Using Precision Agriculture Technology for Precise Placement and Variable Rate Fertilizer Application

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1. Precision agriculture and site-specific nutrient management

Precision agriculture, as the name implies, is useful technology for growing and fertilizing horticultural crops more precisely or efficiently and consequently can help retain water and nutrients in the root zone. Three techniques with which precision agriculture can help achieve this objective are 1) collect spatial data from pre-existing conditions in the field (e.g. remote sensing, canopy or yield measurement), 2) apply precise fertilizer amounts to the crop as, when and where needed, 3) record detailed logs of all fertilizer applications for spatial and temporal mapping. Thus precision agriculture can help us determine exactly where to place the nutrients and how much to apply, and then to track the applied nutrients with accumulation logs and GIS maps.

Site-specific management (SSM) is a crop management strategy of precision agriculture which addresses within-field variability by optimizing inputs such as pesticides and fertilizers on a point-by-point or small area basis. Thus nutrients are applied only as needed within a field, rather than applying them uniformly across the entire field for the average field requirements. Successful implementation of SSM relies on accurate quantification of the spatial variation of important soil and crop factors and their interpretation into variable rates of agrochemical that are targeted only to crop canopies and root zones. Various sensors are used to quantify the spatial variation, including those for soil electrical conductivity, yield monitors, canopy size and canopy color. Sensor data are either real-time or "on-the-go" which measure the soil or crop directly from the application equipment, or they can be previously sensed data such as from remote sensing surveys and yield mapping, both of which are used to create prescription maps for site-specific application of agrochemicals at a future time. Real-time SSM generally does not need geographic positioning system (GPS) data because decisions about agrochemical rate and crop target are made on the spot at the time of the measurement. Prescription map SSM needs GPS technology so that the correct place in the field which matches with a prescribed rate on the map can be located accurately. Both types of SSM are widely used for fertilizing agronomic and horticultural crops. Precision agriculture instruments such as variable rate or irrigation controllers automatically keep detailed computerized records or logs of how much fertilizer or water was applied, when it was applied, and where. Good record keeping is crucial for instant accountability, plotting historical trends, and ultimately better management of nutrients and water.

SSM implemented as variable rate fertilization (VRF) is one of the best precision agriculture tools for keeping nutrients in the root zone because it simultaneously optimizes both nutrient rates and placement for a particular crop. Nevertheless, large yield increases resulting from VRF have been quite difficult to demonstrate consistently in most crops, but input cost savings due to reduced fertilizer and fuel consumption, and environmental benefits due to the resulting reduction in nutrient loadings per acre are immediate and well documented. The objective of this paper is to examine the existing knowledge on using precision agriculture and particularly variable rate technology to improve nutrient and water management in horticultural crops.

2 Components of precision agriculture technology

Modern precision agriculture technology offers the tools which can be used for more efficient nutrient management of horticultural crops. They are remote sensing, GIS/GPS, mobile and embedded computing, and soil or crop mapping.

2.1 Remote sensing

Remote sensing typically involves acquiring and processing satellite or aerial images photographed in the visible or near-infrared portions of the electromagnetic spectrum. Useful information derived from remote sensing could include crop variability, canopy size and health, soil type and water stress. Figure 1 is an example aerial image from Google Earth™ (a free online GIS program) showing the extent of citrus canopy growth variability resulting from different soil series in an orchard. The white unproductive soil in the middle is St. Lucie fine sand, while the surrounding darker colored more productive soils are Myakka, Tavares, and Placid fine sands.

