commercial fields across the desert, it was collected in very small fertility plots within these fields and was not vulnerable to the variation across the larger production area.

The prospect of variable rate pre-plant P fertilizer application has not been extensively evaluated in desert vegetable cropping systems. A present, there is no cost effective, non-intrusive, or image based technology to index P soil fertility, and accurate results depend on a laboratory P soil tests. The efficacy and economic viability of variable rate application would depend on developing soil sampling protocols that minimize soil sample testing costs but capture the in-field variability for generating accurate prescription maps. For example, determination of soil test P on a one acre composite would cost about $20.0 per acre, which may or may not be covered by fertilizer savings or increased production at current fertilizer prices and commodity value. However, sampling on a five acre grid or directed sampling on zones based on some known index of in-field variability, might bring cost down to $5.0 per acre or less which is likely covered by fertilizer savings and/or production return.

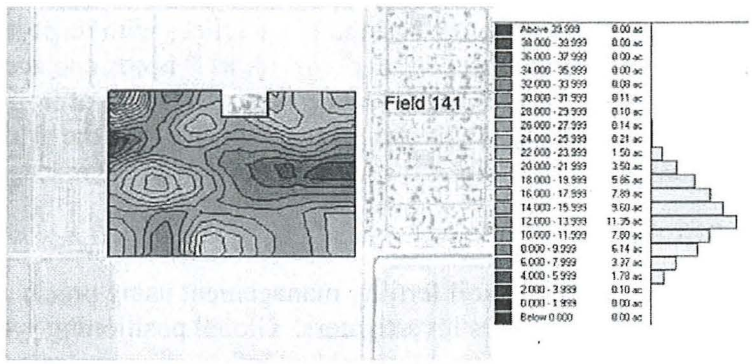


**Figure 2.** One acre grid sampling for soil test P on a typical production block in the desert (unpublished data of Sanchez and Nolte).

2. CDFA FREP goals

This project addresses six of eight of FREP goals. This project will develop protocols for accurately predicting P fertilizer requirements based on pre-plant soil tests. This project will improve P fertilization practices by applying only the amount needed in a variable manner across commercial production blocks. This project specifically develops protocols for site specific P fertilizer application. This project is using GPS and VRT for more precisely and economically using existing soil test diagnostic tools. This project will be conducted in producer fields and has a planned outreach component.

3. IMPACT

Overwhelmingly vegetable producers in the desert typically apply 550 lbs MAP (about 140 kg P/ha) to every production field every year. They have been disinclined to utilize soil test based P fertilizer recommendations based on anxiety of crop yield and quality. Based on the variation in P soil test we observed in commercial production fields, I now understand their anxiety about applying P based on a composite soil test. However, protocols for the economic utilization of VRT are lacking. This project aims to develop and demonstrate such protocols. We anticipate that the successful implementation of this project will positive economic impacts for growers, reduced environmental impacts on water quality within the region, and enhance food security by using a finite and geopolitical stratified resource (P) more efficiently.

## 4. LONG-TERM SOLUTIONS

Our progress toward more sustainable practices with respect to P fertilization will come from many fronts. However, correct diagnosis of P needs and accurate and efficient correction of deficiency will be paramount among these. Because of in-field variation of not only P, but chemical and physical soil components which affect the availability of P, VRT will be an essential part of the long term solution for efficient P management.

## 5. RELATED RESEARCH

The improvement of soil fertility management using precision agriculture technologies has been evaluated by numerous investigators. Global positioning systems (GPS), yield monitors, various forms of remote sensing, geographical information systems (GIS), and variable rate application technologies are available for use by fertilizer retailers and producers. Further, some successes have been realized by researchers across the United States in utilizing variable rate technologies (VRT) for the applications of fertilizers to major crop production systems. Yang et al. (2001) used VRT nitrogen (N) and phosphorus (P) fertilization to effectively increase yields when compared to a uniform rate (UR) application in sorghum and the VRT treatment produced positive relative economic returns over the UR treatment by an average of \$25 $ha^{-1}$ over the two-year study. Wittry and Mallarino (2004) compared VR and UR fertilization with phosphorus in a corn-soybean rotation. While the VRT did not affect crop yield it resulted in 12 to 41% less fertilizer and a decline in the amount of variability in soil test phosphorus. In a preliminary evaluation of variable rate P application for cotton in the desert, Norton et al. (2004) found yield was not affected by P application but VRT resulted in 27% less P used resulting in a savings of \$7.0 per acre to the grower.

