Understanding Geographic Information Systems and Global Positioning Systems in Horticultural Applications

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SUMMARY. New technologies such as differential global positioning systems (DGPS) and geographical information systems (GIS) are making it possible to manage variability in soil properties and the microenvironment within a field. By providing information about where variability occurs and the patterns that exist in crop and soil properties, DGPS and GIS technologies have the potential of improving crop management practices. Yield monitoring systems linked to DGPS receivers are available for several types of horticultural crops and can be used in variety selection and / or improving crop management. Precision soil sampling and remote sensing technologies can be used to scout for infestations of insects, diseases, or weeds, to determine the distribution of soil nutrients, and to monitor produce quality by measuring crop vigor. Combined with variable rate application systems, precision soil sampling and remote sensing can help direct fertilizer, herbicide, pesticide, and / or fungicide applications to only those regions of the field that require soil amendments or are above threshold levels. This could result in less chemical use and improved crop performance. As with any information driven system, the data must be accurate, inexpensive to collect, and, most importantly, must become part of a decision process that results in improvements in crop yield, productivity, and / or environmental stewardship.

Producers recognize that variability exits in almost every aspect of the crop environment and the benefits that could be obtained from managing inputs based on the specific needs of each plant. However, until the advent of positioning systems and computerized data manipulation systems, the time and labor involved in surveying sites, recording yields, and applying inputs made site-specific horticulture impractical. New technologies that can pinpoint sites within a field, store and retrieve vast amounts of data, monitor yields on the go, and apply varying rates of fertilizer and chemicals on small areas within the field have ushered in a new era of precision management. Possible benefits to using these technologies include increased efficiency and profits with a decline in the negative environmental impacts of fertilizers and pesticides.

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Spatial variability in the microenvironment within a farm field has been well documented (McGraw and Hemb, 1994; Pierce et al., 1994). Topography, depth to rock or clay, nutrient levels, pH, crop yield, and a host of other factors have been shown to change within a farm field (Heiniger, 1996; Sudduth et al., 1996). Historically, growers have compensated for some of these variables by differential application of fertilizers and cropping practices based on soil characteristics. However, as farm size and mechanization increased, the ability of growers to apply specific farming practices to small field areas declined. In fact, in order to maintain maximum productivity, it became more important to apply large amounts of fertilizers and chemicals to the land. Today, as farm input costs increase in respect to crop prices and concerns mount over the damage to water quality and environment from nonpoint source pollution, growers must improve the efficiency of crop production by using site-specific farming methods.

The renewed interest in site-specific farming is the result of new technologies that make it possible for producers to recognize multiple crop production variables within small areas of a field and to customize their management to those variables (Robert et al., 1992). These technologies include DGPS, GIS, yield monitors, remote sensing, and variable rate application equipment. DGPS provides x, y, and z coordinates which enable a grower to locate his position within the field. When a DGPS receiver is connected to a yield monitor or soil sensor, it is possible to produce field maps showing changing yield or nutrient levels. These maps help identify areas within a field that require attention. Once a problem within the field has been diagnosed, variable rate application equipment can be used to differentially apply inputs to that problem site. This entire system of using technologies and site-specific management to address agricultural problems is known as precision farming.

It is important to recognize that precision farming systems are driven by information collected from the farm field and used in the decision process. As with any information-based system, there are several key concepts which much be understood in order to increase profits by using precision farming techniques in a horticultural enterprise. First, the information must be accurate. Inaccurate information can actually lead to decisions that result in misapplication of inputs and increased costs (Sawyer, 1994; Wollenhaupt et al., 1994). Second, the information must be collected as inexpensively as possible. Information that costs more to collect than the value of the produce cannot possibly improve farm profits. Finally, the grower or farm manager must be able to use that information to improve crop management practices, decrease inputs, or to effect some other positive outcome. To effectively manage nutrients, pests, and chemical inputs, within-field variation must be reliably interpreted (Babcock and Blackmer, 1992; Sawyer, 1994). A successful precision farming system incorporates information on variability in soil nutrients, insects, weeds, diseases, plant growth and yield into a decision cycle. The ideal decision cycle collects information, analyzes that information through the interpretation of relationships found among field variables, and then formulates a management response. That management response is then evaluated using within-field yield patterns to determine the impact on output and profit.