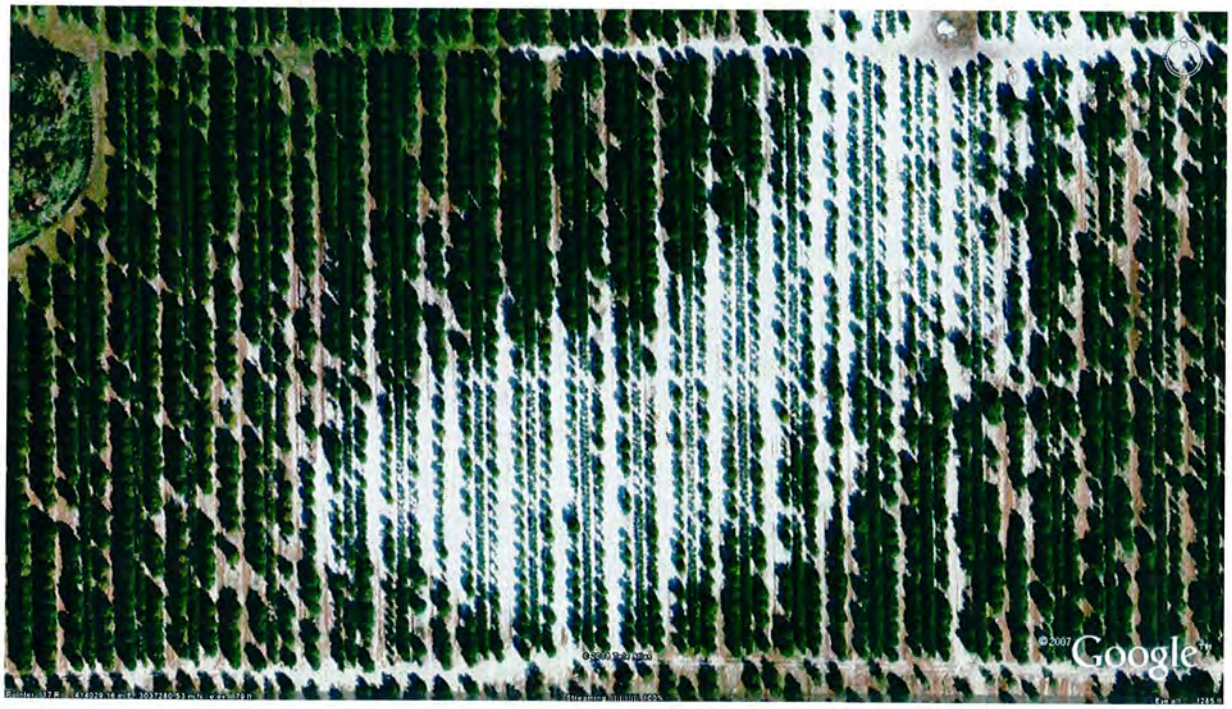

Figure 1. Color aerial photograph of a citrus orchard in Hardee county Florida, showing the unproductive white-colored St. Lucie fine sand soil series in the center of the field.

A frequently used calculation applied to aerial photographs containing the near-infrared (NIR) and Red bands of the electromagnetic spectrum is the normalized difference vegetation index (NDVI, Eq. 1). The NDVI is useful to highlight green vegetation in aerial photographs and can also help to discriminate healthy productive crops from stressed unproductive crops (Fig. 2).

Johnson et al (2001) evaluated the use of airborne, digital, multispectral imagery for delineation of sub–block management zones in vineyards. They used NDVI to delineate low, moderate, and high vigor zones.

