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# PRECISION HORTICULTURE: APPLICATION ON APPLE ORCHARDS

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*Happiness Only Real When Shared*
(Christopher McCandless)

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# ABSTRACT

Precision horticulture and spatial analysis applied to orchards are a growing and evolving part of precision agriculture technology. The aim of this discipline is to reduce production costs by monitoring and analysing orchard-derived information to improve crop performance in an environmentally sound manner. Georeferencing and geostatistical analysis coupled to point-specific data mining allow to devise and implement management decisions tailored within the single orchard. Potential applications range from the opportunity to verify in real time along the season the effectiveness of cultural practices to achieve the production targets in terms of fruit size, number, yield and, in a near future, fruit quality traits. These data will impact not only the pre-harvest but their effect will extend to the post-harvest sector of the fruit chain. Chapter 1 provides an updated overview on precision horticulture , while in Chapter 2 a preliminary spatial statistic analysis of the variability in apple orchards is provided before and after manual thinning; an interpretation of this variability and how it can be managed to maximize orchard performance is offered. Then in Chapter 3 a stratification of spatial data into management classes to interpret and manage spatial variation on the orchard is undertaken. An inverse model approach is also applied to verify whether the crop production explains environmental variation. In Chapter 4 an integration of the techniques adopted before is presented. A new key for reading the information gathered within the field is offered.

The overall goal of this Dissertation was to probe into the feasibility, the desirability and the effectiveness of a precision approach to fruit growing, following the lines of other areas of agriculture that already adopt this management tool. As existing applications of precision horticulture already had shown, crop specificity is an important factor to be accounted for. This work focused on apple because of its importance in the area where the work was carried out, and worldwide.

# CHAPTER 1

# FROM PRECISION AGRICULTURE TO PRECISION HORTICULTURE

## 1 Introduction

> *Give me a place to stand and with a lever I will move the whole world.*
> **Ἀρχιμήδης** (Archimedes)

Borrowing from Archimedes, precision agriculture (PA) can be linked to a lever, constructed from information gathered from a broad array of new technology and tools, that combined can help modify the agricultural world vision. These disciplines focus on the causes underpinning the variability found in the fundamental components of agricultural production: the soil (Webster and Oliver, 1992), the weather and environment (Reuter et al., 2005), plant genetics (Fernandez-Cornejo et al., 2001) and their interaction (Pringle et al., 2003). This fundamental knowledge must be complemented with information on machinery performance (Shueller et al., 1999, Qiao, 2005), and all physical, chemical and biological inputs used in the crop production (Cupitt and Whelan, 2001, Taylor et al., 2007b).

In our context, the term "precision" refers to the quality or state of being precise, where precise means minutely exact, a term similar to correct (Pierce and Nowak, 1999). PA thus becomes a mode of crop management where "correct" agricultural inputs and practices have to be applied at specific places within a field, in order to do "the right thing", in the "right place", at the "right time", and in the "right way" (Pierce et al., 1994).

The increasing interest aroused by PA is based on the concept that “knowledge is power”. For a long time, detailed, real time knowledge about a crop’s progress in agriculture and horticulture has been unavailable or was prohibitively expensive to acquire, thus resulting in the fact that management is still normally based on a farmer’s experience, subjective knowledge of the crop production system and data recorded usually at a block or orchard level using non-spatial descriptive statistics, such as the mean and variance of production attributes (Miranda Jimenez and Royo Diaz 2004). Advances in electronics and software over the past decades have made the acquisition of much of this information at finer temporal and spatial scales quite possible and economical. Inexpensive sensors, microprocessors and software, coupled to satellite communications now enable growers and natural resource managers to collect vast amounts of data, including geo-referenced data, with the aim of improving agricultural and processes (Auernhammer, 1994; Wilson, 2000).

According to Berry (1995), PA represents a tool to access information coming from the field and to translate it into knowledge. Pierce and Nowak (1999) proposed perhaps the most complete definition of PA as “the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production for the purpose of improving crop performance and environmental quality”. PA thus becomes a management strategy that uses all available information technologies (IT) to assess agricultural production systems with the aim to increase the production and minimize environmental impact. The concept of sustainability here, is meant not only as low environmental impact resulting from reduced , more rational application of inputs (Cox, 2002; Bongiovanni and Lowenberg-Deboer, 2004) but can also be read as a new method for supporting the economic sustainability of agriculture in developed and developing countries (Maohua, 2001). PA can be conceptualized as a new system approach that aims to further bring the agricultural world toward a low input, high efficiency and sustainable agriculture.

In this definition the idea of site-specific crop management (SSCM) is included, implying that under PA management choices should be characterized both across space and time to accommodate the variability in crop and soil (Whelan and McBratney, 2000).

## 1.1 The scientific Vs. applied nature of PA

Whelan and McBratney (2000) assert that, as with all such endeavors to further knowledge in science-based discipline, the concept and acceptance of PA management will ultimately rest on the successful completion of scientific experimentation and assessment. This is correct from the scientific point of view but it is not the only driver for acceptance of PA technologies by producers. Probably the most important at the moment, even where experimental results are excellent, is the "test of fire" that is represented by the expected economic benefit and intended increase is profitability for the grower. The perception of usefulness, intended as reducing production costs, increasing yields, protecting the environment, minimizing risk, and providing information to help and implement new technologies to manage farms, is also a positive attribute of PA. Of course these characteristics need to be adapted to the specificities of the farms size, the farmer's age and educational level, which is relevant due to the adoption of new skills (i.e. the use of sensors and other tools) and the use of computer software and other IT (Adrian et al., 2005).

Up to now PA has been predominantly applied to cropping industries, but it is important to remember that PA relates to all farming systems. The term Site-Specific Crop Management (SSCM) describes the application of PA to cropping systems. SSCM may be defined as: “Matching resource application and agronomic practices with soil attributes and crop requirements as they vary across a field” (McBratney and Whelan, 2001) or, as defined by Robert (1999), is “just” a part of PA philosophy not to be confused with a more open concept that incorporate animal industries, fisheries and forestry. Collectively these actions are referred to as the ’differential’ treatment of field variation as opposed to the ’uniform’ treatment that underlies traditional management systems. Thus, SSCM, is just a part of the PA philosophy and a term used to avoid confusion with the more open PA concept that incorporate animal industries, fisheries and forestry.

On a section of their website the CSRIO (Commonwealth Scientific and Industrial Research Organization), the nationally founded agricultural research organization of Australia, presents the key questions facing framers, land managers and researchers about a site specific approach to cropping field (http://www.csiro.au/science/PrecisionAgriculture.html#CSIROResearch). These are:

- Is variation predictable? Are patterns of yield variation constant from year to year or otherwise predictable? If they are, PA may increase the likelihood that a particular management action will deliver a desired or expected outcome.
- Does variation in yield equate to variation in quality? Are patterns of variation in yield matched by patterns of variation in quality?
- What drives variation and can it be managed? What are the key drivers of variation? If these are known and manageable, is there an opportunity to both tailor inputs to a specific economic or environmental goal and selectively harvest the outputs into different product streams?
- Are there economic or environmental benefits for targeted management? Does targeting management deliver an economic or environmental benefit over

conventional uniform management - a practice which assumes that paddocks are homogenous with respect to potential productivity?

Most of these questions are concerned with the variability in field, which is probably the main difficulty to overcome in SSCM analysis.

## 1.2 Variability in the field

Webster and Oliver (1992) state that it would be very simple to describe the Earth surface if it were the same everywhere. In the same way if the environment had no variability the concept of PA would be denied. Pierce (1995) notes that for PA to be useful the variation must be known, of sufficient magnitude, spatially structured (nonrandom), and manageable. It is essential to have high accuracy measurements in the field to obtain useful results from the analysis. If spatial and temporal variability did not exist, then the most obvious strategy would be a uniform management. In all fields (Florin et al., 2008), the magnitude of temporal variability appears much greater than that of spatial. Given this large temporal variability, relative to the spatial variation, there is a need to determine if uniform or differential management is the optimal risk aversion strategy (Whelan and McBratney, 2000; Fig. 2).

Spatial and temporal variability can be then linked to other spatially or temporally variable factors in the field. These can be due to perturbations imposed by:

- Climate/Environment
- Management practices
- Crops type

Thus variability in an agricultural field may be due to man-made or natural sources. A natural variability may be due to seasonal change in weather pattern or rainfall over several years while examples of man-made variability include improper distribution of irrigation/drainage facilities for field or excessive/deficit application of farm inputs and managements. Consequently in PA, "Variability of production and quality equals opportunity" (McBratney and Taylor, 2000). The efficacy of a PA management strategy is affected by the source of variation in production. It maybe possible for example that, even though variability exists, it would not be economically sustainable to address it because too small or too randomly distributed within the field or variability may be driven by a factor that cannot be controlled or altered easily.

## 1.3 Precision Horticulture

Precision Horticulture (PH), although young, is quickly developing. That is witnessed by the fact that the International Society for Horticultural Science (ISHS) has created a Working Group focused on PH (http://www.ishs.org/science/HE7.php) and the increasing numbers of paper presented at conferences as the International Conference of Precision Agriculture (ICPA), the European Congress of Precision Agriculture (ECPA), FRUTIC (Information and Technology for Sustainable Fruit and Vegetable Production ) and others issue presented at horticultural/other subjects symposia. The goal of PH, like PA, is improving the efficacy of management decisions such as yield mapping (Aggelopoulou et al., 2007), fertilization (Mueller et al., 2001) or irrigation (Capraro et al., 2008), pest management (Hetzroni et al., 2003) etc., by measuring and managing the spatial and/or temporal variations in crop production. Understanding these variations allows management to be tailored to specific crop needs at each location (site) in the orchard, hence optimizing production.

The most relevant source of information available to a horticultural producer is on-site information specific to that system (Whitney et al., 1999); despite this however, the recording of objective crop development information is not a common practice in many horticultural crops (Schueller et al., 1999). High yield performances result from the integration of various components, which, pieced together, constitute the “orchard system puzzle” (Barritt, 1992). They are implemented at two different time scales: (a) a set of initial choices which determine the configuration of the orchard during its life-span: rootstock and cultivar, tree spacings, the support system; and (b) a set of annual procedures that is closely related to the training system but evolves from one year to the next as pruning, training, thinning practices, etc. (Costes et al., 2006).

PH relies heavily on technology: Righetti and Halbleib (2000) used both internet and spreadsheet/computer software to manage and assess the information flow in an orchard. Also investigations into the spatial yield variability and other fruit quality parameters in pipfruit (Praat et al., 2000; Gillgren, 2001; Aggelopoulou et al., 2007), kiwifruit (Woodward et al., 2007; Taylor et al., 2007a), citrus (Qiao, 2005, Annamalai et al., 2004) and other fruit crops (Pettygrove et al., 1999; Plana et al., 2002; Sepulcre-Cantó et al., 2007) have been undertaken. This literature is directed at quite a wide range of fruit and vegetables, however variety knowledge is still lacking to quantify the variability both within season, at harvest and post-harvest in many horticultural crops.. It is clear that the earlier any estimation of crop status can be made, the more useful such knowledge becomes for the management of the orchards. Monitoring crop progress and other parameters is indeed important for making real-time decisions management, particularly for thinning and harvest. Remote sensing has shown to be one method of gathering within season on crop status in broadacre (Chang et al., 2003; Shepers et al., 2004) as well as viticultural (Lamb et al., 2004) and horticultural (Ye et al., 2006, Sepulcre-Cantó et al., 2007) crops.