Several factors make the use of precision farming systems attractive to fruit and vegetable growers. First, the large amounts of fertilizer and pesticides used in vegetable and fruit production could be decreased through precise knowledge of where a nutrient deficiency or insect infestation exists within the field or greenhouse and the site-specific treatment of that problem. Second, the high value of the produce means that gains in yield derived from early treatment of a pest infestation or nutrient deficiency could translate into significantly higher profits. Finally, site-specific management of nutrients or pests could enhance fruit or vegetable quality, making them more appealing to the consumer. This paper examines the potential applications of precision farming technologies in horticulture, and describes what the decision cycle might look like for each application.

Horticultural applications

MONITORING YIELDS OF HORTICULTURE CROPS. The ability to measure yield from different locations within a field is perhaps the most exciting and useful precision agriculture tool available. Because yield integrates all of the various factors, environment, genetics and management, that go into producing a crop, yield maps give the agronomist the opportunity to determine which component was most limiting (Heiniger and Brake, 1996). While automated yield monitoring systems have been used for harvesting grain crops for over 5 years, automated monitors for horticultural crops have only just recently become available. The HarvestMaster 500 yield monitoring system (Harvestmaster, Logan Utah), developed primarily for potatoes (*Solanum tuberosum* L.), tomatoes (*Lycopersicon esculemtum* Mill.), onions (*Allium cepa* L.), etc., uses idler pulleys mounted on load cells to measure the weight of produce flowing

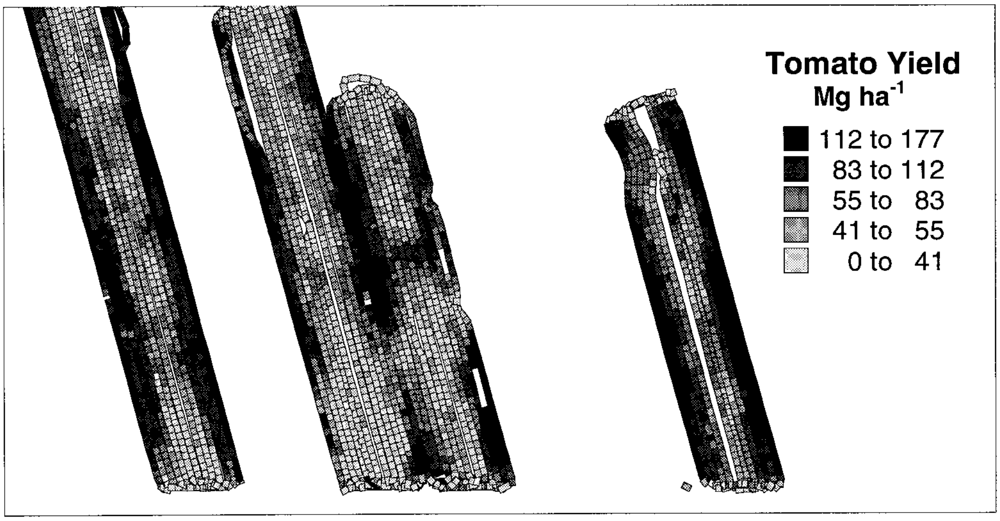


Fig. 1. Yield of tomatoes in a field in eastern North Carolina; 1 Mg·ha^{-1} = 0.446 tons/acre.

over a chain conveyor running from the digger or picker to the truck or wagon. The monitor takes measurements every second and provides information to the operator about the weight of the produce harvested. When linked to a DGPS receiver, the yield monitor has the capability of producing a map of crop yield within a field (Fig. 1). Tests in potatoes and tomatoes have shown that yields of these crops can be measured with an accuracy of <2% (Rawlins et al., 1994).

Another system for measuring crop yields in horticulture is the use of signal buttons (Agricultural Data Systems, Laguna Niguel, Calif.) or bar code readers (Brumit, 1997). Growers can place magnetic markers on fruit trees or in rows of produce which are coded for location as determined by a DGPS receiver. When the fruit is picked from the tree or the row of produce is harvested, an automatic reader is pressed against the button to record the location and then the weight or number of baskets of produce is entered into the system manually. This gives growers who use manual labor the opportunity to record yields based on field location (Fig. 2), the number of baskets or bushels of produce picked by farm labor, and the time that the produce was picked. Such as system could have important uses in tracking produce picked from certain parts of the field all the way to the marketplace.