These applications of VRT technology use different sources of information such as previous year's yield maps, or soil grid sampling to define the P rates. Applied research continues in the area of VRT schemes for P management based on prescription mapping. This approach is backed by the unprecedented amounts of field-ready technology available for application control. Another approach that will continue to develop is the use of soil sensors for real-time control of P applications. One example of real-time VRT application of P was developed by Maleki et al. (2008) who used a spectrophotometer embedded in a shank. Field deployment of this on-the-go system produced VRT applications in corn ranging from 0 to 100 kg $ha^{-1}$, and resulted in average yields of VRT plots 386 kg $ha^{-1}$ higher than the uniform application plots. In spite of promising performance, high cost and field operational limitations of soil spectroscopy technology reduce the potential for practical application.

Much less work has been done with vegetable which require large amounts of P for yield and quality. One exception is potato where the availability of yield monitors has facilitated this research. It has been shown that spatial variability of P contents in the soil affects yield and tuber quality (Cambouris et al., 1999; Kunkel et al., 1991). In one study VRT resulted in similar yields to conventional application but increased tuber quality and resulted in less required fertilizer and increased profits (Cambouris et al., 1999)

Recently, we have conducted high resolution soil sampling on commercial lettuce productions fields in the desert (one field is shown in Figure 1 above). The data show very large in-field variability in soil test P levels within production units (CVs from 18 to 90% usually exceeding 50%). This variation in soil test P within production unit clearly shows that it would be extremely difficult to develop a sampling scheme for collection of a meaningful composite soil sample. In nearly every instance, using a composite sample would results in significant portions of the field being both under fertilized and over fertilized. Lettuce is extremely sensitive to P deficiency and the portions of the fields under fertilized would result in significant economic loss to growers. Further, the portion of the field over-fertilized not only represents unneeded expenditures by the grower, it can result in very high available P levels over part of the field and adverse production consequences such as P induced micronutrient deficiency (particularly Zn) affecting production.

It is clear the most promising approach for exploiting soil testing is coupling it with variable rate technologies (VRT). From these fertilizer recommendations we approximated fertilizer costs (sampling, soil analysis, application costs and fertilizer costs) to various application technologies compared to the standard grower practice (GSPU) of applying 550 lbs MAP to the acre every season (Table 1). We wish to note that these estimates only represent fertilizer savings and do not consider production implications since we do not have this data at this time. The greatest saving appears to be associated with uniform application based on composite soil sampling (CSTU) since sampling and analysis costs are minimal. However, as noted above, using this approach will likely have economic consequences in production because the variation in soil test across a production unit is large and a significant portion of the field would be under fertilized. Interestingly when evaluating the one acre sampling resolution VRT strategy (VRT1), 8 of the 11 sites showed fertilizer costs savings, one was break even, and two were a loss due to sampling costs exceeding fertilizer cost savings. Again we did not consider production implications. A number of studies have shown similar yields to uniform and VRT application strategies but significant cost savings in fertilizer to VRT (Yang et al., 2001). However, most of these studies were conducted with crops less responsive to P than lettuce. We speculate that a production increase to applying sufficient but not excess P across the entire field is possible for lettuce. The results show greater fertilizer costs savings to 5 acre resolution VRT (VRT5) compared to the VRT1because sampling and analysis costs are substantially less. However, again the lower resolution sampling would result in some under and over fertilization, albeit less than field wide composite sampling, and we have no data to determine production consequences.