$$NDVI = \frac{NIR - \mathrm{Re}d}{NIR + \mathrm{Re}d} \qquad (1)$$

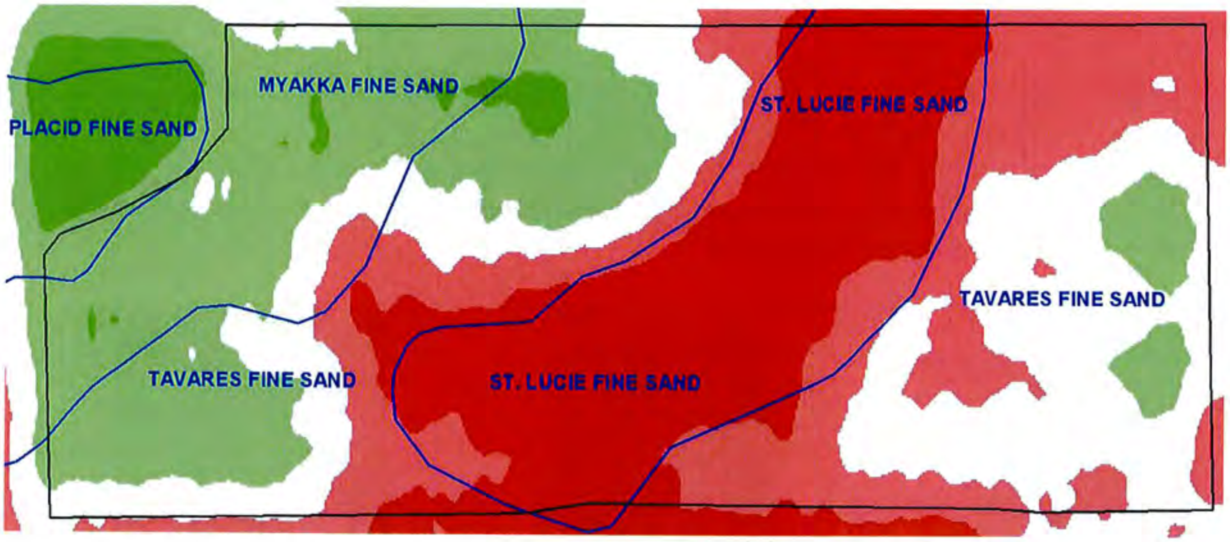

Figure 2. Map of five productivity zones in a citrus orchard calculated from remotely sensed color-infrared aerial photography and the NDVI.

Once the relationships between the remotely sensed NDVI and the soil and crop properties at selected ground truth points have been established, additional aerial or satellite images could be used to assess the extent of soil and crop variability in neighboring fields. The productivity classes in Fig. 2 could also be converted into nutrient management zones once the nature of the variability is better understood.

2.2 Geographic information systems and global positioning systems

A geographic information system (GIS) is a computerized 'graphic database' allowing storage, retrieval, display and processing of any digital images or drawings with known positions on the earth's surface. The NDVI map in Fig. 2 was produced with the Arcview 3.2 GIS software (ESRI, Redlands, CA). Position location, or georeferencing of data, observations, objects, maps and images with the global positioning system (GPS) is an essential prerequisite for meaningful processing and display on a GIS. The GPS is the only fully functional Global Navigation Satellite System (GNSS) and was developed by the United States Department of Defense. Utilizing a constellation of at least 24 Medium Earth Orbit satellites that transmit precise microwave signals, the system enables a GPS receiver to determine its location, speed, direction, and time anywhere on earth. For the higher measurement accuracy of less than one meter required in variable rate fertilization of horticultural crops, the GPS calculation is further enhanced with differential correction, as implemented in a DGPS receiver.

2.3 Mobile computing and data storage

Mobile or handheld computers are indispensible for making and recording field observations during scouting, leaf sampling or soil surveying. When used in conjunction with a GPS and GIS software, the handheld computer can be used for navigation in the field which allows location and marking of plants, plots, soil types or other information already contained in the GIS (Figure 3). Some handheld computers have an integrated GPS receiver, making the device ideal for hand-held scouting and navigation.

Embedded microcontrollers are specialized computers used to control and automate specific processes in precision agriculture. Examples are the computer controllers for variable rate fertilization or automatic irrigation (Fig. 3). These computers are usually built to very rugged standards and have limited user interfaces but powerful automatic data logging capabilities for recording all fertilizer or water applications.

Figure 3. Examples from left to right of a hand-held Pocket PC with Arcpad GIS software (ESRI), variable rate controller for a fertilizer spreader, and an automatic irrigation system controller.

2.4 Soil, crop yield and canopy mapping

Ground-based sensor surveying and mapping of soils, crop yield and canopy characteristics is an alternative to remote sensing. Both sensing methods collect georeferenced data about the soil and crops to characterize their spatial variability and develop SSM programs. Soil mapping with geophysical survey or electromagnetic induction instruments such as the EM38 (Geonics, LTD, Mississauga, Ontario, Canada), or the Veris 3000 (Veris Technologies, Salina, KS) allows rapid collection of georeferenced soil electrical conductivity data in the field, which can be correlated with chemical and physical properties of soil profiles such as salinity or groundwater levels. Soil data is usually collected from an instrument pulled behind a vehicle driving in a predetermined path through the fields. Cambouris et al. (2006) evaluated the efficiency of EC for delineating homogenous soil management zones for potato production and they found significant differences in soil water regime, some soil physico-chemical properties (soil organic matter, soil P, soil pH) and in potato yields between the two management zones. Soil water potential is a good indicator of productivity and can be used as tool to delineate management zones. Ojeda et al. (2005) used water potential to delineate management zones in viticulture and found reduction in vigor and yield with decreasing water potential.