Spatial variation is to be expected in all of agriculture (McBratney and Pringle, 1999) and in horticulture as well (Taylor et al. 2007a).

PH offers a the possibility of a differential management strategy in complicated and complex horticultural system (fig. 3), giving the growers who are aware of quality and quantity variation in their fields options to improve performance, and making it possible to obtain quality with less inputs, i.e. reducing costs and increasing sustainability.

## 1.4 Precision Agriculture and Horticulture Requirements

The development of PA and PH relies on technologies and methodologies that have become increasingly available in recent years. Often, early applications of PA have been based on zone management. The identification and management of regions within the geographic area that can be defined as a management zone or a management class strategy. A management class is the area to which a particular treatment may be applied. A management zone is a spatially contiguous area to which a particular treatment may be applied (Taylor et al., 2007b). A management class (fig. 6) typically consists of numerous zones, whereas a management zone can contain only one management class (Taylor et al., 2007b). Generating management zones is often quite difficult because it can be complicated by different factors, such as: which information should be used to differentiate the zones; how to analyze and integrate the information into a unique management unit; is there any limit in number of managing zones in a field (Fridgen et al., 2004).

The development of decision support systems (DSS) has lagged behind technological development and is usually the bottleneck which impedes the adoption of PA (Tisseyre et al., 2007). Different protocols, methodologies and differential indexes have been proposed in the literature. For example, Pringle et al., (2003) proposed an opportunity index to asses SSCM while Fridgen et al., (2004 (MZA Software)) and Taylor et al., (2007b) suggest a protocol to asses SSCM in fields crops; Kitchen (2008) proposed an integrated view of the technologies available.

Generally the PH and PA approach can be conceptualized in a “wheel” (Fig. 1) from which five main points can be extrapolated:

- Georeferencing
- Monitoring environmental and crop quality parameters
- Data analyzing
- Decision making
- Differential actions

### 1.4.1 Georeferencing

Georeferencing allows information within a field/row to be given a discrete spatial location. This is usually done using one of two systems, the NAVSTAR Global Positioning System (GPS), which is the most ubiquitous and is owned and operated by the government of the United States of America, and the Global Navigation Satellite System (GLONASS), controlled by the Russian Government. Two other systems (not totally functioning yet) are the European Space Agency’s Galileo system, and one lunched by a Japanese consortium while China has plans to build up its own satellite system by 2015. The accuracy of geolocation depends on the quality of the receiver and the satellite signals. In the GPS system, 24 satellites are in orbit, each of which have an atomic clock, and create a constellation. Time synchronization of the coded signals transmitted by the satellites allows receivers on Earth to compute their distance from each satellite currently in view. At least three satellites (good results are given from five) must be visible for a receiver to be able to compute its position on the Earth surface. Several errors are inevitable, due to satellite errors, receiver errors, atmospheric errors, multipath errors and from the satellite geometry and can be reduced by various corrections (Auernhammer, 1994). Normally in PA/PH applications the geolocation is done with a differential GPS (DGPS) receiver that has an accuracy of approximately one meter. A field-level geographic information system which couples field data with georeferencing, has been developed (Zhang et al., 1999). This system provides special analytical functions useful for research in precision farming. Others PA-GIS (specially devised GIS for PA), such as SST, AgLink, AGIS, RedHen etc. are also available. A key requirement of this type of software, besides ease of use, is the ability to handle yield-monitor data well and to write the appropriate files for variable-rate controllers (McBratney and Whelan, 2001).

### 1.4.2 Monitoring Environmental and Crop Parameters

In the literature there are many examples of sensors and monitors that already exist to measure a variety of crop, soil and climatic variables. To review them all would be a chapter in itself. This section will focus on applications targeted specifically at perennial horticultural crops.

One of the best indicators of crop development is the canopy (biomass) of the plant. In various crops canopy sensors, often based on the Normalized Difference Vegetation Index (NDVI) have shown spatial variation in horticultural and viticultural fields. A direct application of canopy sensing is demonstrated by CropMaps, (http://cropmaps.com/?p=3a), which estimates apple yields by quantifying with aerial or satellite images the canopy density for an entire orchard. And taking advantage of the relationship between apple yield and light interception published by Wünsche and Lakso (2000). At a finer scale Monestiez et al., (1990) applied geostatistics and spatial dependences to describe fruit position in a tree, in effect building a “cartography” of the entire tree. That approach has been the driver for many other studies of fruit tree training systems and architecture and their relations to fruit quality (Smith et al., 1992; De Silva, 2000; Costes, 2006). As a follow-up of this work, optical sensors and digital imaging systems have been studied for fruit counting and yield monitoring (Regunathan and Lee, 2005; Stajnko et al., 2004), although they are still a bit far from field adoption due to calibration accuracy problems. Optical sensors of leaf chlorophyll content as an indicator of photosynthesis have also been used to measure and map nitrogen concentration in response to fertilizer application (Haboudane et al., 2002).

An interesting, low cost sensor of fruit growth during the season, suitable for monitoring plant water stress has been also proposed (Morandi et al., 2007). Sepulcre-Cantò et al., (2007) monitored water stress on olive and peach trees and found that stress can be detected in orchards even when they are subjected to a “correct” water management scheme. Zude et al., (2008) exploit near-infrared spectroscopy (NIRS) on citrus to evaluate the soluble solids content demonstrating that non-destructive sensors can be integrated within PH.  A precision system to asses the variable-rate application of agrochemicals, nutrients and water, according to specific needs of each individual plant exploiting precision spraying by matching spray volume to tree size and foliage density has also been developed (Hetzroni et al., 2003)

#### 1.4.2.1 Data transfer

One of the issue of PA is the data transfer from the sampling location to the analysis tools. Many technologies are available on the market to achieve this. Wireless sensors are an important sector due to their increasing importance. This technology includes infrared light (IrDA) and Bluetooth protocols for short-range, multi-hop wireless local area network (WLAN) for mid-range and cellular phone systems, such as GSM/GPRS, for long distance communications. It has been used in PA to assist in spatial data collection manage, precision irrigation systems, variable rate treatment and for supplying data to farmers (Wang et al., 2006).

Increasing in importance for ductility is mesh networking. This is a way to route data, voice and instructions between nodes. It allows for continuous connections by “hopping” from node to node until the destination is reached. Mesh networks differ from other networks in that the component parts can all connect to each other via multiple hops, and they generally are not mobile. Mesh networks are self-healing: the network can still operate even when a node breaks down . This concept is applicable to wireless networks, wired networks, and software interaction.

Another key data transferring tool is the RFID (radio frequency identification). This is a dedicated short range communication (DSRC) technology, which encompasses various technologies that use radio waves to automatically identify objects. RFID technology is similar to bar code identification systems; however RFID does not rely on the line-of-sight reading that bar code scanning requires.

Although this wide range of technologies makes for a formidable weaponry, PH remains a study needing human inputs. Computers and data collection give an automated and objective point of view, but there always remains a need of best interpreting the analysis before implementing a strategy.

### 1.4.3 Data analyzing

Spatial data need spatial statistic (geostatistics). A common method for the modeling and estimation of spatial patterns is the semivariogram (or variogram). This is an analytic tool used to describe the relationship between variables at several discrete distance intervals from a specific point of the field/orchard (Rossi et al., 1992).

Experimental variogram estimation can be performed with a wide range of software programs, one of which is VESPER (Minasny et al., 2005). With this software both the experimental and theoretical variogram can be determined and fitted. The theoretical variogram provides parameters, $c_0$, $c_1$, and $r$, to describe the spatial variation (Fig. 5). As described by Taylor et al., (2007a), the $c_0$ (the nugget) estimates the amount of variance at a lag distance of 0 m and is a function of stochastic effects and measurement errors. The $c_1$ value estimates the amount of autocorrelated variance in these data and contributes with $c_0$ to define the sill ($c_0 + c_1$) or the total amount of variance in these data. The range ($r$) defines the distance over which data are autocorrelated, i.e. the distance at which the sill is reached. To provide some indication of spatial structure the Cambardella Index (Cambardella et al., 1994) can also be calculated. This index is a ratio between the nugget ($c_0$) and the sill ($c_0+c_1$) that indicates the quantity of autocorrelated variance and subsequently the amount of variation that is potentially manageable.

Semivariogram models provide the necessary information for kriging, which is a method of interpolating data at unsampled points. Kriging differs from other types of interpolation in that it provides a measure of error associated with each predicted value (Rossi et al., 1992; Cupitt and Whelan, 2001). Maps of kriged estimates provide a visual representation of the arrangement of the population and can be used to interpret spatial trends in variation. Finally the data interpolation can be represented and mapped in desktop professional GIS packages, such as ArcView and MapInfo.

Other interpolation methodology include Inverse Distance Weighting (IDW) and the Nearest Neighbor (NN). The first is based on the assumption that the nearby values contribute more to the interpolated values than distant observations . In other words, for this method the influence of a known data point is inversely related to the distance from the unknown location that is being estimated. The advantage of IDW is that it is intuitive and efficient. This interpolation works best with evenly distributed points. The NN simply uses the value from the closest sampling point and is most useful for mapping nominal data. With continuous data it produces a highly discontinuous interpolation map.

### 1.4.4 Decision Making

Many protocols of data analysis for decision support system (DSS) have been described in PA for generating management zones and for generating variable rate input maps. Taylor et al., (2007b) described a protocol developed at the Australian Centre for Precision agriculture (ACPA) to assess the data flow coming from a field crop. The protocol quantifies and locates potential management classes using multivariate clustering of layers such as soil apparent electric conductivity (ECa) maps, crop yield maps, and digital elevation models These MCs form the basic for the direction of soil/crop sampling and analysis to investigate the practical causes of variation and to interpret test results and to issue prompt remedial actions, if warranted.

Variability management can be achieved by two approaches: either a map-based approach or a real-time “on-the-go” sensor-based approach (Zhang et al., 2002). The former is normally easier to use as the decision process can be done over-time and with consultation with the grower and agronomist. The latter technically does not require a positioning device as the sensing, decision support and application are done in real-time during the management operation. However a positioning device is recommended to be able to spatially record the measured and applied response.

At the field production level a number of models have been developed to improve the production/quality of horticultural crops. The purpose of models, programs and protocols designed for operational management support range from tree and pest management to fertilizer and water recommendation and timing, etc. The techniques used for implementing these tools encompass optimal control theory, regression models, dynamic simulation models, including expert systems (Lakso et al., 1995; Grossman and Dejong, 1995; Genard et al., 2007; Morandi et al., 2008). By applying in real time the appropriate technologies a seamless information system can, in theory, be a formed for horticultural products that will track fruit from the tree to the retail market (Bollen et al., 2001). This DSS would have the potential to bring the information back to the whole chain, from the marketers to the producer highlighting bottle necks along the chain (fig. 4). A similar PH protocol will transform data with spatial and temporal interpretation into powerful knowledge tools (Praat et al., 2001). One of the main challenges for pH is to take these field based DSS and apply them spatially within the production systems.