Yield information can easily become a key tool in a decision cycle for managing horticultural crops. For instance, one of the most important processes in agriculture is evaluating new genetics. Yield information from different genetic materials planted in close proximity can be used to determine which varieties or cultivars to plant in a given environment. Such evaluations have been used for decades on research stations. Now the same process can be used to refine decisions for an individual farm. Similar in-field trials can be used to evaluate a range of crop management practices from seeding rates and planting dates to fertility applications. In each situation, different practices can be applied to strips across the field. Yield information from these strips can be compared using maps which show the differences between the strips in different areas of the field (Peterson, 1996).

Growers can then evaluate the success or failure of the practice on different soils or in different situations (Fig. 3). Growers can also take advantage of the natural variation in soil properties and the resulting differences in crop yield to help them find ways of managing for drought, poor drainage, and nutrient stress. Although the cost of yield monitoring systems is high ($7000 to $10000), research has shown that small increases in yield can be expected from decisions that result in selecting improved genetics and crop management, and that these small increases are enough

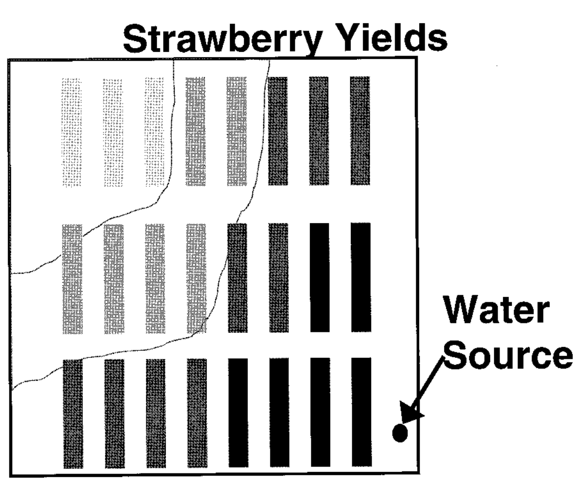


Fig. 2. Strawberry [*Fragaria virginiana* (L.) Duch.] yield map made by recording yields from beds using magnetic buttons and an electronic recording device.