We compared the areas under and over fertilized using VRT1 as a basis. Under fertilization has potentially large production and economic consequences in lettuce. Depending on a number of factors including soil test P conditions, and crop yield potential as related to factors other than P fertility, we may or may not detect production differences when 50 lbs MAP less than that recommended is applied. However, almost invariably we should detect differences to a deficiency of 100 lbs MAP/A. Therefore the total area shorted 50 lbs/A MAP or more and 100 lbs/A MAP or more are shown (Table 2). These data do not include the grower standard practice uniform application (GSPU) since these received a uniform application of 550 lbs MAP/acre, our highest recommendation at lower soil tests, and this would not be shorted by our soil test

Table 1. Estimated fertilizer costs savings to soil testing including composite sample (CSTU), VRT on one acre grid (VRT1), and VRT on five acre grid (VRT5) compared to grower practice.

| | Soil Test P (mg/kg) | | Fertilization cost savings ($/acre)[a] | | |
|---|---|---|---|---|---|
| **Field** | **Mean** | **Range** | **CSTU** | **VRT1** | **VRT5** |
| 141 | 14.0 | 1.9 to 35.5 | 18.4 | 6.2 | 18.1 |
| 180 | 31.1 | 7.2 to 67.7 | 93.2 | 85.3 | 106.8 |
| 184 | 12.6 | 0.1 to 25.7 | 17.8 | 0.05 | 15.9 |
| 358 | 13.5 | 0.7 to 23.0 | 18.3 | 1.51 | 8.5 |
| 360 | 13.0 | 6.4 to 85.8 | 18.2 | 2.88 | 18.8 |
| 366 | 16.7 | 11.3 to 22.2 | 36.5 | 10.6 | 30.2 |
| 368N | 18.2 | 5.2 to 30.4 | 35.7 | 17.3 | 30.2 |
| 368S | 29.1 | 0.2 to 63.7 | 72.9 | 68.5 | 75 |
| 676 | 22.7 | 16.5 to 30.6 | 55.6 | 34.9 | 56 |
| 679 | 9.0 | 1.8 to 22.5 | -0.47 | -12.9 | 7.1 |
| 680 | 9.1 | 1.4 to 29.3 | -0.57 | -15.8 | 3.4 |

[a]We have estimated costs of soil sampling, analysis and VRT of $20 per sample and fertilizer cost of $750 per ton.

recommendation criteria. Overall, these data show that CSTU and VRT5 were not appreciably different in area under fertilized compared to VRT1. The actual the production consequences of excess P are less certain. While excess P can tie up micronutrients, our soils are well buffered by calcium carbonate and this response is not readily predictable. It is our experience that producers should not be concerned about adverse production effects to excess soil P until soil tests exceed 50 mg/kg. Nevertheless, excess P does have economic consequences in that producers are purchasing an input not needed and excess P has potential adverse environmental impacts on surface water. The area over fertilized was extremely large for GSPU (Table 4). The areas over fertilized by 50 lbs/A MAP or more were similar for CSTU and VRT5 both of which were substantially less than GSPU. Interestingly, VRT5 did not result in over fertilization by 100 lbs/A MAP or more. The economic viability of these various strategies needs to be addressed in future studies which actually measure production impacts.

Current research and extension work at the University of Arizona in the use of VRT includes the use of yield maps and apparent soil electrical conductivity to create management zones for site-specific management of nitrogen fertilizer in cotton and durum wheat. Recommendations for sensor-based N management are based on establishing functional relationships between sensor signals and crop conditions as characterized by years of applied agronomic research by UA extension specialists. In a new front, there is ongoing work in the use of spectral and displacement sensors to measure the crop canopy light reflectance and plant height to direct VR applications in real-time.

Table 2. Estimated area of field under fertilized by 50 and 100 lbs MAP/acre when comparing CSTU and VRT5 to VRT1.

| Field | Area of field (%) under fertilized by >50 lbs MAP/acre | | Area (%) under fertilized by >100 lbs MAP/acre | |
|---|---|---|---|---|
| | CSTU | VRT5 | CSTU | VRT5 |
| 141 | 19 | 26 | 0 | 0 |
| 180 | 23 | 16 | 7 | 0 |
| 184 | 31 | 45 | 0 | 10 |
| 358 | 7 | 58 | 0 | 0 |
| 360 | 17 | 21 | 0 | 10 |
| 366 | 45 | 14 | 0 | 0 |
| 368N | 5 | 46 | 2 | 32 |
| 356S | 2 | 2 | 1 | 1 |
| 676 | 5 | 29 | 0 | 0 |
| 679 | 0 | 7 | 0 | 0 |
| 680 | 0 | 11 | 0 | 3 |

CSTU=uniform application based on soil test from composite sample, and VRT5=variable rate application based on a five acre resolution sampling.