Schumann and Zaman (2003) used an EM38 instrument to successfully map the depth of shallow groundwater in a citrus orchard (Fig. 4). Knowledge of the water table variation in a field could be used to improve field drainage and to predict where citrus roots and nutrients might be impacted by flooded conditions.

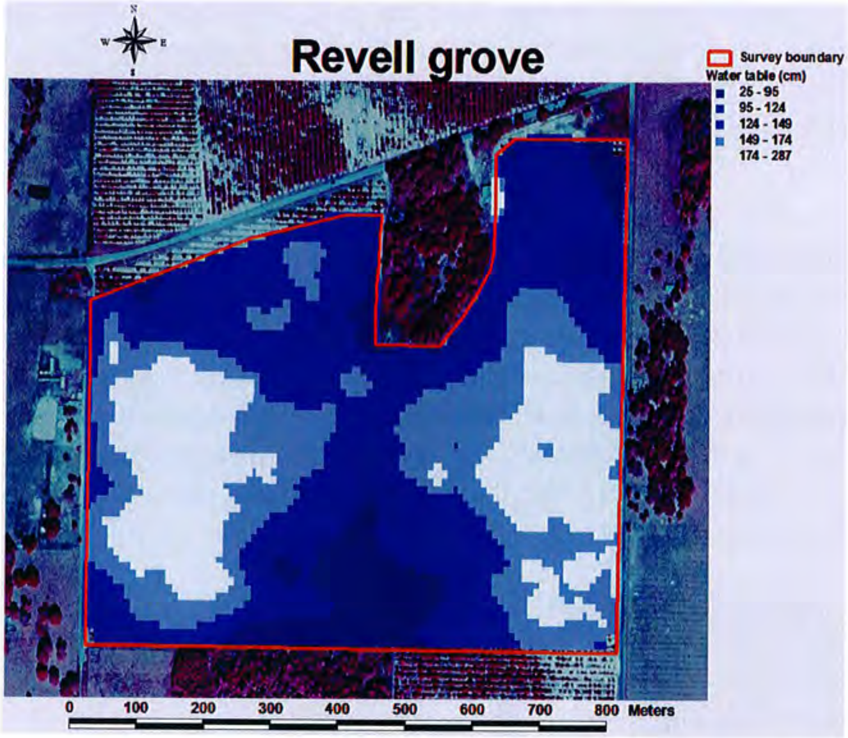

Figure 4. Groundwater map of a citrus orchard obtained from detailed ground conductivity measurements taken with an EM38 instrument and DGPS mounted on a vehicle.

Georeferenced soil grid sampling has proven to be an effective tool in defining soil variability within a field. Once critical soil or nutrient properties are identified, maps can be developed and steps can be taken to address field problems as needed for each location within a field. Precision maps can be produced based on the soil or crop properties and the field can be divided into management zones and variable rates of fertilizers are applied according to the prescription map. A management zone can be defined as a sub-region of a field that expresses a homogeneous combination of yield limiting factors for which a single rate of a specific crop input is appropriate (Doerge, 1999). Soil type is major factor in causing yield variability and a field can be divided into different zones based on soil type for variable rate application of fertilizers. Babcock and Pautsch (1998) compared single rate and variable rate application of fertilizers in corn, based on soil types. They found that applying variable rates would increase yield by 3 to 32 kg/ha, and would reduce fertilizer costs by $2.93 to $16.87 per acre.

Computerized canopy measurement sensors have been used for rapid assessment of tree canopy volumes and heights in whole citrus blocks for GIS mapping and development of variable rate prescription zones (Schumann and Zaman, 2005; Zaman and Schumann, 2005). Nutrient contents, particularly nitrogen (N) concentrations of crop canopies can be estimated by sensing and quantifying the greenness or amount of chlorophyll in the foliage. Optical instruments like the Greenseeker (Ntech Industries, Ukiah, CA) or the Minolta SPAD (Konika Minolta, Ramsey, NJ) use the NDVI calculation (Equation 1) with a ground-based sensor to determine the N sufficiency of crop canopies for GIS mapping and variable rate nutrient application.