A caveat with any DSS could read: ‘‘Models that are developed by researchers and then left to the commercial world are unlikely to succeed in the long term. There are always problems and modifications needed’’ (Kearney, 1992). Information and analysis systems provide a collection of methods and techniques to represent parts of the ‘real world’ in a ‘formal world’ (Lenz, 1998), making the use of DSS more and more difficult when a combination of simulation and optimization methods is implemented and a link with the creativity and intuition of the grower/consultant is necessary.

Despite the increasing research and development in the area of DSS in horticulture, the experience is that most of the available DSS are not widely used by farmers. Some conditions essential to implement a DSS include (Lenz, 1998):

- The system must convince the researchers and be trusted by its users
- It must be capable of adapting to changing conditions and requirements
- The various components of the information system must be streamlined to provide support to the systems user

### 1.4.5 Differential actions

Differential action in agriculture/viticulture/horticulture is often translated in Variable Rate Technology (VRT), an application system matching management practices with the field location(s) where they are needed. In the case of PH, VRT applies to water, fertilizer and agrochemical application, canopy management (pruning and/or thinning). An add value behind VRT is to increase inputs to areas highly lacking them or willing productivity (to improve quality), and decrease them in areas where they are not necessary. VRT has received widespread attention in PA research and from the mid 1990s is probably the best developed part of the PA cycle (Searcy, 1995).

VRT represent somehow the most advanced and effective use of the precision management techniques that have evolved from research in this field examples of interesting solutions exist for PV, but the fruit sector is lacking behind. There are several reasons why this may be so, including the fact that fruit trees have a more complex structure and larger canopy then grape vines; that for fruit the quality attribute of each individual fruit matters; that in general greater variability in fruit ripening, size and color is formed in fruit then in grape.

## 1.5 Conclusion

The literature regarding the application of PA to horticulture is not strong. Horticulture encompasses a wide variety of different genotypes and production systems which are much more complex than the genetic and production diversity in broadacre crops. This is probably the main factor that has slow down PH development comparing to PA. Examples of this are given by the fact that principally PA treats with cereals as grain, corn, barely and other field crops as soybean, cotton. In fact even this crops have different characteristics and treatment strategies this are just few compared with all the different managing techniques and problem to study and overcome in fruit crops. The three dimensional shape, the perennial behavior, the irrigation schedule, the hand harvesting, the intensive management practices and the quality answer from the market are just few of the variable to connect and overcome during data recording and interpreting in the fruit crop production.

Particularly lacking in fruit are tools supporting the growers on decisions related to the control in real-time of the crop load, fruit growth, and forecast of orchard yield and its distribution in size classes. Again, this is due to inherent difficulties nested in the peculiarities of fruit species.

The present thesis is concerned with addressing some of the issues that hinder the application of VRT to fruit (apple) species.

## 1.6 Bibliography

Aggelopoulou, K.D., D. Pateras, S. Fountas, T.A. Gemtos and G.D. Nanos. 2007. Soil spatial variability in small Greek apple orchards. 6th European Conference on Precision Agriculture, June 3-6, 2007.

Adrian, A. M., S. H. Norwood, and P. L. Mask. 2005. Producers’ Perceptions and Attitudes toward Precision Agriculture Technologies. Computers and Electronics in Agriculture. 48, 256-271.

Annamalai, P., and W. S. Lee. 2004. Identification of green citrus fruits using spectral characteristics. ASABE Paper No. FL04-1001. St. Joseph, Mich.: ASABE.

Auernhammer, H. 1994. GPS in Agriculture. Computer and Electronics in Agriculture. 11, 1, special issue.

Barritt, B. H. 1992. Intensive orchard management. Good Fruit Grower. Yakima, Washington, USA.

Berry, J.K. 1995. Implications of a Humane GIS. Association for Geographic Information, London, England, 1995, pages 57-62.

Bollen, A.F., Praat, J.P., and Yule, I. 2001, "Precision horticulture: progress, opportunities and requirements in the supply chain", First Australian Geospatial Information and Agriculture Conference, Sydney, Australia, 17-19 July 2001.

Bongiovanni, R. and Lowenberg-Deboer J. 2004. Precision Agriculture and Sustainability. Precision Agriculture, 5, 359–387.

Cambardella, C.A., T.B., Moorman, J.M., Novak T.B.,, Parkin, D.L., Karlen, R.F., Turco, and A.E., Konopka. 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58, 1501–1511.

Capraro, F., Patifio, D., Tosetti, S., and Schugurensky, C. 2008. Neural Network-Based Irrigation Control for Precision Agriculture. International Conference on Networking, Sensing and Control. 6-8 April 2008. 357–362.

Chang, J., Clay, D.E., Dalsted, K., Clay, S., and O’Neill, M. 2003 Corn (*Zea mays* L.) Yield Prediction Using Multispectral and Multidate Reflectance. Agron. J. 95, 1447–1453.

Costes, E., Lauri, P.E., Regnard, J.L.. 2006. Analyzing Fruit Tree Architecture: Implications for Tree Management and Fruit Production. Horticultural Reviews. 32, 1-61.
Cox, S. 2002 Information technology: the global key to precision agriculture and sustainability. Computer and Electronics in Agriculture. 36, 93-111.

Cupitt, J. and Whelan, B.M. 2001. Determining potential within-field crop management zones. In: G. Greinerand S. Blackmore (eds.). Proceedings of the Third European Conference on Precision Agriculture. June 18-20, 2001, Montpellier, France. pp7-12.

De Silva, H.N., Hall, A.J., Cashmore, W.M., Tustin, D.S., 2000. Variation of fruit size and growth within an apple tree and its influence on sampling methods for estimating the parameters of mid-season size distributions. Ann. Bot. 86, 493–501.

Fernandez-Cornejo, J, Daberkow, S and McBride W.D. 2001 Decomposing the size effect on the adoption of innovations: agrobiotechnology and precision agriculture. Agbioforum. 4-2. 124-136

Florin, M., A.B. McBratney, and B.M. Whelan. 2008. Inverse meta-modelling of yield monitor data for estimation of soil available water capacities at a spatial resolution of 10 metres across farms. In: Proceedings of the 1st Global Workshop on High Resolution Digital Soil Sensing and Mapping. ACPA, Sydney, Australia, p. 10.

Fridgen, J.J., Kitchen, N.R., Sudduth, K.A., Drummond, S.T., Wiebold, W.J. and Fraisse C.W. 2004. Management Zone Analyst (MZA): Software for Subfield Management Zone Delineation. Agron. J. 96:100–108.

Génard, M., Bertin, N., Borel, C., Bussières, P., Gautier, H., Habib, R., Léchaudel, M., Lecomte, A., Lescourret, F., Lobit, P., and Quilot, B. 2007. Towards a virtual fruit focusing on quality: modelling features and potential uses. Journal of experimental botany 58, 917-28.

Gillgren, D. 2001. Finding the fruit: A spatial model to access variability within a kiwifruit block. Proceeding of 13th Annual Conference of the Spatial Information Research Centre. University of Otago, Dunedin, New Zealand, 2–5 Dec. 2001

Grossman, Y. L. and T. M. Dejong. 1995. Maximum fruit growth potential following resource limitation during peach growth. Annals of Botany. 75, 561-567

Haboudane, D., Miller, J.R., Tremblay, N, Zarco-Tejada, P.J., and Dextraze, L., 2002: Integration of Hyperspectral Vegetation Indices for Prediction of Crop Chlorophyll Content for Application to Precision Agriculture, Remote Sens. of Environ., 81, 416-426.

Hetzroni, A., Meron, M., and Fatiev, V.2003. Pest management module for tree-specific orchard management GIS as part of the PRECISPRAY project. Proceedings of the 4th ECPA. 291-296.

Kearney, M., 1992. User requirements of computer models in Decision Support Systems in orchards. Acta Horticolture. 313, 165–171.

Kitchen N.R. 2008 Emerging technologies for real-time and integrated agriculture decisions. Computers and Electronics in Agriculture 61, 1-3

Lakso A.N., L., Corelli Grappadelli, J., Barnard, and M.C., Goffinet 1995. An expolinear model of the growth pattern of the apple fruit. J. Hort. Sci. 70, 389–394

Lamb, D.W., Weedon, M.M. and Bramley, R.G.V., 2004. Using remote sensing to predict grape phenolics and colour at harvest in a Cabernet Sauvignon vineyard: Timing observations against vine phenology and optimising image resolution. Australian Journal of Grape and Wine Research 10, 46–54.

Lentz, W. 1998. Model applications in horticulture: a review. Scientia Horticulturae. 74, 151–174.

Maohua, W. 2001 Possible adoption of precision agriculture for developing countries at the threshold of the new millennium. Computer and Electronics in Agriculture. 30, 45-50.

McBratney, A.B. and M.J., Pringle 1999. Estimating average and proportional variograms of soil properties and their potential use in precision agriculture. Precision Agr. 1, 125–152.

McBratney, A.B. and Taylor, J.A. 2000. "PV or not PV" . Precision Management Workshop. Proceedings of the 5th International Symposium on Cool Climate Viticulture and Oenology, January 16-20, 2000, Melbourne, Australia.

McBratney, A.B. and Whelan, B.M. 2001. Precision Ag - Oz style. Proceedings of the 1st Australian Conference on Geospatial Information in Agriculture, NSW Agriculture pp 274-282.

Minasny, B., A.B., McBratney and B.M., Whelan. 2005. VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW. 2006. <www.usyd.edu.au/su/agric/acpa>.

Miranda Jiménez, C. and J. B., Royo Díaz 2004. Statistical model estimates potential yields in 'Golden Delicious' and 'Royal Gala' apples before bloom. J. Am. Soc. Hort. Sci. 129, 20–25.

Monoestiez, P., Habib. R., Audergon, J.M. 1990. Geostatistics, spatial dependencies in a tree A new approach in fruit tree studies. Acta Horticulture. 276, 257-263

Morandi, B., Rieger, M., and Corelli Grappadelli, L. 2008. Vascular flows and transpiration affect peach (prunus persica batsch.) fruit daily growth. J. Exp. B. 248, 1-7.

Morandi B, Manfrini L, Zibordi M, Noferini M, Fiori G, Corelli Grappadelli L. 2007b. A low-cost device for accurate and continuous measurements of fruit diameter. HortScience 42, 1380–1382.

Mueller,T. G., Pierce, F. J., Schabenberger, O. and Warncke D. D. 2001.Map Quality for Site-Specific Fertility Management. Soil Sci. Soc. Am. J. 65, 1547–1558

Pettygrove, G.S., Upadhyaya, S.K., Young, J.A., Miyao, E.M. and Pelletier M.G. 1999. Tomato Yield Variability Related to Soil Texture and Inadequate Phosphorus Supply. Better Crops. 83, 2.

Pierce, F.J., D.D. Warncke, and M.W. Everett. 1995. Yield and nutrient availability in glacial soils of Michigan. p. 133–151. In P.C. Robert, et al. (ed.) Proc. of the Int. Conf. on Site Specific Management for Agricultural Systems, 2nd. Bloomington/Minneapolis, MN. 27–30 Mar. 1994. ASA, CSSA, and SSSA, Madison, WI.