Table 3. Estimated area of field over fertilized by 50 and 100 lbs MAP/acre when GSPU, CSTU, and VRT5 are compared to VRT1.

| Field | Area of field (%) over fertilized by >50 lbs MAP/acre | | | Area of field (%) over fertilized by >100 lbs MAP/acre | | |
|---|---|---|---|---|---|---|
| | GSPU | CSTU | VRT5 | GPU | CSTU | VRT5 |
| 141 | 81 | 49 | 16 | 29 | 9 | 0 |
| 180 | 100 | 24 | 16 | 98 | 24 | 0 |
| 184 | 68 | 29 | 46 | 29 | 10 | 0 |
| 358 | 82 | 33 | 57 | 33 | 0 | 0 |
| 360 | 83 | 12 | 20 | 12 | 9 | 0 |
| 366 | 100 | 8 | 14 | 55 | 0 | 0 |
| 368N | 86 | 41 | 55 | 55 | 17 | 0 |
| 356S | 100 | 37 | 37 | 96 | 13 | 0 |
| 676 | 100 | 11 | 29 | 100 | 0 | 0 |
| 679 | 35 | 35 | 7 | 2 | 6 | 0 |
| 680 | 14 | 14 | 12 | 1 | 6 | 0 |

GSPU=uniform application by grower standard practice, CSTU=uniform application based on soil test from composite sample and VRT5=variable rate application based on a five acre resolution sampling.

Sampling costs remains a significant challenge. One possible approach around this is defining management zones. The might include aerial imagery and surveys. Our group has constructed a salinity assessment survey vehicle equipped with GPS, EM 38, and computer processing equipment. The vehicle also has a hydraulic driven sampling probe for statistically directed ground truth sampling associated with the electronic conductance surveys. The survey vehicle is a modified high clearance spray-coupe that had its spraying attachments removed. Numerous modifications made on the vehicle to enable it to carry a tube that houses the sensor during transportation and salinity survey. The tube is attached beneath the vehicle in a manner that allows, through a series of control switches located in the driver's cabin, the tube to be extended for survey and retracted during transport. The vehicle is equipped with a global positioning system. The software suite is composed of two interfacing and one separate software all loaded into a laptop computer housed in the driver's cabin of the salinity vehicle. The first software is the Salinity Surveyor, which records the EM38 conductivities and the corresponding GPS data. The second software in the series is the Post Process Data software, which strips excess data taken with the Salinity Surveyor. The data is then imported into ESAP software from USDA-ARS Salinity Laboratory.

Another tool used to survey the electrical response of the soil in bulk is the Veris EC sensor manufactured by Veris Technologies (Salina KS). This sensor consists of a series of coulter discs that engage the soil while in motion; these discs function as electrodes for the flow of electrical current through the soil profile up to a depth of 3ft. The Veris sensor has low power requirements and is operated as a pull-behind implement that can be towed with a small tractor or pick-up truck depending on soil firmness. The controller of the Veris EC sensor collects voltage drop signals that are converted to apparent electrical conductivity values expressed in milliSiemens per meter (mS/M) units at two depths (0-12" and 0-36"). A differential correction GPS receiver is connected to the controller to geo-reference the EC data. Output files contain EC values collected once per second. In a typical operation speed of 3 mph, the Veris sensor generates one data point every 4 ft. This sensor is particularly sensitive to changes in soil texture, and other properties related to the water-holding capacity of the soil, therefore the use of the Veris sensor is a practical way to carry out large-scale EC surveys for soil characterization.

We have made extensive use of the Veris EC sensor in a variety of applications across Arizona.. On-going research and extension work with the Veris EC sensor includes studies for variable rate application of fungicides for nematode control in cotton production (Norton et al. 2011). Since nematode distribution exhibits a higher distribution in sandy soils, the output of the Veris EC sensor is used to delineate zones with higher than normal concentrations of nematodes to treat with higher rates of fumigants. Another application is a study on the soil physical properties in palm date production in the Yuma Valley (Andrade-Sanchez and Wright, 2012) where we have found higher levels of subsoil compaction where soil texture tends to be dominated by finer particles. Clayey soils have a higher response to the Veris sensor, which allows detection of areas prone to develop excessive soil densification.