The spatial variation of soil and crop properties affect the yield of the crop and thus variation in profits when whole fields are managed with same farm practices. Spaans and Quiros (2003) divided a banana plantion into different zones based on profit maps and found a good correlation between the yield and soil properties from the zones.

Crop yield map data are most often collected at the time of harvesting with mobile computers and sensors mounted on harvesting machinery. Typically optical or weighing sensors are used to detect and quantify the stream of harvested produce being collected by a mechanical harvester while a DGPS records the positions of the measured yield for mapping on a GIS. Using a weighing device with load sensors, Pelletiera and Upadhyaya (1999) found that there were significant spatial variations in processing tomato yield over a field (Fig. 5). The lowest 20% yielding area within a field produced less than half the tomatoes compared to the highest 20% yielding area within the same field.

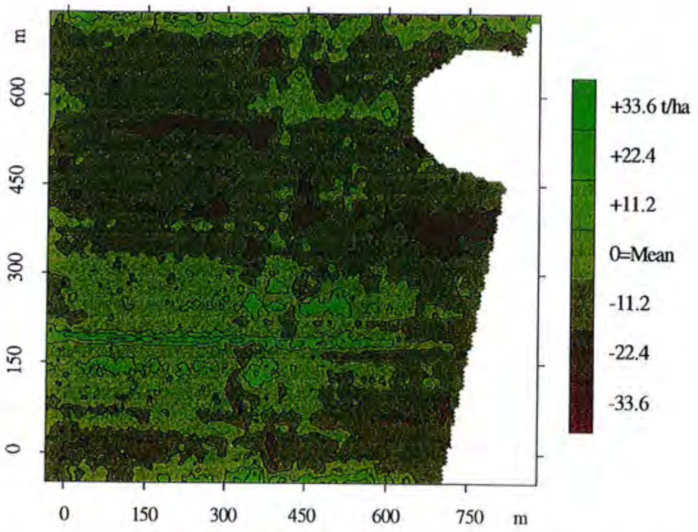

Figure 5. A yield map obtained using a weighing tomato yield monitor. The map shows deviation from the mean yield of 88 t/ha (Pelletiera and Upadhyaya, 1999).

3 Variable rate application technologies

Variable rate application of granular fertilizers (VRF) allows improved placement in root zones and rate matching of fertilizers to crop requirements (Schumann et al., 2006). The two main functions of VRF are (1) to find the best fertilizer rate to match the crop and soil requirements and (2) to place the fertilizer as accurately as possible in the root zone or canopy. This implies that no fertilizer is ever applied to bare soil where there are no active crop roots to absorb the nutrients. Figure 6 illustrates the potentially large amount of fertilizer that would be wasted in a citrus orchard not using VRF, even if the fertilizer is not broadcast. A wider-spaced crop can save more fertilizer with VRF than a densely planted crop (Fig. 6). Recent studies in Florida citrus have demonstrated up to 40% reduction of fertilizer consumption in widely spaced (10.64 x 5.32 m) orchards when using VRF (Zaman et al., 2005). Fruit yields and foliage nutrient levels were not detrimentally affected because the nutrient rate per tree was still optimal.