Pierce, F.J., Nowak, P., 1999. Aspects of precision agriculture. In: P.L. Sparks (Ed.) Advances in Agronomy, vol. 67. pp. 1-85.

Pierce, F.J., P.C. Robert, and G. Mangold. 1994. Site-Specific Management: The Pros, the Cons, and the Realities. Pp. 17-21. In: Proceedings of the International Crop Management Conference, Iowa State University, Ames, Iowa.

Plana, V., Ruiz, A., Ruiz-Sanchez, M.C., Franco, J.A. and Abrisqueta, J.M. 2002. Spatial representativity of the possible sites for measuring the water balance of apricot trees. Agricultural water management. 57, 145-153.

Praat, JP., A.F., Bollen, I.J., Yule and C., Empson 2000. Applied Information Management Systems. Conference Proceedings from Achieving change through improved knowledge systems. Centre for Agricultural and Veterinary Continuing Education, Massey University. Palmerston North, New Zealand. 281–288

Praat, JP., Bollen, F. & Yule, I. 2001. Precision Horticulture: Progress, Opportunities and Requirements in the Supply Chain. Proceedings of 5th Annual Symposium, Geospatial Information and Agriculture, Sydney, Australia. 17-19 July.

Pringle, M. J., A. B., McBratney, B. M., Whelan and J. A., Taylor. 2003 . A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. Agr. Systems. 76, 273–292.

Qiao, J., A., Sasao, S., Shibusawa, N., Kondo, and E. , Morimoto. 2005. Mapping yield and quality using the mobile fruit grading robot. Biosystems Eng. 90, 135–142

Regunathan, M. and W. S., Lee 2005. Citrus Fruit Identification and Size Determination Using Machine Vision and Ultrasonic Sensors. ASAE Meeting. Paper No. 053017. St. Joseph. Mich. : ASAE.

Reuter, H.I., Kersebaum K.C., and Wendroth O. 2005 Modelling of solar radiation influenced by topographic shading—evaluation and application for precision farming. Physics and Chemistry of the Earth. 30,1-3 143-149

Righetti, T. L., Halbleib, M. D. 2000. Pursuing precision horticulture with the internet and a spreadsheet. HortTechnology. 10 (3):458-467

Robert, P. 1999. Precision Agriculture: Research needs and status in the USA. In: J.V. Stafford (ed.). Precision Agriculture ’99: Proceedings of the Second European Conference on Precision Agriculture. July 11-15, 1999, Odense Congress Centre, Denmark. pp19-33

Rossi, R. E., Mulla, D. J., Journel, A. G., & Franz, E. H. 1992. Geostatistical tools for modeling and interpreting ecological spatial dependance. Ecological Monographs. 62, 277-314.

Schepers, A.R. Shanahan, J.F., Liebig, M.A., Schepers J.S., Johnson S.H., and Luchiari Jr, A. 2004. Appropriateness of Management Zones for Characterizing Spatial Variability of Soil Properties and Irrigated Corn Yields across Years. Agron. J. 96:195–203.

Schueller, J.K., J.D., Whitney, T.A., Wheaton, W.M., Miller and A.E., Turner. 1999. Low-cost automatic yield mapping in hand-harvested citrus. Computers Electronics Agr. 23, 145–154.

Searcy, S.W. 1995. Engineering Systems for Site-specific Management: Opportunities and Limitations. In : P.C. Robert, R.H. Rust and Larson, W.E. (eds). Proceedings of the Second International Conference on Site-Specific Management for Agricultural Systems, March 27-30, 1994, Thunderbird Hotel, Minneapolis, MN.

Sepulcre-Cantó, G., Zarco-Tejada, P.J., Jiménez-Muñoz, J.C., Sobrino, J.A., Soriano, M.A., Fereres E., Vegad V., Pastor, M. 2007. Monitoring yield and fruit quality parameters in open-canopy tree crops under water stress. Implications for ASTER. Remote Sensing of Environment 107, 455–470.

Smith, G. S.; Curtis, J. P.; Edwards, C. M. 1992. A method for analysing plant architecture as it relates to fruit quality using three-dimensional computer graphics Annals of Botany. 70,265-269.

Stajnko D., M., Lakota and M., Hočevar. 2004. Estimation of number and diameter of apple fruits in an orchard during the growing season by thermal imaging. Computers Electronics Agr. 42, 31–42.

Taylor, J.A., JP., Praat and A.F., Bollen. 2007a. Spatial Variability of Kiwifruit Quality in Orchards and Its Implications for Sampling and Mapping. HortSci. 42, 246–250.

Taylor, J. A., A. B., McBratney, and B. M., Whelan. 2007b. Establishing management classes for broadacre agricultural production. Agron. J. 99,1366–1376

Tisseyre, B., H., Ojeda and J.A., Taylor 2007. New technologies and methodologies for site-specific viticulture. J. Int. Sci Vigne. Vin. 41, 63–76.

Wang, N., Zhang, N., Wang M. 2006.Wireless sensors in agriculture and food industry—Recent development and future perspective. Computers and Electronics in Agriculture. 50, 1–14

Webster, R., and Oliver, M.A. 1992. Sample adequately to estimate variograms of soil properties. Journal of soil science 43,177-192

Whelan, B.M. AND McBratney, A.B. 2000. The null hypothesis of precision agricolture management. Precision Agriculture, 2, 265-279.

Whithney, J.D., W.M., Miller, T.A.,Wheaton, M., Salvani, and J.K., Schueller 1999. Precision farming: applications in Florida citrus. App. Eng. Agr. 15, 399–403.

Wilson, J.N. 2000. Guidance of agricultural vehicles — a historical perspective. Computer and Electronics in Agriculture. 25. 3–9.

Woodward, T.J., Green, T. G. A., and Clearwater M. J. 2007. Between-vine Variation in ‘Hayward’ Kiwifruit Vine Income: The use of Lorenz curves and Gini Coefficients to

Describe Variation and Assess the Potential for Zonal Management. Europ.J.Hort.Sci., 72 (6). 280–287

Wünsche, J.N. and A. N. Lakso. 2000. Apple tree physiology - implications for orchard and tree management. Compact Fruit Tree 33, 82-88.

Ye, X., Sakai, K., Ortega Garciano,L., Asada, S.I., Sasao A. 2006. Estimation of citrus yield from airborne hyperspectral images using a neural network model. Ecological modelling. 198, 426–432.

Zhang, N., Runquist, E., Schrock, M., Havlin, J., Kluitenburg, G. and Redulla C. 1999. Making GIS a versatile analytical tool for research in precision farming. Computers and Electronics in Agriculture 22, 221–231.

Zhang, N., Wang, M.,Wang, N. 2002. Precision agricolture - a worldwide overview. Computers and Electronics in Agriculture 36, 113-132.

Zude, M., Pflanz, M., Kaprielian. C.,, Bryan L. Aivazian B.L. 2008. NIRS as a tool for precision horticulture in the citrus industry. Biosystem Engineering. 99, 455–459.

## 1.7 Figures and Tables

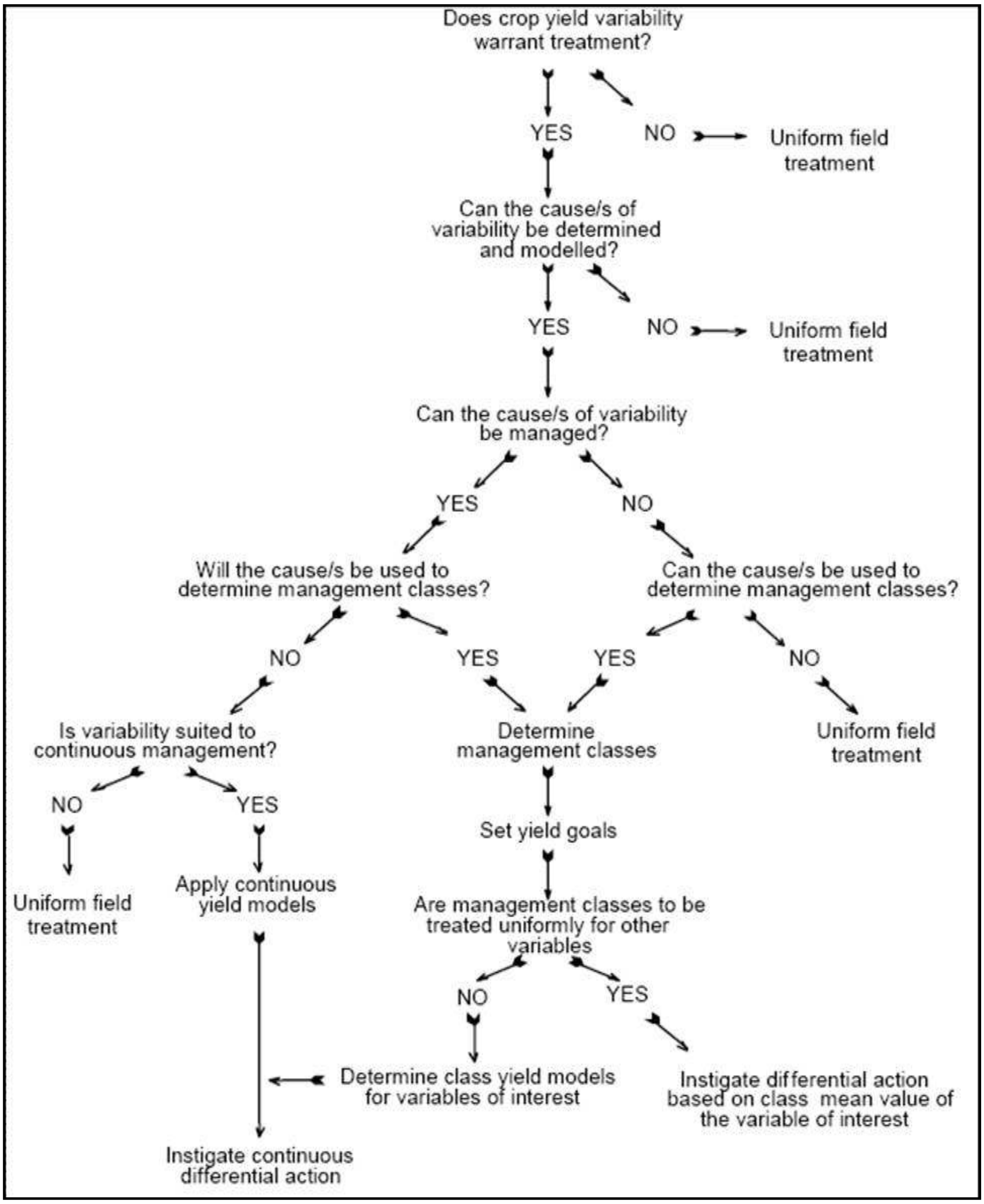


Fig. 1 Model tree for site specific crop management. A simple model based on the economic imperative (http://www.usyd.edu.au/su/agric/acpa/pag.htm)