Successful implementation of VRT also requires accurate application equipment. The new trend in application equipment is CAN bus technology integrated to cab-mounted terminals. Current configurations include a seamless connection between auto-steer, position/navigation, GPS, electronic rate/section and flow control hardware. Currently, the precision agriculture research/extension program at UA has acquired the necessary equipment to carry out this type of research. Some of the VRT equipment available include: GPS instrumented 120HP tractor; Trimble FieldIQ controller; liquid injector frame with Rawson controller and side-dressing tooling; low-pressure top-dressing applicator with Raven spraying control components; Trimble modules for chemical application. These hardware components are all connected to the Trimble FMX for operation via prescription files or manual control.

At the University of Arizona we have developed both capacity and expertise in the use of specialized field-ready application hardware. An essential component in our outreach efforts focused on the application of VRT is the use of on-board computers that enable multiple functions of tractors, sprayers, or spreader rigs. The capacity of these monitors to control auto-steer guidance and VRT, among other functions, is fully described by Andrade-Sanchez and Heun (2012). In this project we will implement the latest in VRT available from commercial vendors to interface the multifunction display in the power unit with control systems in the spreader spinner servo-valves and achieve automatic adjustment of the delivery rates. It will be important to enable auto-steer functions during fertilizer application to avoid overlapping and ensure proper distribution of fertilizer material. Specific guidelines for GPS-based VRT applications of granular materials through spreaders are presented by Fulton et al. (2010).

Progress with high value fresh vegetable crops has been slower due to the lack of user friendly yields monitoring technologies. Especially, since many of these are hand harvested for quality discrimination. More recently as part of a project aimed at developing produce trace back technology we have developed a system using RFID and integrated GPS technologies that has proved useful for tracking yield as well. As shown in figure 3 and 4 (below), a sub-inch global positioning satellite receiver (Trimble Navigation Limited) (A) collects microwave signals from the GPS satellite network (B) that communicates geocoordinates to a field computer (C). Computer Radio Frequency Identification (RFID) integration software (Warren Point Communications Limited) (C) transiently links captured geocoordinates, user inputted field records, crop information and day of harvest information into a format recognized by RFID encoding hardware (D), with remote antenna (Sirit Inc.) (E). An energized ratiofrequency signal, containing specific crop and geocoordinate data, is wirelessly transmitted from RFID encoder/antenna devices to RFID inlays attached to field cartons (F). The remote field computer (C) serves as a crop harvest and field history data storage device prior to data delivery from the field to a local area network via a wireless mobile broadband interface (Verizon Communications, Inc.) (G). Georeferenced crop harvest and field data, administered by RFID computer software (Warren Point Communications Limited) (C), is instantly processed and uplinked from the field to a local area network via a wireless remote broadband connection (G). Individual carton and field history data is wirelessly received for data management and storage (H) or for later manipulation (I) to be made immediately available to internet users via network servers (J) or used later in harvest yield operations (K).