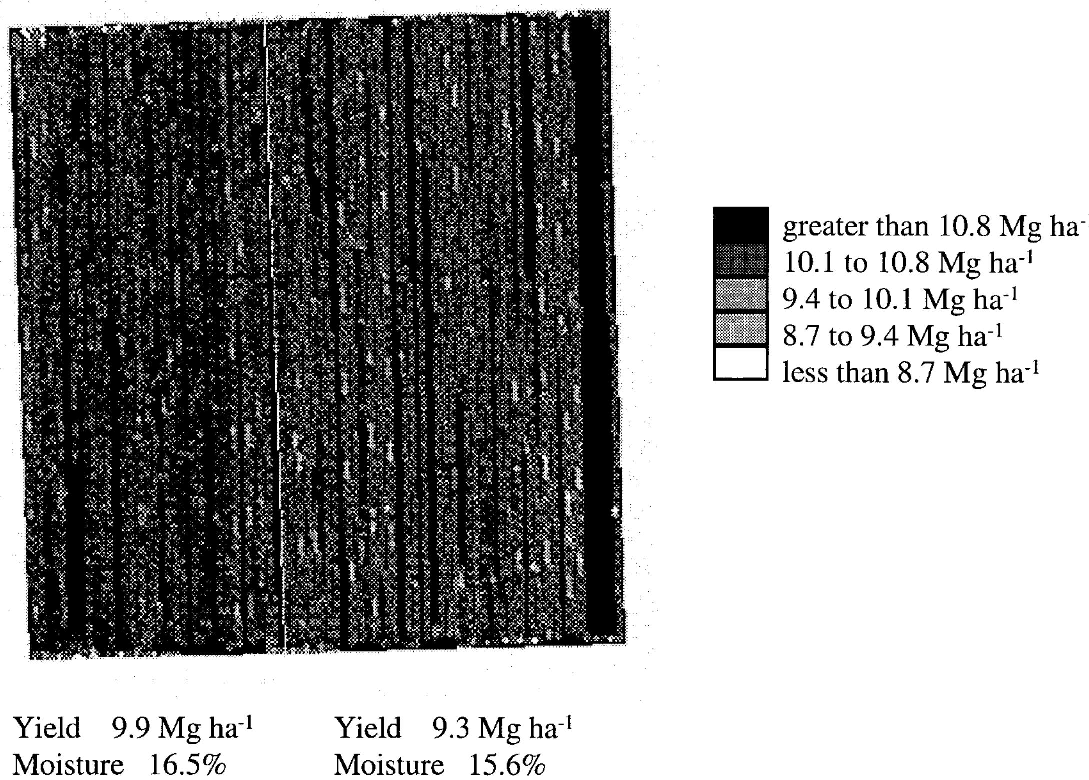


Fig. 3. Corn (*Zea mays* L.) yields in 1995 on a 260-ha (640-acre) block on Open Ground Farms. The left half of the block has been in continuous no-till while the right half is conventionally tilled using standard practices for the area; 1 Mg·ha^{-1} = 0.446 tons/acre.

to pay for the system over a period of 5 to 7 years (Heiniger, 1996).

MANAGING VARIABILITY IN SOIL PROPERTIES. Another precision agriculture tool available to producers growing horticulture crops is the use of DGPS computer-guided soil sampling, often referred to as precision soil sampling. Using DGPS and GIS technologies, producers can design more intensive soil sampling schemes to determine the distribution of nutrients in a field. Since soils often vary greatly in nutrient levels, composite soil test results cannot accurately represent all portions of a field. In many cases, composite soil samples mask areas of higher and / or lower levels of plant nutrients. Precision soil sampling provides information to 1) identify localized regions of nutrient deficiencies and excesses within fields, 2) increase lime and fertilizer use efficiency by directing applications to specific sites, and 3) correct nutrient deficiencies on specific soil types.

The first step in the process is to map soil fertility. This is done by using a DGPS equipped all terrain vehicle for collecting the soil samples. This vehicle is used to map the field boundary using the DGPS to provide coordinates. Then the field is divided into grids and soil samples are pulled from each grid. The DGPS guidance system linked to an on-board computer provides the information necessary to determine where the samples are to be taken. Once the soil sample is taken, its true position is logged into the computer for future reference. The resulting soil samples are tagged with their reference number and sent off for analysis. When the laboratory analysis is received, the data is matched to its location within the field and a contour map is created using one or more geostatistical methods (Isaaks and Srivastava, 1989). When fertilizer is spread on the field, the spreader uses a computer-guided variable rate technology (VRT) controller to adjust fertilizer application rates on the go. Using the nutrient map, the computer sets the rate to be applied on the VRT controller according to the position of the spreader in the field. The controller then adjusts the rate at which the fertilizer spreader unloads the material. Numerous companies are now building fertilizer equipment for VRT applications including ruggedized computers, controllers, and software. Costs for soil sampling equipment (excluding the all-terrain vehicle) run from $4000 to $8000, and for VRT equipment (excluding the spreader truck) costs range from $8000 to $12000. Many commercial suppliers for fertilizer materials now offer precision soil sampling and VRT application at prices ranging from $24 to $44 / ha ($9.70 to $17.80 / acre).

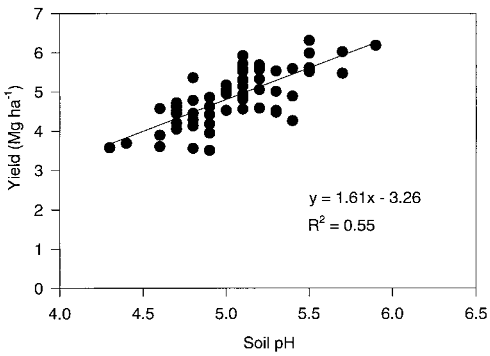


Fig. 4. Linear relationship between wheat (*Triticum aestivum* L.) yields and pH developed by comparing soil test values with yield data collected from the same location using a yield monitor; 1 Mg·ha^{-1} = 0.446 tons/acre.