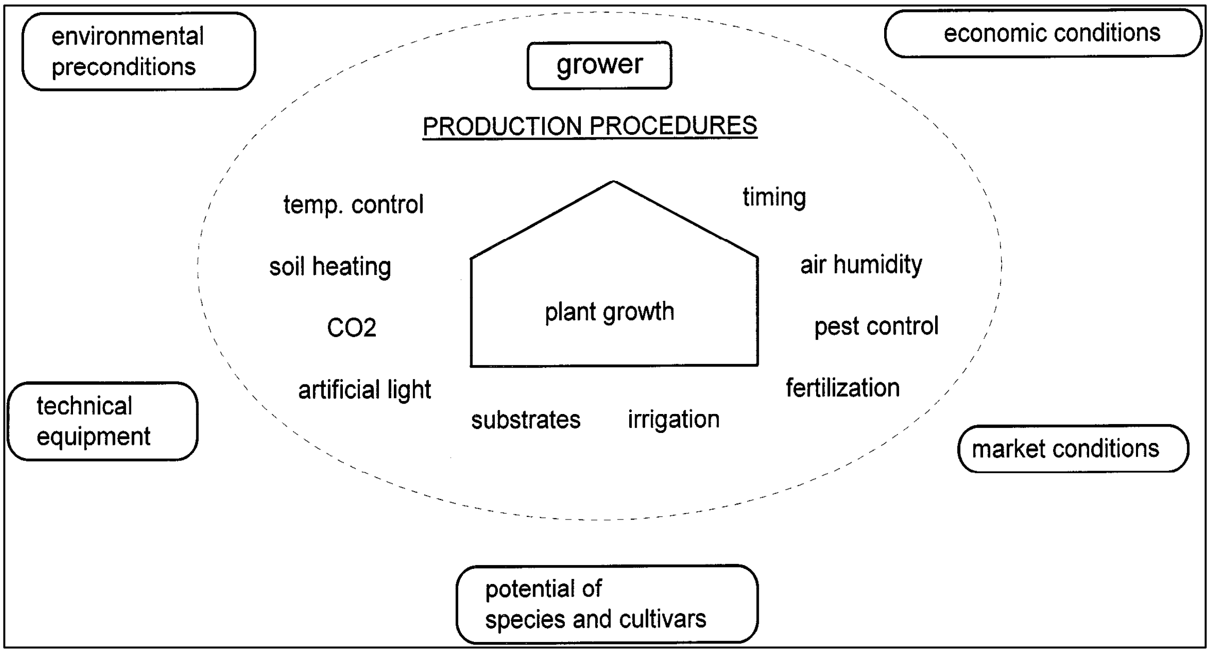


**Fig. 2 Situation of a grower in a complicated and complex system (according to Krug, 1989)**

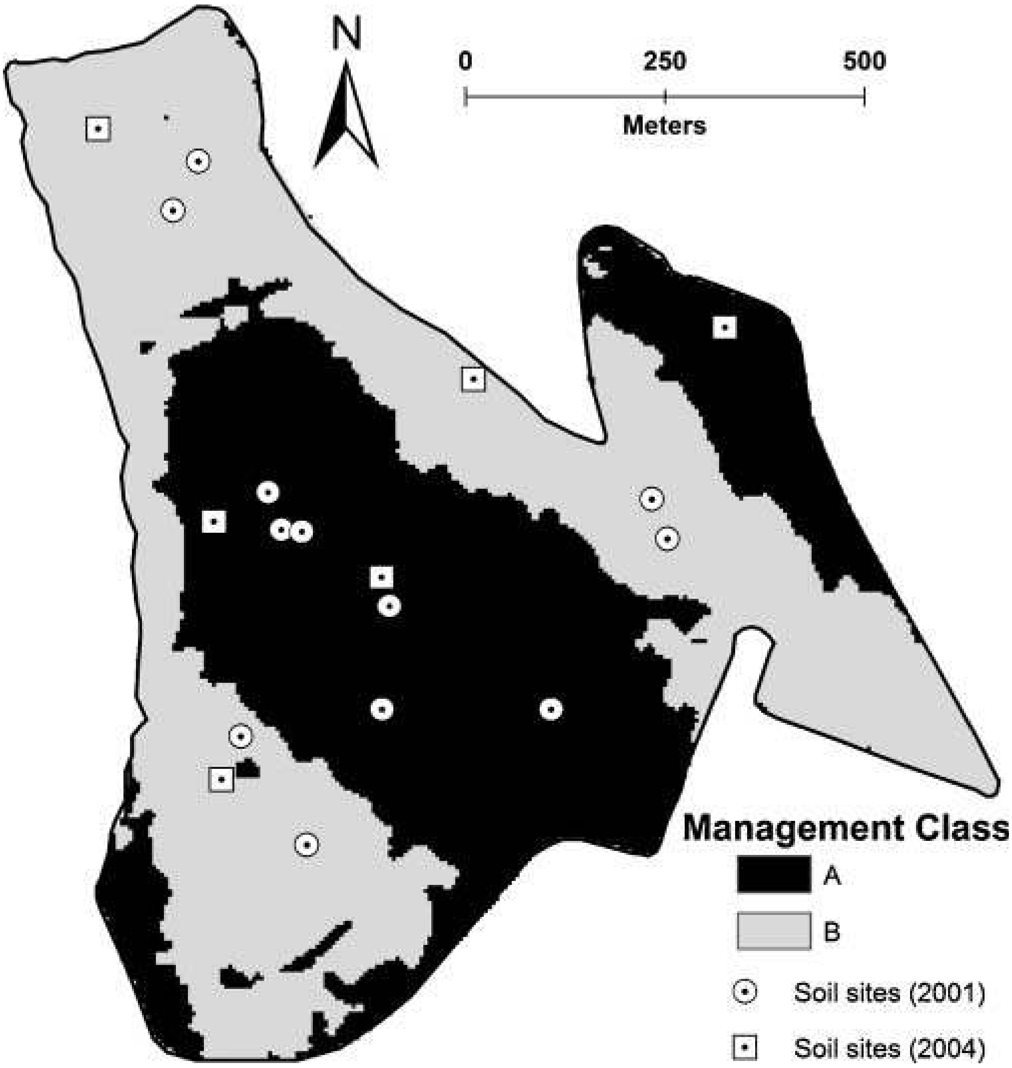


**Fig. 3 Example of two management class map overlain with the stratified soil sample locations**

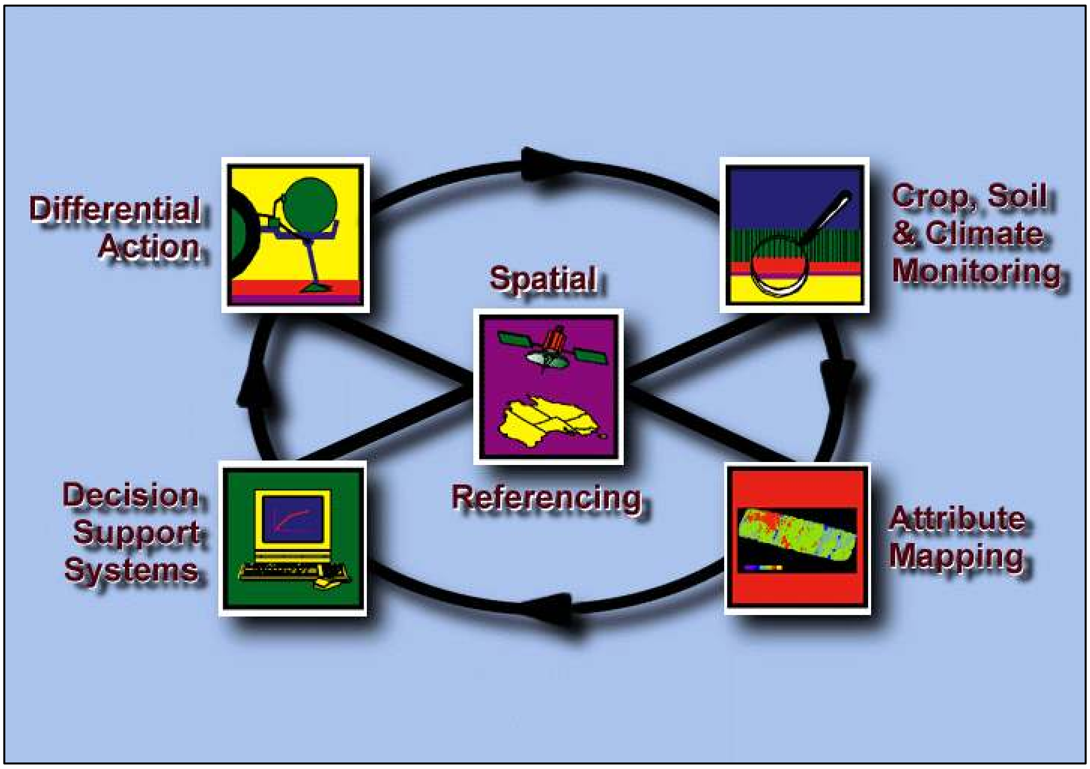


**Fig. 4 The Precision Agriculture wheel model showing the five main processes for a site-specific management system (courtesy of the Australian Centre for Precision Agriculture, http://www.usyd.edu.au/su/agric/acpa).**

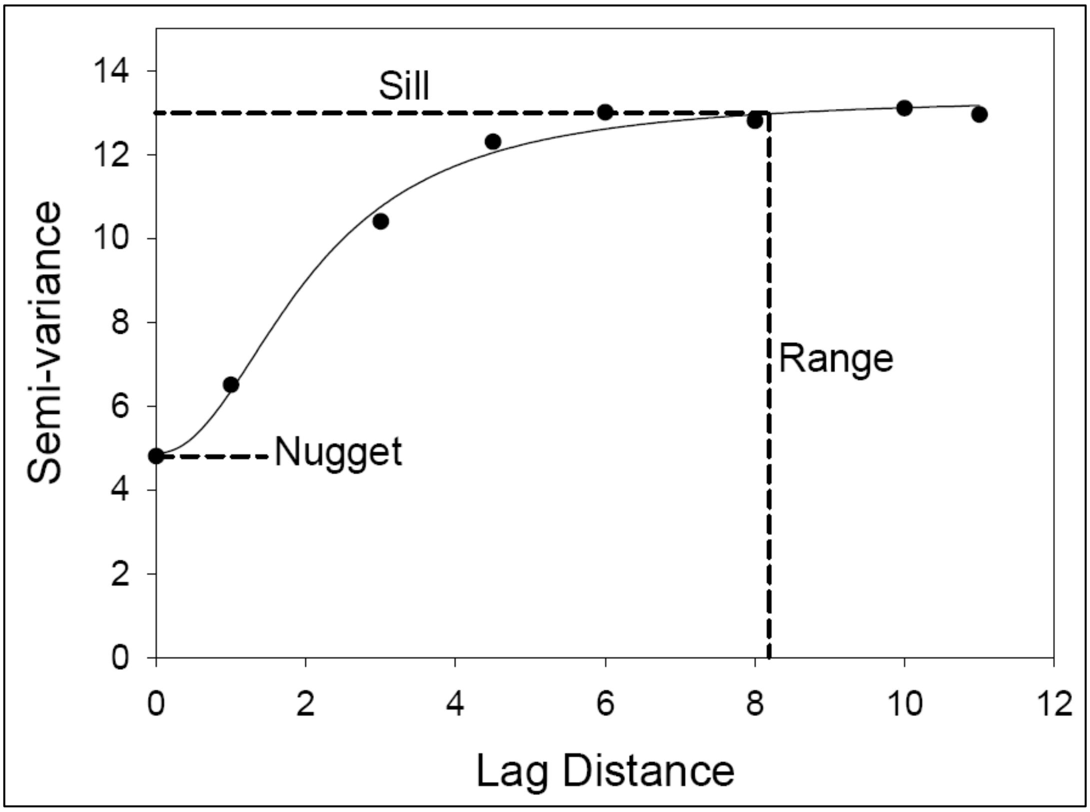


**Fig. 5 Example of experimental semivariogram. The spatial relationship described by a fitted model illustrate the Nugget, Sill and Range.**