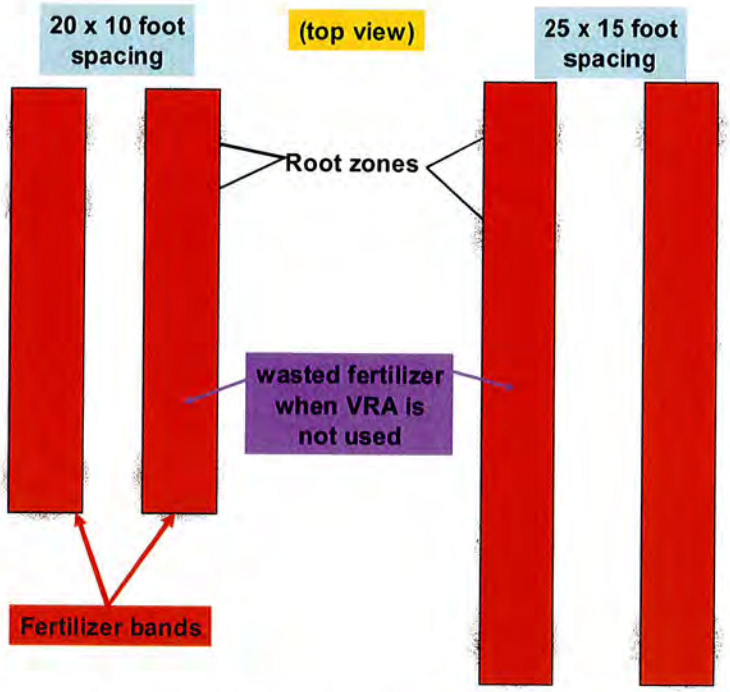

Figure 6. Schematic diagram showing the wasted fertilizer which is not placed in root zones when fertilizing citrus tree rows without variable rate equipment.

3.1 VRF methods and types of fertilizer applicators

Applicators used for variable rates of granular fertilizers include spinner and pneumatic spreaders. Spinner applicators normally vary only one product rate at a time by changing the gate opening or changing the speed of the conveyor belt. However spinner applicators for horticultural fruit crops such as citrus typically have independent left and right spinners and conveyor belts, so that two rows of trees may simultaneously receive their own prescribed rate of fertilizer. Pneumatic applicators have centrally located bins and air tubes lead from a metering unit to the point of discharge through which chemicals are suspended in the air stream and it can apply single or multiple products.

Liquid fertilizer applications can be made through most pesticide or herbicide spray booms for small vegetable crops provided that the fertilizer solution does not harm the foliage or stems of the crop. Narrow-angle fan nozzles and drop-arms are used instead of broadcast cone nozzles along the spray boom in order to concentrate the fertilizer solution safely in the root zone of each row rather than spraying the entire field. Further improvements could be made by triggering each nozzle individually to spray fertilizer only when a crop plant has been detected and to regulate the dose according to the crop requirement. Giles and Slaughter (1997) developed a precision, ground-based application of foliar sprays to rows of small plants and validated it on tomatoes and lettuce. They developed a machine vision guided spray boom system with servo control for nozzle angle and spray pattern width to spray pesticide and found that the precision system allowed spray application rates to be reduced by 66 to 80% and increased spray deposition efficiency on the target plants by 2.5 to 3.7 times greater than conventional broadcast spraying.

3.2 Real-time sensors for VRF

Development of real time sensors to monitor critical parameters can complement map based data. Sensors to measure soil fertility, soil water content, plant stress, or pest populations could allow management decisions to be implemented automatically with appropriate control technology and management. Alchanatis et al. (2005) developed a multi-spectral sensor, and the signal processing algorithm to provide real time assessment of nitrogen status of Sweet corn cv Jubilee. A commercial mobile mini spectrometer was used to acquire leaf reflectance spectra in the field to assess leaf nitrogen. They found that leaf nitrogen status can be predicted in-field, using a non-contact optical sensor based on single leaf spectral reflectance.

Water and nutrients for horticultural crops in greenhouses can be managed by integrated systems for monitoring and control of the nutrient solution, plant growth and product quality. Elings et al. (2004) used plant sensors for photosynthesis, radiation interception and fresh growth rate and validated the plant-substrate model against greenhouse experiments for tomato. The optimal set points for the fertigation regime were selected, and were implemented by a real-time system. In comparison with normal cultivation, optimization of water and nutrient application resulted in reduced application and drainage rates, increased fruit growth rate, and a dry matter concentration indicating that the monitoring and control system offers good prospects for efficient control of water and nutrients.

Plant N can be estimated using spectral reflectance measurements and N demand can be rapidly mapped. Pfenning et al. (2007) scanned the leaves of two broccoli cultivars cv. Parthenon and Marathon, with a digital imager and measured reflectance and their results indicated a possibility of continuous measuring of leaf N content to adjust fertilizer application in real time. Measuring water and N in real time and adjusting irrigation and fertilizers based on the real time data can be very helpful to maintain water and nutrients in the root zone of crops.