Intuitively, the application of information gained from precision soil sampling should result in a better match between soil nutrient levels and application rates, and, in the final analysis, should result in better crop yields or lower application rates. However, what many are discovering is that increasing soil nutrient levels does not always result in increased yield, even in areas of the field where nutrient levels are low. If soil nutrients are not the limiting factor in crop production, then a yield response to changing nutrient levels is not likely. Precision soil sampling will only improve yields and profit if there is an indication that the nutrient or soil property in question is limiting yield. A good example of this is the variability in pH in soils in North Carolina. Yield maps and precision soil testing indicated a clear relationship between pH and crop yields (Fig. 4). As a result, VRT applications of lime produced yield gains that resulted in a \$25 / ha (\$10.17 / acre) gain in profit over uniform applications of lime. Likewise, when two years of corn and soybean yields showed patterns that matched field variability in phosphorus levels (Fig. 5), VRT applications of phosphorus and potassium produced a \$26 / ha (\$10.50 / acre) profit when compared to uniform applications (Table 1) (Heiniger, 1998). Growers of horticultural crops can determine the potential for increasing profits through reducing the amount of nutrients applied or by increasing yields by comparing the distribution of soil nutrient levels within a field and examining the relationship between nutrient levels and yield. When the mean of the soil nutrient level in the field is greater than the median level found when examining the data from precision soil samples, then the amount of fertilizer applied using VRT methods increases (Fig. 6). In this situation, the grower is depending on crop yield increases to return a profit from precision soil sampling. Conversely, when the mean of the soil nutrient level in the field is less than the median level found when examining the data from precision soil samples, then less fertilizer will be applied using VRT methods (Fig. 7). In this case, profitability will depend on how much precision soil sampling costs when compared to the fertilizer saved.

In certain crops, precision nutrient management can improve quality as well as yield. In these situations, profitability is increased by the increased value of the produce. A good example is the use of precision nitrogen (N) management in sugar beets (*Beta vulgaris* L., Crassa Group J. Helm) in the Red River valley between Minnesota and North and South Dakota (Kerr, 1996). The sugar content of sugar beets is directly related to N levels in the plant. N levels that are too low result in small beets and less tonnage. N levels that are too high reduce sugar levels in the beets and result in poor quality. Because nitrate levels in fields are so variable, it is difficult to apply N without putting on too much in some spots and too little in others. By using precision soil sampling to determine changing N levels within a field, sugar beet growers can apply

Fig. 5. Map of soybean [*Glycine max* (L.) Merrill] yield from a 240-ha (640-acre) field and the corresponding phosphorus index for the same field. Index values below 12.5 note very low available phosphorus, while values above 62.5 are excessive; 1 Mg·ha^{-1} = 0.446 ton/acre.