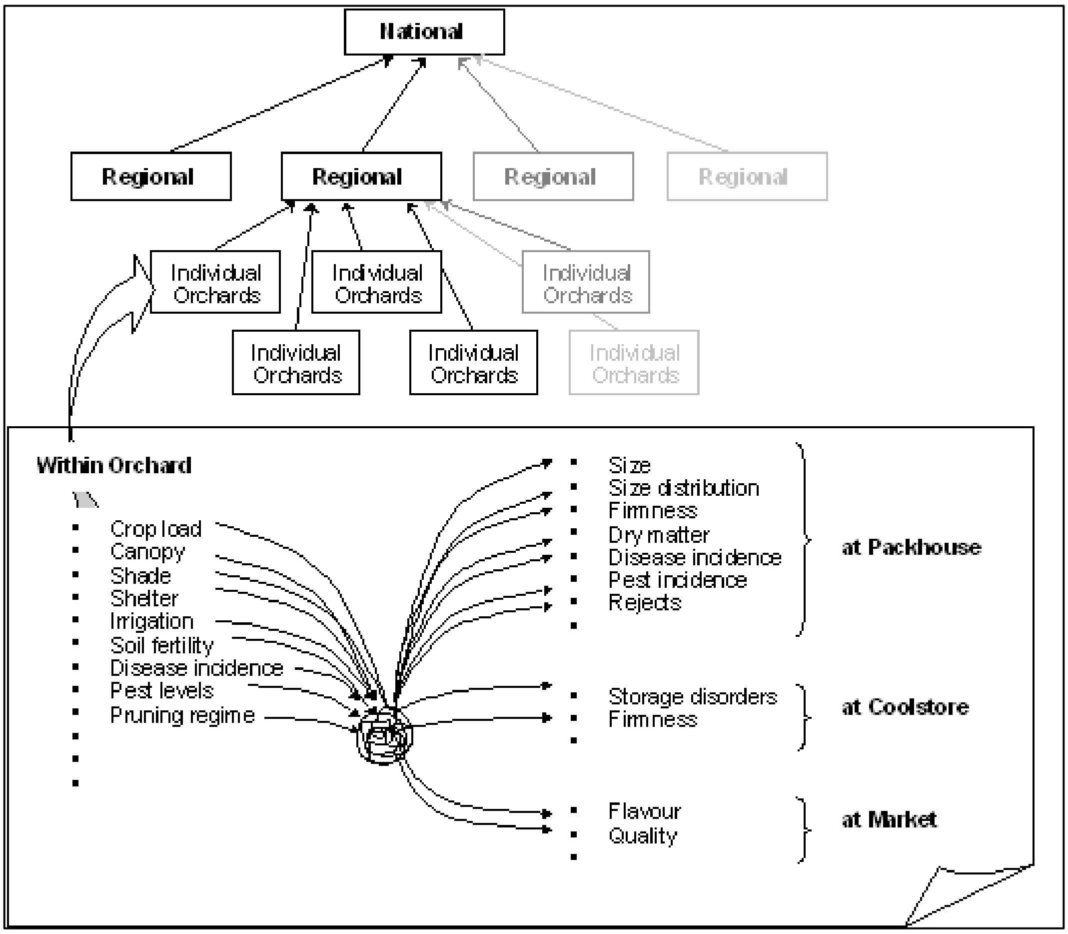


Fig. 6 Fruit quality and orchard operation information structure (from Bollen et al., 2001)

# CHAPTER 2

# SPATIAL ANALYSIS OF THE EFFECT OF FRUIT THINNING ON APPLE CROP LOAD

## 2 Summary

There has been very little literature on the mid season spatial variability of fruit production in horticulture crops published to date. Most of the existing literature refers to data collected post-harvest. Crop load data taken prior to hand thinning and prior to harvest were collected in 3 blocks of a commercial apple (*Malus domestica* Borkh.) orchard in the province of Ferrara, Italy. The purpose of the survey was to characterize the within field variability of crop load, using spatial statistics, and assess the effectiveness of the hand-thinning treatment. Crop load estimations were taken at 156 sites pre and post hand-thinning over a defined distance (0.8 m) and the data used to model a variogram and associated spatial., Variation in the spatial distribution of the fruit load prior to the hand-thinning was observed, indicating a possibility to spatially differentially manage the orchard. No spatial variation in fruit number was observed prior to harvest (post thinning), indicating that thinning had removed the previously observed spatial variation in crop load. Under the current uniform management approach this indicates that thinning has been effective implemented. However, the spatial variation observed prior to thinning may indicate that a differential crop load management strategy may be optimal for maximizing quality in the orchard.

## 2.1 Introduction

For any crop production system the most relevant source of information available to a producer is on-site information specific to their system (Whitney et al., 1999). Despite this, the recording of objective crop development information is not a common practice in many horticulture crops (Schueller et al., 1999). Orchard management is frequently based on a grower's experience and subjective knowledge of the crop production system. When data are recorded, it is usually done at a block or orchard level using non-spatial descriptive statistics, such as the mean and variance of production attributes (Miranda Jimenez and Royo Diaz 2004). Rarely does the analysis take into account within-block variation (e.g. Gillgren 2001; Praat et al., 2000). In the horticulture literature there are very few studies where site-specific data have been collected even though such data provides better quality information (Praat et al., 2000; Tysseyre et al., 2007) and the option of interpreting the data in either a uniform or spatial context. Investigations into the spatial variability of yield in pipfruit, kiwifruit, citrus and other fruit crops have been undertaken (Praat et al., 2000; Taylor et al., 2007a, Quiao et al., 2005; Gillgren 2001), however these studies have focused on quantifying yield during or immediately after harvest. There are no horticultural publications about the spatial variability of within season crop yield estimation, despite this being a routine operation in many orchard systems and the development of digital imaging systems for fruit counting (Stajnko et al., 2004; Regunathan and Lee 2005). To date these imaging systems have only been used for uniform (block) yield estimation or as machine-vision for automated harvesting systems.

Within-season estimation of crop yield is important for making real-time, correct management decisions, particularly for crop thinning and labor logistics at harvest.

Orchard yield is a function of crop load and fruit size and can be accurately assessed by fruit load per tree (Lakso et al., 1995; Hester and Cacho 2003; Lötze and Bergh 2004; Miranda Jimenez and Royo Diaz 2004). The earlier this estimation can be made the more useful the information is for management. To this end different methods have been tried to calculate (mean) fruit load early in the growing season. Jessen (1955) and Pearce and Holland (1957) initially proposed randomized branch sampling to estimate crop load and, since then a wide variety of methods have been developed for estimating crop load. However all these methods are aimed at producing orchard mean estimates (Zhang et al., 1995); none of them are suited or designed for spatial analysis.

The analysis of spatial data in orchards, termed Precision Horticulture (PH), is a relatively new area of study. PH aims to improve a variety of management decisions, such as crop thinning, fertilization or irrigation, by understanding the spatial and/or temporal variations in crop production. Understanding these variations allows management to be tailored to specific crop needs at each location (site) in the orchard, hence optimizing production. Application of this management philosophy as been adopted in broadacre agriculture and more recently in viticulture (Tisseyre et al., 2007; Taylor et al., 2007b).

The collection and analysis of spatial data may be expensive and time consuming and is therefore usually facilitated by automated sensors. For situations where manual measurements are required (or necessitated due to the absence of relevant sensors), as in PH, the design of the sampling scheme is important in optimizing the value of the data collected  The most common approach to hand-sampling relies on grid point sampling. However, gridded sampling may give erroneous results because of the regular sample alignment. Other regularly spaced patterns associated with treatment and field management, such as drainage tiles, ditches or fertilizer spreading, may cause a repeating pattern that, if aligned with the sampling grid, will seriously bias results. When existing spatial information is available, e.g. a soil survey, an aerial image or possibly existing local knowledge, then this *a priori* information can be used to develop a site-directed survey. Site-directed and randomized sampling schemes have been shown to be more effective than grid sampling (Pocknee et al., 1996) especially when nested transects are incorporated to improve variogram estimation (Pettitt and McBratney 1993). However, when *a priori* knowledge does not exist to generate a site-directed sampling scheme, then grid sampling at an appropriate density in combination with block kriging (interpolation) can be used for mapping and managing crop parameters (McBratney and Pringle 1999).

Precision agriculture (PA), and more particularly precision horticulture are relatively new concepts based on spatial information. When starting with PA or PH it can take many years to generate a database of information, for example harvest data can only be generated once a year. To facilitate adoption it is often possible to use existing or legacy data, provided the data is of sufficient density and quality to warrant spatial analysis i.e. individual site data is required, which has not been aggregate or mixed into a composite sample for analysis, and contains an accurate site location. Site location does not need to be a geographic reference (e.g. latitude and longitude). It can be an accurate orchard description that can easily be revisited or geo-referenced (e.g. the 6th tree in the 10th row from the eastern edge of Block 6). Although rare, such legacy data in horticulture does exist, particularly from previous research studies rather than in commercial applications, and the data is usually collected on some form of grid.

The aim of this paper is to analyze medium density legacy crop load data for spatial variation pre and post hand-thinning. The goal of the analysis is to illustrate a) how spatial analysis can be used to identify variation in apple production and, b) how thinning impacts on spatial variation in crop loads. The authors acknowledge that the legacy data sampling scheme is sub-optimal, however the number of data (156) is sufficient for variogram analysis (Webster and Oliver 1992) and therefore spatial analysis. Recognizing and accounting for limitations in spatial analysis of legacy data is an important concern for PH, particularly during its infancy. Given the results, a brief discussion is also presented on the potential opportunities afforded by managing the observed spatial variation in crop load.

## 2.2 Materials and Methods

The study was conducted during the 2007 growing season in a commercial apple orchard located in Medelana, Ferrara, Italy. Data were collected from three blocks of apple “Fuji” denoted M9-1998 (3.1 ha), M9-1995 (2.5 ha) and M9-2001 (1.4 ha). Apart from a different year of planting (as indicated in the block identifier) trees in all the blocks were grafted on M9 rootstock, trained as slender spindle at a density of 3571 trees ha-1 (0.8 X 3.5 m), and were under the same standard management. All three orchards have an approximate North-South orientation. For these characteristics, the three blocks can be considered a uniformity experiment.