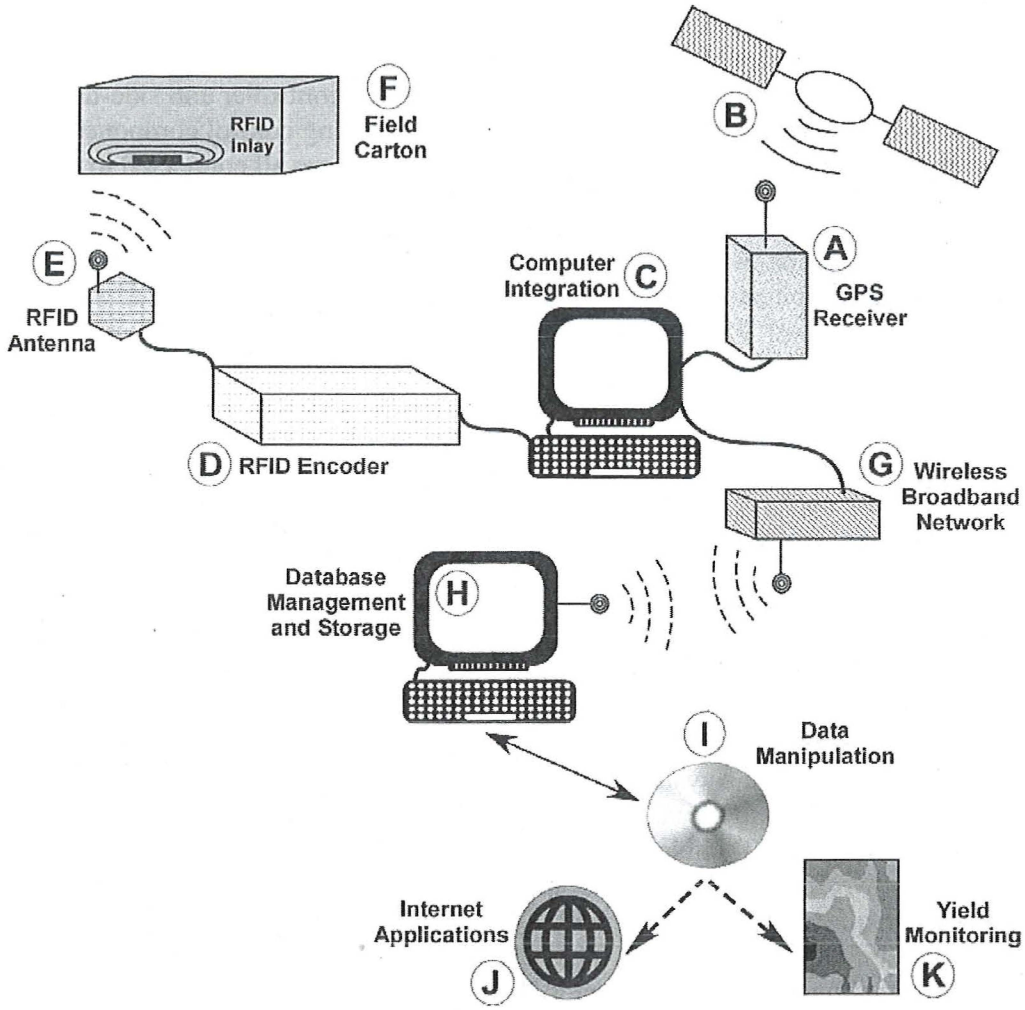


**Fig. 3. Conceptual overview of lettuce carton tracking system. For details and description, see text.**

The system was field tested with a grower/cooperator on 3 iceberg lettuce fields in Yuma County. The field tests consisted of pre-labeling 5000 field cartons with RFID tags (Generation 2, Sirit, Inc.) and integrating them into the harvesting operation. Figure 4 provides a summary of system field testing. Although the equipment used to construct the lettuce carton tracking system is currently available and used in similar inventory management, the integration of real-time GPS into RFID technologies makes this approach unique.