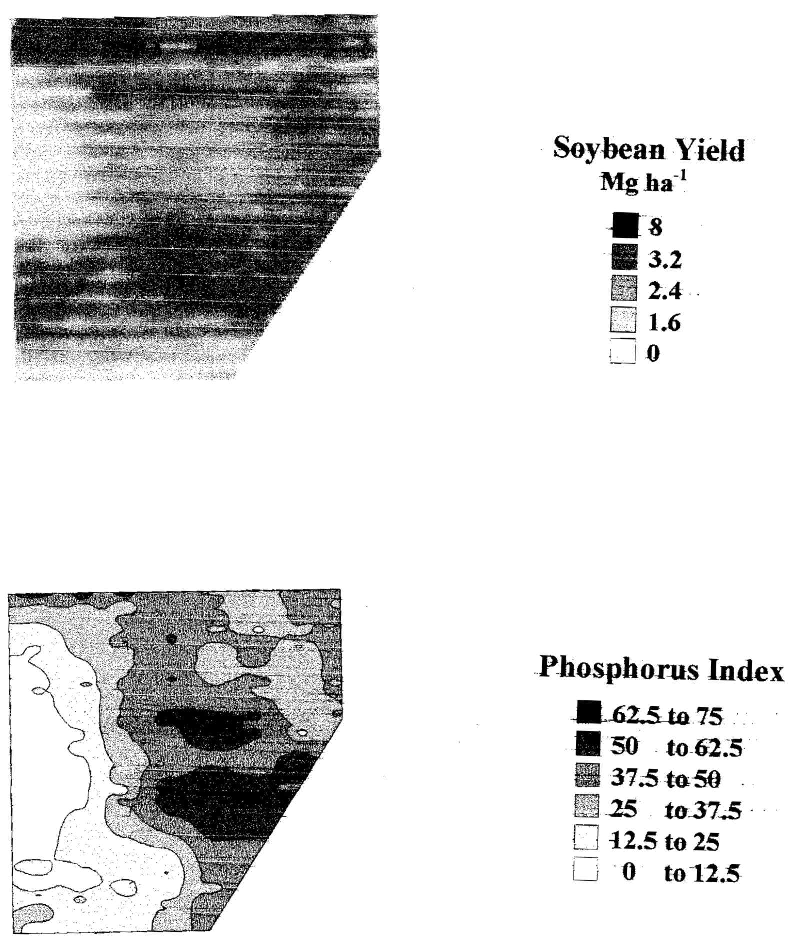


Table 1. Cost-profit analysis for variable rate technology (VRT) versus uniform fertilizer application.

	Cost ($ for 13.83 ha[z])		
Operation	**Grid sample**	**Uniform sample**	**Difference/advantage**
Phosphorus	432.03	254.19	–177.84
Potassium	265.96	251.80	–14.16
Additional yield income	$229.44 / Mg × 5.98 Mg[y]		1371.36
Cost of soil sampling	239.12	68.32	–170.80
Variable rate spreading	444.08	341.60	–102.48
	Profit / loss to VRT		906.08
Profit / hectare = $65.51, Profit / acre = $26.52			

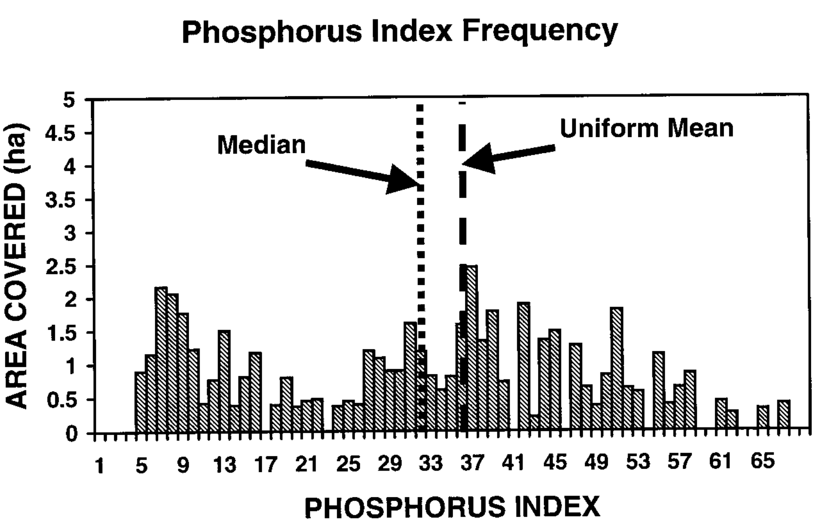
[z]13.83 ha = 34.17 acres.
[y]1 Mg = 1.1 tons.

the right amount of N to each area. The result has been an increase in sugar production and quality which has more than paid for the addition cost of precision soil sampling (Table 2). Such a situation would apply to many horticultural crops where, to a large extent, quality is controlled by plant nutrition.

PRECISION SCOUTING FOR WEED, INSECT, AND DISEASE PROBLEMS. There are many potential uses for precision technologies that are just beginning to be explored. One of the most exciting of these is the use of precision tools for scouting weeds, insects, and diseases. There are numerous benefits that could be gained from the identification of weed, insect, or disease patterns within a field and the early application of treatments to those spots (Weisz et al., 1996). First, by identifying spots where weed, insect, or disease levels were above threshold, treatments could be applied early before the problem spreads to other field areas. Second, early treatments are more effective in controlling pests and pathogens. Third, treatment rates could be tailored to adequately control the levels of pest or pathogen found in a specific area rather than averaged across the field. Fourth, since the area covered by the treatment is smaller, there will be less herbicide or pesticide used when compared to treating the entire field. Finally, by only applying materials such as chemical treatments to certain field areas, there is less chance of the pest or pathogen developing resistance to the treatment. Equipment for marking the scouting location and recording data is available in the form of backpack DGPS units which are then connected to small hand-held computers. Software programs written specifically for scouts are used to record the data with links to the coordinates at that location. Costs for this equipment run from $4000 to $10000.