In the orchard, pollenizer rows are interspersed within the main cultivar ones. Pollenizer rows were not considered during crop estimation. In M9-1995 and M9-1998 the ‘Fuji’ rows adjacent to the pollenizer rows were also omitted. The remaining 21 and 24 rows in the two blocks respectively were sampled. In M9-2001 every second row was selected for a total of seven rows. In each block, the rows were divided into three sectors (blocks), North, Centre and South, and for each sector 4 ‘trees’ were counted randomly. The mean crop load from the 4 ‘trees’ was assigned to the sector and geo-referenced with the midpoint of the sector. Figure 1 illustrates the sampling strategy. For each block, M9-1995, M9-1998 and M9-2001 respectively there were 63, 72 and 21 data. This grid-oriented sampling strategy was initially designed for a whole-block crop yield estimation, not for spatial analysis, however sufficient information (156 data) allows to undertake relevant preliminary spatial data analysis across the 3 blocks. There is insufficient data (< 100 points) within individual blocks for accurate variogram analysis (Webster and Oliver 1992), hence the need to aggregate the data.

Crop load estimation was done in the first week of May, after standard Carbaryl-based chemical thinning but before final hand thinning (also a standard practice), and then in September before harvest. As described above, 4 random locations ('trees') were counted within each sector then averaged to give a sector mean. A each location fruit were counted within a 'frame' or 'window' 0.8 m wide (equivalent to the distance between trees along the row) and as high as the trees. Thus 3.2 m of row were counted in each sector and averaged to a 'tree' (0.8 m) value. This approach was adopted due to the tight spacing along the row causing overlapping of fruit-bearing branches between adjacent trees. Using a window equivalent to the spacing between trees (0.8 m) means that the window does not need to be perfectly centered on the trunk of the tree nor do the inter-twining of branches of adjacent trees cause a problem with counts. This reduces the need to always identify the tree to which a given fruit was attached, which is time consuming. Fruit counts were performed manually but only on the western side of the rows again to decrease the time needed per tree and to allow more locations to be counted within a given time frame. An assumption is made that the two halves (eastern and western) of the inverted conic shaped spindle trellis will generate equal fruit counts). Total crop load per 'tree' is obtained by doubling the western half fruit count.

The desired fruit load of about 61 fruit per tree was calculated after a target mean fruit weight (220 g) and yield (50 t ha-1) were identified, and knowing the tree density (3571 trees ha-1). The May crop load indicated that the average fruit load across the blocks (60.6 fruit tree-1) (Table I) was close to optimal., On the basis of this value a decision not to thin the fruit would be made. However, observation of the fruit set showed a high degree of fruit clustering. This is an undesirable production feature thus hand-thinning was undertaken primarily to achieve a maximum of 3 fruitlet per cluster. This was done across all three blocks by simply removing random fruitlets from clusters with 4 or more fruitlets until only 3 fruitlets remained.

The same sampling protocol described above was used for the post-thinning (pre-harvest) crop load estimation in September. In each sector 4 ‘trees’ (0.8 m sections) were again randomly chosen i.e. the same area of canopy was not necessary counted in May and September however the same amount of canopy (3.2 m) in each sector was.

Non-spatial data analysis (mean, variance and coefficient of variation) for the blocks were done in JMP 6.0 (SAS Institute; Table I). Variogram estimation was performed in VESPER (Minasny et al., 2005). Variogram clouds are plots of the semi-variance between points separated by a certain distance i.e. each point in Figure 2 represents the mean semi-variance between all possible pairs of points in the data set that are separate by the lag (distance) indicated on the abscissa axis. For interpolation and spatial analysis a theoretical model is usually fitted to the variogram cloud. Various models were fitted and a theoretical spherical model (Equation 1) found to have the best fit according to the Akaike Information Criteria in VESPER. The theoretical variogram parameters, $c0$, $c1$, and $r$, for the fits were recorded. As described by Taylor et al., (2007a), the $c0$ value estimates the amount of variance between adjacent points, i.e. points that are separate by a distance (or lag) of ~0 m, and is a function of stochastic effects and measurement error. The $c1$ value estimates the amount of autocorrelated variance in these data and contributes with $c0$ to define the sill ($c0 + c1$) or the total amount of variance in these data. The range ($r$) defines the distance over which data are autocorrelated i.e. the distance at which the sill is reached. To provide some indication of spatial structure the Cambardella Index (Cambardella et al., 1994) was calculated.

This index is a ratio between the nugget (*c0*) and the sill (*c0+c1*), which indicates whether data contains trends and spatial features or represents either random noise or a uniform value, neither of which have a spatial structure. For data that exhibits a spatial structure, the amount of autocorrelated variance provides an indication of the amount of spatial variation that is potentially manageable (Pringle et al., 2003).

Interpolation was done in VESPER onto a 2 m square grid using block kriging (5 x 5 m blocks) and the global variogram defined above. As fruit counts are known to have an error of ~20% (Stajnko et al., 2004), the σ2 (uncertainty) option in VESPER was used (Minasny et al., 2005) and a value equivalent to 20% of *c*0 was chosen as an estimation of σ2. The interpolated data was mapped in ArcMap 9.2 (1999-2006, ESRI inc., Fig. 3).

## 2.3 Results and Discussions

The non-spatial and spatial statistics for the May (pre hand-thinning) and September (Post hand-thinning) data counts are shown in Table I. The global (all data) mean crop load for the three blocks is lower in May (60.6) than September (63.3), but not significantly different ($p<0.44$). This is despite the fruit being thinned in between the counts. The primary reason for this is the light level of thinning pressure applied due to a quite low crop load verified after the chemical thinning. Secondly, a probable under-estimation in the May counts due to the difficulty in locating all the fruit when the fruitlets are small, green, cluster organized and camouflaged in the canopy. Crop counts in September are usually more accurate as the fruit are large, redder and less clustered together and therefore more obvious. The option to use random 'trees' for both counts, rather than the same 'trees', will also introduce some variance in the counts. Despite the similar global means , the September counts had a lower CV indicating more uniformity in production post-thinning.

The intention of the original sampling survey was to gather accurate mean measurement of fruit count on a block basis. The individual block means showed different responses. For M9-1995 and M9-2001 the mean block crop load increased significantly ($p<0.05$) by 19.35 and 26.31 fruit tree-1 post-thinning respectively. Crop load in these blocks was lower than the target level (60 fruit tree-1) and the blocks would have received very light hand-thinning. Fruit, in fact, where more distributed in single fruitlet clusters. This gives the appearance of better fruit distribution in the canopy, which also contributes to a lower thinning pressure. September counts are known to be more accurate, due to the larger fruit, therefore the increased fruit count in these blocks is attributed to the fact that the amount of fruit thinned is less than the fruit not counted pre hand-thinning.

However M9-1998 had a significant decrease ($p<0.05$) of 18.84 fruit tree-1. The mean crop load in this block was well above the target rate and would have received more rigorous hand-thinning. The apple “bunch” reduction is a typical cultural practice during thinning in order to speed up the process and maximize the final product quality. This resulted in the amount of fruit removed being greater than the fruit not counted in May. Given that more fruit is expected to be counted in September, a large proportion (we estimate ~50%) of the fruitlets must have been lost in M9-1998. This may not be just due to hand-thinning. The high fruit set in this block may prompt greater natural fruit drop due to a higher competition at fruit clusters level further contributing to the loss of fruitlets/fruit as have been reported by Westwood (1978). The hypothesis of loss of fruit from high crop load trees in M9-1998, either through thinning or fruit fall, is also obvious in the spatial patterns of the raw data in M9-2001. Despite the majority of the block having a low crop load, the North-East corner has very high crop load (Fig. 3). When the crop load is reassessed post hand-thinning the spatial patterns in the block have changed, with the NE corner now being characterized by lower raw data counts (Fig. 3) than the rest of the block.

The experimental variogram clouds for fruit counts and fitted theoretical spherical variogram models are shown in Fig. 2. The variogram parameters are listed in Table 1. In the pre hand-thinning plot, the lag at 19 m (indicated with an arrow) is omitted from the fitting process as it had a low number of pairs, compared with its neighbours, for the semi-variance estimation. This is an artifact of the sampling design. The variograms show a marked difference between the two counts. The pre hand-thinning variogram count (Fig. 2A) exhibits some spatial autocorrelation ($r$ = 35.24 m), i.e., trees separate by distances < 35 m exhibit less variance than trees separated by > 35 m, or, stated another way, it is more likely that two trees separated by < 35 m will require the same management than for two trees separates by > 35 m. This is probably the normal situation in an orchard prior to hand-thinning. The aim of thinning an entire orchard is to produce a more homogeneous fruit load which is easier to manage. The post-thinned September count (Fig. 2B) has no spatial auto-correlation ($c1$ and r values of 0), which is the desired outcome under current management approaches. The Cambardella Index for the May counts (66.14) indicates a moderate spatial dependency (structure) while the index post-thinning (100) is indicative of no spatial dependence.

In production systems with spatial structure a management class or management zone approach is possible and may be preferable. When there is no spatial structure a uniform or mean approach to management is the most practical current approach, unless trees can be managed individual on a tree-by-tree basis. The moderate spatial dependency indicated by the Cambardella Index and the short range over which auto-correlation occurs in May ($r$ = 35.24), indicates that the distance (area) over which trees exhibit a more uniform crop load response is quite small. This distance (area) has implications on the ability to manage the autocorrelated (structured) variation in the production system. If the grower cannot adjust management over distances of less than 20 - 30 m then it may not be possible to manage the observed variation.

The presented crop load maps (Fig. 3) provide a visual reinforcement to the spatial analysis. In May, intra-block spatial patterns in production are present. For example, there are North-South oriented features in M9-1995, despite the sampling being more densely oriented East-West (Fig. 1). With this legacy sample scheme, E-W artifacts may be expected but are not present. Likewise, M9-2001 shows a trend across the block with crop load diminishing from the North-East to the South-West corner. M9-1998 presents a more uniform map (in agreement with its lower CV value in Table I) but there is still some spatial patterns to observe. The September maps are effectively mean block maps. The flat variogram structure means that all the data used for interpolation are weighted equally, thus an average value is derived. The interpolated crop load block means for M9-1995 and M9-1998 approximate the block means in Table 1 derived from the raw count data. For M9-2001, the interpolated block mean is underestimated as the kriging process has used data from the other blocks during the interpolation. If the number of points used in the interpolation is confined to 21 (the number of data in M9-2001) the interpolated crop load mean approximates the raw data mean (results not shown).

In Figure 3 the raw data points have also been shown using the same legend. This visually shows the spatial variance in the raw data. The September data is more noisy with adjacent points more often dissimilar than in May. However, the overall variance and CV is lower in September (Table 1). This highlights one of the problem with using CV as an indicator for spatial variance (Pringle et al., 2003).

These simple spatial analyses and associated maps provide an ability to quantify the effectiveness of thinning within the orchard in reducing variability in the crop load of the trees. In this case the data indicates that thinning has removed the spatial structure associated with crop load in the orchard and reduced the CV across the blocks.

However, there is still a large amount of variation across the orchard blocks (CV of 43.69 post hand-thinning) and this variation appears to be stochastic in nature. Is this level of stochastic variation between adjacent trees acceptable to growers and what implications does it have on fruit quality, particularly fruit size distribution at harvest? This preliminary investigation did not collect harvest data to answer this question however it is certainly a question which needs further investigation.