Kim et al. (2002) used real-time N sensing and fertilization using a multi-spectral imaging sensor connected with a variable rate liquid application system for supplemental N supply to corn crops. Sensors provided a real-time N and chlorophyll estimate of the corn derived from the multi-spectral imaging reflectance responses of crop canopies. The sensor-based variable rate supplemental N treatment improved the crop N status and increased the yield over most of plots.

3.3 Customized real-time VRF blending of individual nutrients

Variable rates of mixed N-P-K ferilizers are normally applied from a single bin attached to the controller and the actuator. Sometimes the variable rate application of mixed N-P-K fertilizer may not necessarily match the specific nutrient requirement of the crop or soil, thus there is the possibility of different bins for specific feritlizers and controlling variable rate application of different bins separately. Radite et al. (2000) developed and tested such a variable rate applicator in rice paddy fields. The equipment could apply accurate varying rates of two granular fertilizers using a broadcast type granular applicator with 12 nozzles supplied from six metering devices. A variable rate applicator that can simultaneously apply varying rates of two liquid fertilizers was tested by using a control system on a side dressing applicator. Grain sorghum was fertilized by applying two uniform and one variable rate fertilizer treatment (Yang, 2001). Mean application rate errors for the two fertilizers (N32 and 11-37-0) were, respectively, 2.5 and 5.2% in 1997 and 2.8 and 5.8% in 1998.

A self propelled Terra Gator 1803 twin bin pneumatic distributor spreader has its bin divided into chambers and can be used to spread two different type of fertilizers. Sedlak et al. (2001) used phosphorus (53.2 to 158.4 kg/ha) and potassium (0 to 336.3 kg/ha) fertilizer in separate bins. The variable dosing of fertilizers from both bins was based on data from prescription maps and the position of the machine in the field.

3.4 Variable rate fertilization of citrus in Florida – principles and implementation

Variable rate granular fertilizer spreaders for citrus use sensors, computers and GPS technology to continuously monitor trees along the row in order to make adjustments to the rate of fertilizer delivered to each tree. Granular fertilizer is accurately placed in independent left and right bands under the trees. The amount of fertilizer is regulated according to either a GPS-guided prescription map, or by the number of sensors that detect a tree canopy in left- or right-hand rows (Fig. 7). Most importantly, spaces with missing trees are never fertilized, which significantly reduces unnecessary nutrients, fertilizer costs per acre and ground water pollution while discouraging weed growth. Tree roots, the primary targets for fertilizer applications, are located approximately under the tree canopy. Thus the first assumption of VRF is simply that if a canopy and therefore roots are not present, then fertilizer is not applied. The second assumption of VRF is that small immature resets should get less fertilizer than mature trees. Since canopy volume is related to tree height and fruit yield, fertilizer rates can be adjusted based on tree height that is measured "on-the-go" by canopy sensors. Each sensor is responsible for a different range of canopy height, and the cumulative sensor result is used by the variable rate computer controller to adjust the fertilizer rate on each side of the spreader (Fig. 7). Therefore a fully grown mature tree will activate all sensors on its side and receive the full fertilizer rate.

VRF in citrus orchards operates on "single tree prescription zones" since each tree in the orchard should be measured and have its own customized fertilizer rate, delivered directly to its root zone. Perfectly uniform orchards with no gaps between canopies will not benefit from VRF. The VRF technology is most effective in orchards with different tree sizes because VRF is designed to exploit that variability. Thus, an orchard containing young trees with non-overlapping canopies, or a mixture of large trees, young trees, and/or resets will benefit the most from VRF.