A good example of the use and benefits of precision scouting and application of chemical treatments comes from a study by Weisz et

Fig. 6. Difference between the mean of soil samples collected for the uniform application and the median of the samples collected for variable rate technology (VRT) along with the difference in fertilizer used and cost for phosphorus fertilizer in the form of diammonium phosphate (DAP); 1 ha = 2.47 acres, 1 kg = 2.2 lb.



Available phosphorus	Area (ha)	VRT sample DAP (kg)	VRT sample Total cost ($)	Uniform sample DAP (kg)	Uniform sample Total cost ($)	Difference ($)
Very low	3.48	969.6	261.59	237.1	63.96	–197.63
Low	1.79	334.0	90.11	121.9	32.88	–57.23
Medium	3.36	261.0	70.40	228.9	61.75	–8.65
High	2.96	36.8	9.93	201.7	54.41	44.48
Very high	1.68	0	0	114.5	30.89	30.89
Excessive	0.56	0	0	38.2	10.30	10.30
Total	13.83	1601.4	432.03	942.3	254.19	–177.84

al. (1996). Using customized scouting methods, infestations of colorado potato beetle (*Leptinotarsa decimlineata* Say) were mapped in a potato field. Using these maps, chemical treatments were applied differentially across the field. These techniques reduced chemical use from 40% to 70% with no reduction in potato yield or quality, and there was a reduction in the rate at which the insects developed resistance to the chemical treatments. However, one problem with using this technique for scouting pest infestations is that it is extremely time consuming and difficult to use. Quicker and more simplified procedures must be developed before precision insect management can be used on a large scale.

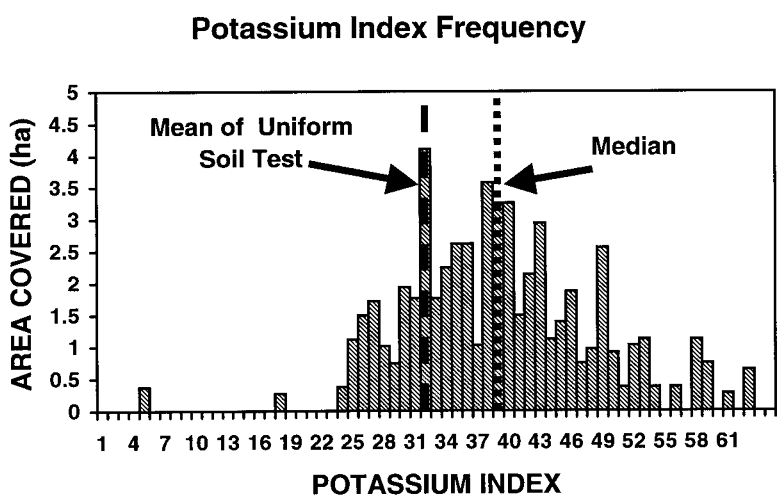
One method of reducing the time and expense of scouting weeds, insects and diseases is the use of infrared images. Infrared photographs are commonly used in several states to scout for weeds, diseases, and insects. Infrared images taken on a regular schedule can help the grower identify changes within the field that can be indicators of pests or pathogens (Nichols, 1997). Remote sensing technologies such as infrared images help identify problem areas quicker and result in more timely treatment applications.

MANAGING QUALITY WITH REMOTE SENSING. Remote sensing can also be used to manage the quality of the produce. By monitoring crop vigor and health, growers can take steps to control quality within a field. Because quality is an important factor in marketing produce, the benefits of managing produce quality within a field can be substantial. A good example of this type of application comes from studies done on vineyards in California (Lang, 1997). The sugar content of the grape (*Vitis vinifera* L.) is related to the vigor of the vine. Remote sensing is being used to identify areas within the vineyard where excessive growth is occurring. By controlling nutrients and / or water, growth can be regulated in certain areas of the vineyard resulting in a more uniform product and high quality wine.