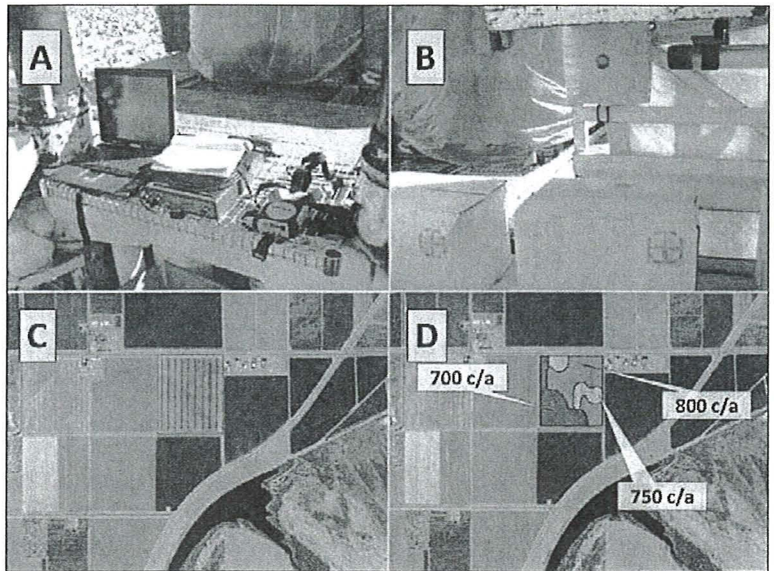


**Fig. 4. Field testing of RFID Lettuce Traceback system. A, computer, wireless aircard (not shown), GPS receiver and RFID encoder installation. B, RFID antenna and label attached to lettuce carton. C, georeferenced harvest passes (red lines) within a field test. D, lettuce yield map produced from georeferenced lettuce cartons. (unpublished data of Nolte)**

## 6. CONTRIBUTION TO KNOWLEDGE BASE

We do not have well developed protocols for using VRT for irrigated vegetables in the desert. This project seeks to fill this data gap.

## 7. GROWER USE

Erratic fertilizer pricing over the past several years has created incentives for improved P use efficiency. Approximately three years ago, the costs of mono-ammonium phosphate (MAP), a formulation widely used for desert vegetable production, exceeded $1,200.0 per ton. Although costs have since declined, rapid increases are anticipated as the world economy recovers and resource demand in the developing world regains momentum. In fact, I have gotten more calls from producers seeking avenues for reducing P fertilizer use the past three years than I got the previous decade. As shown we had no problem finding grower cooperators willing to take the economic risk of reduced production associated with this project. We anticipate growers will adopt these technologies once their efficacy and economic viability is demonstrated.

## D. Objectives

The objective of this project is to 1. Develop economically viable and effective sampling protocols to generate prescription maps for the variable rate application of P, 2, Compare variable rate P application to current methods and evaluate alternative economic outcomes. In the first phase of the project we will test alternative sampling schemes. Sampling schemes evaluated will include grid sampling at various resolutions, samples schemes which seek to define zones directed by other indices of in-field variability. In the second phase we will evaluate the efficacy and economic returns to variable rate P application. Project success will be the development of economically viable protocols for the implementation of variable rate P application technologies.

E. WORK PLAN AND METHODS

**Task 1 (January 2013 through October 2013). Evaluate alternative sampling schemes including various resolutions of grid sampling and zone sampling based on soil properties that may serve as covariates.**

Subtask 1a. We will select 10 production fields of grower cooperators and compare alternative sampling schemes. We will collect grid samples on 1 and 5 acre resolutions and zone sampling based on indirect measurements of soil properties. We will define zones based on Veris and EM38 surveys and aerial imagery. Both these types of surveys are conductance measurements and are related to soil texture and salinity. To simplify data management and manipulation, the values of these soil sensors will be geo-referenced with the addition of GPS information to the output files. We will distinguish between texture and salinity using ESAP directed sampling. ESAP is a software package developed by the USDA ARS Salinity Laboratory and employs statistically directed sampling based on the initial conductance survey. Statistical procedures are used to distinguish soil salinity from texture. All soil samples will be analyzed for saturation percentage, pH, electrical conductance, soil nitrate-N, and sodium bicarbonate P in our laboratory. It should be noted that vegetable production fields in the desert are all laser leveled and much of the in-field variation is associated with soil layering (depth of profiles) below the soil surface. The use of EM38 partially characterizes profile layering. It should also be noted that under these conditions aerial imagery likely has limited utility.

Subtask 1b. Evaluate hypothetical prescription maps, costs of sampling, hypothetical returns based on known algorithms of soil test P and projected P fertilizer recommendation based on prescription maps versus the intended grower practice. We will select the prescription maps showing the potential greatest economic returns.

**Task 2 (October 2013 to April 2014). Field testing of VRA and standard grower practice.**

Subtask 2a. Five of the lettuce production fields sampled above will be split into three sections. One of these sections will receive pre-plant P fertilization according to the grower standard practice, one will receive pre-plant fertilization according to a prescription map generated by grid sampling, and the third will receive pre-plant P fertilization according to prescription map generated from zone sampling. Vegetable growers in the desert exclusively use MAP (11-52-0) as their pre-plant P source. Growers typically do not give this modest rate of N much consideration and apply sidedress and water run UAN32 to meet the crops N nutritional requirement. However, as we vary P we will vary pre-plant N and we are concerned about potential effect on early growth (especially where pre-plant soil test nitrate is less than 25 ppm). Because we do not want an N variable potentially confounding crop response, we will employ an algorithm which adjusts N applied by compensating with urea when MAP is reduced such that the entire field receives uniform N but variable P.