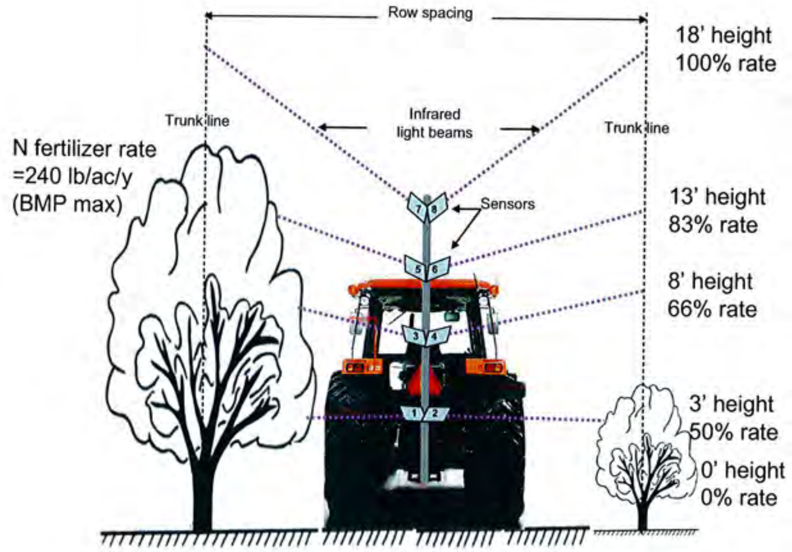

Figure 7. Schematic diagram of the sensor layout and operation on a VRF granular fertilizer spreader for citrus.

Look ahead is a type of precompensation implemented in VRF spreaders which uses the continuous stream of tree size information being collected by canopy sensors. This essential information allows the computer to predict, so that the valve response time, fertilizer particle drop time and other mechanical delays can effectively be subtracted ahead of the fertilizer placement point. If look ahead is not implemented, the fertilizer placement may be inaccurate due to poor synchronization of rates with trees, especially at varying ground speeds. In citrus studies, look-ahead sensing was able to double the accuracy of a DICKEY-john VRF system (Schumann et al., 2006). Similar variable rate nutrient delivery technology could be used for other horticultural tree crops.

In a recent UF/IFAS study, tree canopy sizes were measured with an ultrasonic sensor system in a 17-ha 'Valencia' orange orchard, ranging from 0 to 240 m^3 (Zaman et al., 2006). Six N rates (0, 120, 150, 180, 210 and 240 lb/ac/year) were applied with a VRF spreader according to a prescription map developed from tree canopy size information. For comparison, half of the orchard received the standard uniform N rate of 240 lb/ac/year. Soil leachate samples were collected with vacuum lysimeters at 1.5-m depth from below the root zones of 36 trees in 18 paired plots. The leachate samples from 10 sampling dates in 2005 were analyzed for nitrate-N concentration, and leaf samples were analyzed for leaf nutrient concentrations under VRF and uniform fertilization. Trees with excess leaf N (>3%) under uniform fertilization had smaller canopy volumes (less than 100 m^3), and constituted 62% of the entire orchard. This was evidence of excess fertilization under uniform fertilization management. In contrast, the VRF treatment significantly ($p \leq 0.05$) decreased nitrate loading from leachates leaving the root zone compared to the uniform treatment. Mean leachate nitrate-N concentrations for all VRF treatments ranged from 1.5 to 4.5 mg/L and were below the maximum contaminant level for groundwater of 10 mg/L, while those under uniformly fertilized small and large trees were 28.5 and 14.0 mg/L, respectively. Most leaf nutrient concentrations were not significantly influenced by the VRA fertilization and were within the recommended optimal ranges. VRF used 40% less fertilizer than standard uniform fertilization and therefore also improved orchard profitability.

4. Focus for future research efforts in precision agriculture

Some additional opportunities available for keeping nutrients in the root zone are:

- ✓ Improving knowledge of exactly where the crop plants are located in fields. Precise mapping of where the seeds are planted is a good start, since then fertilizer spreaders can be guided exactly to the root zones during the growth cycle. Highly accurate RTK-GPS receivers and GPS-guided tractor steering systems can make precision seed mapping possible. Griepentrog et al. (2005) measured the average error between the GPS seed map and the actual plant map was about 16 to 43 mm depending on vehicle speed and seed spacing.

rapid VRF response time

- ✓ Variable rate irrigation could greatly improve the retention of nutrients in the root zone by customizing the exact soil moisture requirements for different plants in the field. Although technically feasible, this method is currently very expensive to implement.

- Crop canopy quality data from new sensors, in addition to canopy size, would be valuable to distinguish between healthy living and diseased or dead plants. Sick or dead plants that will not recover should not be fertilized because the nutrients will not be used properly in the root zone. Existing canopy sensors tend to measure only size, and can therefore not discriminate between healthy or dead plants.

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