Remote images have been used to measure tree growth in orchards which is directly related to fruit production. By differentially applying nitrogen based on the growth of the individual tree, better quality, more uniform fruit can be harvested. Potentially, these technologies when combined with yield mapping and coded tags can be used to track produce all the way from the field to the market. This information could help determine soil and environmental factors that result in better quality and longer shelf life.

MANAGING GREENHOUSE PRODUCTION. GIS, hand-held data recorders, and VRT applications can also be important tools in managing large-scale greenhouse production. Maps of the greenhouse showing the location of fans, heaters, shading patterns, etc. can be valuable in determining areas within the greenhouse where insect or disease infestations begin. By monitoring the plants and recording the monitoring locations, greenhouse managers can develop information on insect and disease patterns along with plant growth problems. This could be used to adjust monitoring procedures, reduce chemical applications, and improve greenhouse designs. In greenhouse situations, DGPS equipment would

Fig. 7. Difference between the mean of soil samples collected for the uniform application and the median of the samples collected for variable rate technology (VRT) along with the difference in fertilizer used and cost for potassium fertilizer in the form of potash (0–0–60). 1 ha = 2.47 acres, 1 kg = 2.2 lb.



Available potassium	Area (ha)	VRT sample Potash (kg)	VRT sample Total cost ($)	Uniform sample Potash (kg)	Uniform sample Total cost ($)	Difference ($)
Very low	0	0	0	0	0	0
Low	1.74	300.9	54.16	240.3	43.25	–10.91
Medium	6.88	946.7	170.40	950.3	171.05	0.65
High	5.09	529.1	95.23	703.1	126.55	31.32
Very high	2.09	127.5	22.95	288.7	51.96	29.01
Excessive	0	0	0	0	0	0
Total	15.80	1601.4	342.74	942.3	392.81	50.07

Table 2. Comparison between site-specific and conventional nitrogen management on sugar beets for yield, recoverable sugar, sugar quality, and profit (Kerr, 1996).

Technique	Sugar (%)	Sugar lost to molasses (%)	Yield ($Mg \cdot ha^{-1}$)	Recoverable sugar ($kg \cdot ha^{-1}$)	Gross return (%/ha)
Grid sampled variable rate N	14.9	1.434	6.60	6277	1711.71
Conventionally sampled uniform Rate N	14.8	1.70	43.86	5747	1528.93
Difference	0.1	0.27	2.74	530	182.78
Cost of variable nitrogen application and grid soil sampling = $56.81 / ha ($23.00 / acre)					
Net return to variable rate application = $125.97 / ha ($51.00 / acre)					

[z]1 $Mg \cdot ha^{-1}$ = 0.446 ton / acre.
[y]1 $kg \cdot ha^{-1}$ = 0.892 lb / acre.
[x]$1 / ha = $0.41 / acre.

not be necessary since location could be determined based on the distance and direction from reference points located within the greenhouse itself. Therefore, the cost of collecting information on the spatial patterns associated with insect or disease infestations would be less expensive.

Conclusions

Technologies such as DGPS, GIS, yield monitors, and remote sensing can provide the growers of horticultural crops information on crop yields and yield limiting factors. This information can be used to improve management practices and increase yield. However, there are several problems that must be solved before precision technologies can become standard in horticultural operations. First, growers must be trained in using satellite and computer technologies. Most growers do not have the computer skills necessary to use the hardware associated with yield monitors, precision soil sampling, or remote sensing, nor can they manipulate geographic information to give them the answers to the questions they are asking. Second, techniques for using GPS and GIS in scouting nutrient deficiencies and pest infestations are extremely time consuming, difficult to use, and costly. Accurate information must be collected in an efficient and inexpensive manner. Procedures for scouting horticultural crops will need to be developed. Finally, there is a need for decision support systems which help the grower identify the most limiting factor at each field site and to determine what steps he needs to take to correct the problem. These problems can be solved through research into precision agriculture and from the development of improved hardware and software specific to horticulture systems.

Despite these obstacles, precision management in horticulture will grow as the cost of inputs increase, as nutrient and environmental regulations increase, as the demand for high quality food increases, and as the need for improved efficiency and understanding in the production of horticulture crops increases. Tomorrow's grower will use these technologies and techniques to farm smarter. Our challenge is to find ways to help growers adopt these technologies through an improved understanding of the technologies and techniques behind successful site-specific production systems.

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