Subtask 2b. At maturity yield data will be collected using the RFID GPS system described above. Total yield and uniformity will be measured. Economic returns to VRA will be estimated.

**Task 3 (January 2014 through October 2014). Repeated evaluation of alternative sampling schemes including various resolutions of grid sampling and zone sampling based on soil properties that may serve as covariates.**

Subtask 3a. In this season we may modify sampling protocols evaluated based on what we learned in year 1. We may also explore other indices for directing zone sampling schemes although we will likely retain the most promising from year 1.. We will use five of the same fields sampled in year 1 and evaluate how soil test variability has changed. We will add an additional five field not previously sampled.

Subtask 3b. Evaluate hypothetical prescription maps, costs of sampling, hypothetical returns based on known algorithms of soil test P and projected P fertilizer recommendation based on prescription maps versus the intended grower practice. We will select the prescription maps showing the potential greatest economic returns.

**Task 4. (October 2014 to April 2015). Field testing of VRA and standard grower practice.**

Subtasks 4a. This year we will evaluate VRT schemes on three fields used in year 1 and three new fields in year 2. As before we will split these production fields in three sections. One of these sections will receive pre-plant P fertilization according to the grower standard practice, one will receive pre-plant fertilization according to a prescription map generated by grid sampling, and the third will receive pre-plant P fertilization according to prescription map generated from management zone sampling.

Subtask 4b. At maturity yield data will be collected using the RFID GPS system described above. Total yield and uniformity will be measured. Economic returns to VRT will be estimated.

**Task 5 (April 2015 to December 2015).** We will perform rigorous economic evaluations of alternative soil test sampling schemes, prescription maps generated, and returns to investment.

F. PROJECT MANAGEMENT AND OUTREACH

1. MANAGEMENT

Dr. Sanchez will provide overall direction to the project, oversee all soil sample operations, and perform all laboratory chemical analysis. Dr. Sanchez is also the principal liaison with the grower cooperators involved. Dr. Sanchez plans a presence at all surveys, field applications, and yield assessments but will defer to the expertise of his co-investigators where appropriate. Dr. Sanchez in collaboration with his co-investigators will perform all statistical and economic analysis.

Dr. Andrade will direct all mechanical surveys (Veris, EM38, and others), process the data generated, generate all prescription maps, and calibrate and make field applications using various VRT technologies he has developed as part of his research and outreach program.

Dr. Nolte will provide direction on the use of the RFID and GPS yield monitoring technology he developed.

2. EVALUATION

The success of the research program will be evaluated based on measured improvements in fertilizer use efficiency and calculated potential economic returns to grower. The success of the outreach component will be measured by attendance at our field days and workshops and survey responses from attendees.

3. OUTREACH

The following are planned outreach activities over project period. We wish to note that we will run workshops in the use of technology (i.e. display operation, system installation, system calibration, etc.) in both English and Spanish. Also, we compose an extension bulletin.

**Planned Outreach activities**

| | |
|---|---|
| March 2013 | Field Day at Southwest Agricultural Conference (Yuma, AZ) |
| August 2013 | Presentation at Fall Vegetable Workshop (Yuma AZ) |
| November 2013 | Presentation at Winter Desert Workshop (Holtville, CA) |
| January 2014 | Presentation at grower meeting in Coachella Valley (Indio, CA) |
| March 2014 | Presentation at Southwest Agricultural Conference (Yuma AZ) |
| May 2014 | Presentation at Desert Agricultural Conference (Casa Grande, AZ)) |
| November 2014 | Presentation at Winter Desert Workshop (Brawley, CA) |
| January 2015 | Presentation at Extension meeting in Parker CA. |
| March 2015 | Presentation at Southwest Agricultural Conference (Yuma AZ) |
| November 2015 | Field day at Desert Agricultural Center in Holtville (Holtville, CA) |

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