Given that this study has shown that there is variation in the production system, is a uniform crop load the optimum outcome for the orchard or each block? If canopy variation also exhibits similar variation to the crop loads than the optimal fruit load, relative to canopy size, will differ. Does this provide options for improved productivity and/or profitability through targeted management, such as differential harvesting? Examples from viticulture studies certainly highlight this possibility (Bramley, 2005). Spatial variation in quantity should not necessarily be considered detrimental to production, and if manipulated correctly can be a positive. Spatial variation in quality may be more problematic. For any high value crop the ultimate goal is uniform (high) quality production. Uniform fruit load, with variable environmental effects, may not produce uniform quality.

While this is only a snapshot, and the temporal stability of spatial patterns needs to be determined before using the information for future management decisions, over time these spatial patterns could provide valuable information and feedback on current management strategies and options for future variable or site-specific management. Fruit thinning is one of the most effective techniques to increase the income for the grower. If thinning can be more effectively implemented using variable thinning strategies to match production to the ecophysiological potential of the orchard then increases in fruit quality and subsequently profitability are possible. Furthermore, spatial crop load information can assist the grower in the management of harvest and packhouse logistics.

## 2.4 Conclusion

Thinning is an important management technique that impacts on the profitability of an orchard. Decisions on thinning are made frequently during the season but quite often without clear and quick feedback on the results from previous management (thinning) operations. To date, information on the spatial variability of the fruit load within an orchard has not been used for the targeting of subsequent thinning operations.

The aim of the paper was to investigate the feasibility of spatial analysis in apple orchards to assist growers with decision making. Although the sampling scheme used was not optimized for spatial analysis, the result of the investigation were satisfactory and quite clear. Prior to hand-thinning there was a spatial structure and pattern in crop load. After thinning this spatial structure and pattern was no longer evident. The thinning operation had removed the spatial structure to the crop load variation and reduced the overall CV across the orchard. There is still a large amount of variation across the orchard blocks (CV of 43.69 post thinning) but this variation appears stochastic in nature. When retaining a uniform block management approach, this spatial analysis identifies whether thinning has produced the desired uniform crop load, or where further differential thinning is required to achieve a uniform crop load.

However, given that this analysis indicates that spatial variation exists at a sub-block level, the current uniform approach to management being used may not be the most productive. There may be differential management options available to researchers and growers who are aware of this variation, to increase their potential to respond to market demands for higher quality fruit at a lower cost. This is one of the main objectives of precision horticulture.

## 2.5 References

Bramley R.G.V. 2005. Understanding variability in winegrape production systems: 2. Within vineyard variation in quality over several vintages. Aust. J. Grape Wine Res. 11, 33–45.

Cambardella, C.A., T.B., Moorman, J.M., Novak T.B.,, Parkin, D.L., Karlen, R.F., Turco, and A.E., Konopka 1994. Field-scale variability of soil properties in central Iowa soils. Soil Sci. Soc. Am. J. 58, 1501–1511.

Gillgren, D. 2001. Finding the fruit: A spatial model to access variability within a kiwifruit block. Proceeding of 13th Annual Conference of the Spatial Information Research Centre. University of Otago, Dunedin, New Zealand, 2–5 Dec. 2001.

Hester, M. S. and O., Cacho 2003. Modeling apple orchard systems. Agr. System. 77, 137–154.

Jessen, R. J. 1955. Determining the fruit count on a tree by randomized branch sampling. Biometrics. 11, 99–109.

Lakso A.N., L., Corelli Grappadelli, J., Barnard, and M.C., Goffinet 1995. An expolinear model of the growth pattern of the apple fruit. J. Hort. Sci. 70, 389–394.

Lötze, E. and O., Bergh 2004. Early prediction of harvest fruit size distribution of an apple and pear cultivar. Sci. Hort. 101, 281–290.

McBratney, A.B. and M.J., Pringle 1999. Estimating average and proportional variograms of soil properties and their potential use in precision agriculture. Precision Agr. 1, 125–152.

Minasny, B., A.B., McBratney and B.M., Whelan 2005. VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW. 2006. <www.usyd.edu.au/su/agric/acpa>.

Miranda Jiménez, C. and J. B., Royo Díaz 2004. Statistical model estimates potential yields in 'Golden Delicious' and 'Royal Gala' apples before bloom. J. Am. Soc. Hort. Sci. 129, 20–25.

Pearce. S. C. and D. A., Holland 1957. Randomized Branch Sampling for Estimating Fruit Number. Biometrics. 13, 127–130.

Pettitt, A.N. and A.B., McBratney 1993. Sampling designs for estimating spatial variance components. App. Stat. 42, 185–209.

Pocknee, S., B., Boydell, H.M., Green, D.J., Waters, and C.K. , Kvien 1996. Directed soil sampling, Procedure of 3rd International Conference on Precision Agriculture. 159–168. Madison, Wisconsin.

Praat, JP., A.F., Bollen, I.J., Yule and C., Empson 2000. Applied Information Management Systems. Conference Proceedings from Achieving change through improved knowledge systems. Centre for Agricultural and Veterinary Continuing Education, Massey University. Palmerston North, New Zealand. 281–288

Pringle, M. J., A. B., McBratney, B. M., Whelan and J. A., Taylor 2003 . A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. Agr. Systems. 76, 273–292.

Qiao, J., A., Sasao, S., Shibusawa, N., Kondo, and E. , Morimoto 2005. Mapping yield and quality using the mobile fruit grading robot. Biosystems Eng. 90, 135–142.

Regunathan, M. and W. S., Lee 2005. Citrus Fruit Identification and Size Determination Using Machine Vision and Ultrasonic Sensors. ASAE Meeting. Paper No. 053017. St. Joseph. Mich. : ASAE.

Schueller, J.K., J.D., Whitney, T.A., Wheaton, W.M., Miller and A.E., Turner 1999. Low-cost automatic yield mapping in hand-harvested citrus. Computers Electronics Agr. 23, 145–154.

Stajnko D., M., Lakota and M., Hočevar 2004. Estimation of number and diameter of apple fruits in an orchard during the growing season by thermal imaging. Computers Electronics Agr. 42, 31–42.

Taylor, J.A., JP., Praat and A.F., Bollen 2007a. Spatial Variability of Kiwifruit Quality in Orchards and Its Implications for Sampling and Mapping. HortSci. 42, 246–250.

Taylor, J. A., A. B., McBratney, and B. M., Whelan 2007b. Establishing management classes for broadacre agricultural production. Agron. J. 99,1366–1376.

Tisseyre, B., H., Ojeda and J.A., Taylor 2007. New technologies and methodologies for site-specific viticulture. J. Int. Sci Vigne. Vin. 41, 63–76.

Whithney, J.D., W.M., Miller, T.A.,Wheaton, M., Salvani, and J.K., Schueller 1999. Precision farming: applications in Florida citrus. App. Eng. Agr. 15, 399–403.

Webster, R. and M.A. Oliver. 1992. Sample adequately to estimate variograms of soil properties. J. Soil Sci. 43, 177–192.

Westwood, M.N. 1978. Temperate-zone pomology. W.H. Freeman and Comp. San Francisco.

Zhang, J., G.F., Thiele, and R.N., Rowe 1995. Gala apple fruit size distribution. New Zealand J. Crop Hort. Sci. 23, 85–88.

## 2.6 Figures, Tables and Equations

Equation 1

*Theoretical Spherical Variogram Model*

$$\gamma(h) = \begin{cases} c_0 + c_1 \left\{ \left( \frac{3h}{2a} \right) - 0.5 \left( \frac{h}{a} \right)^3 \right\} & \text{for } h \le a\,, \\ c_0 + c_1 & \text{for } h > a \end{cases}$$

where $c0$ is the nugget variance, $c0 + c1$ is the sill and $a$ is the range

Equation 2

*The Cambardella Index*

$$\text{Cambardella Index} = \frac{c_0}{c_1 + c_0} \bullet 100$$

where $c0$ = nugget, $c0 + c1$ = sill,

and <25 = Strong spatial dependency

25–75 = Moderate spatial dependency

<75 = Weak spatial dependency

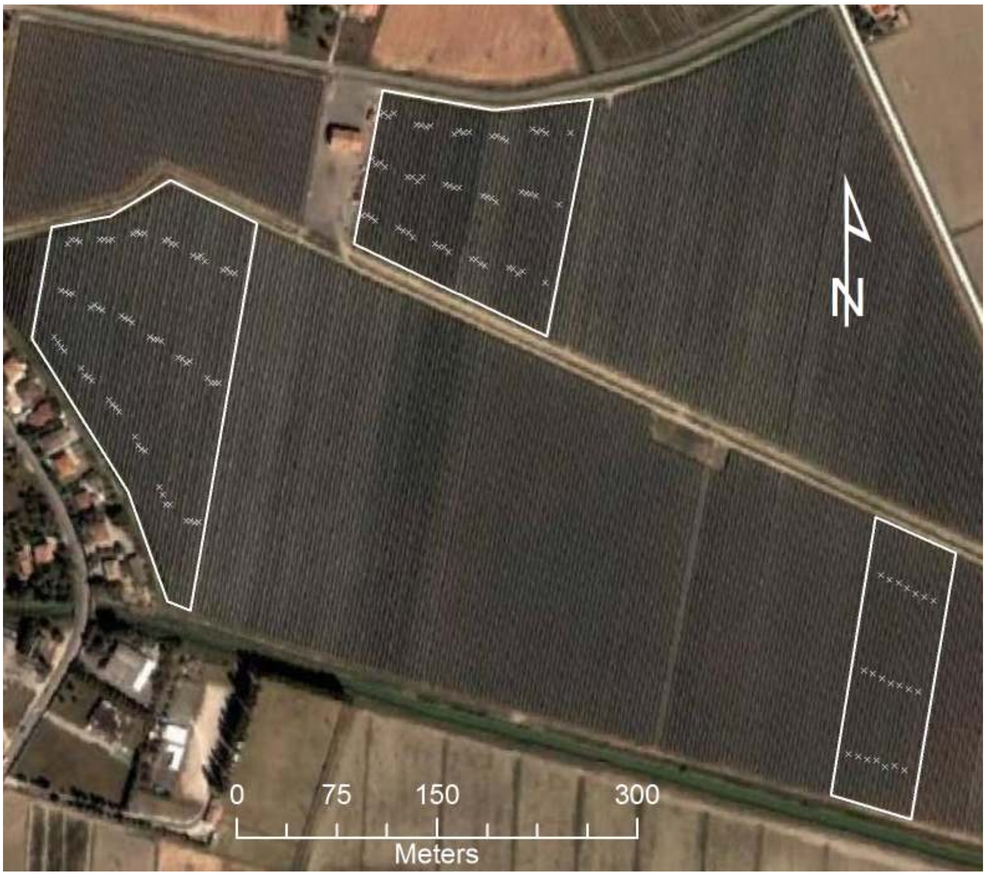


Fig. 1. True colour satellite image of the study site showing the three blocks of Fuji apples surveyed and the centroids of the North, Central and Southern ‘sectors’ in the blocks that the mean crop load data for each sector was geo-referenced to.

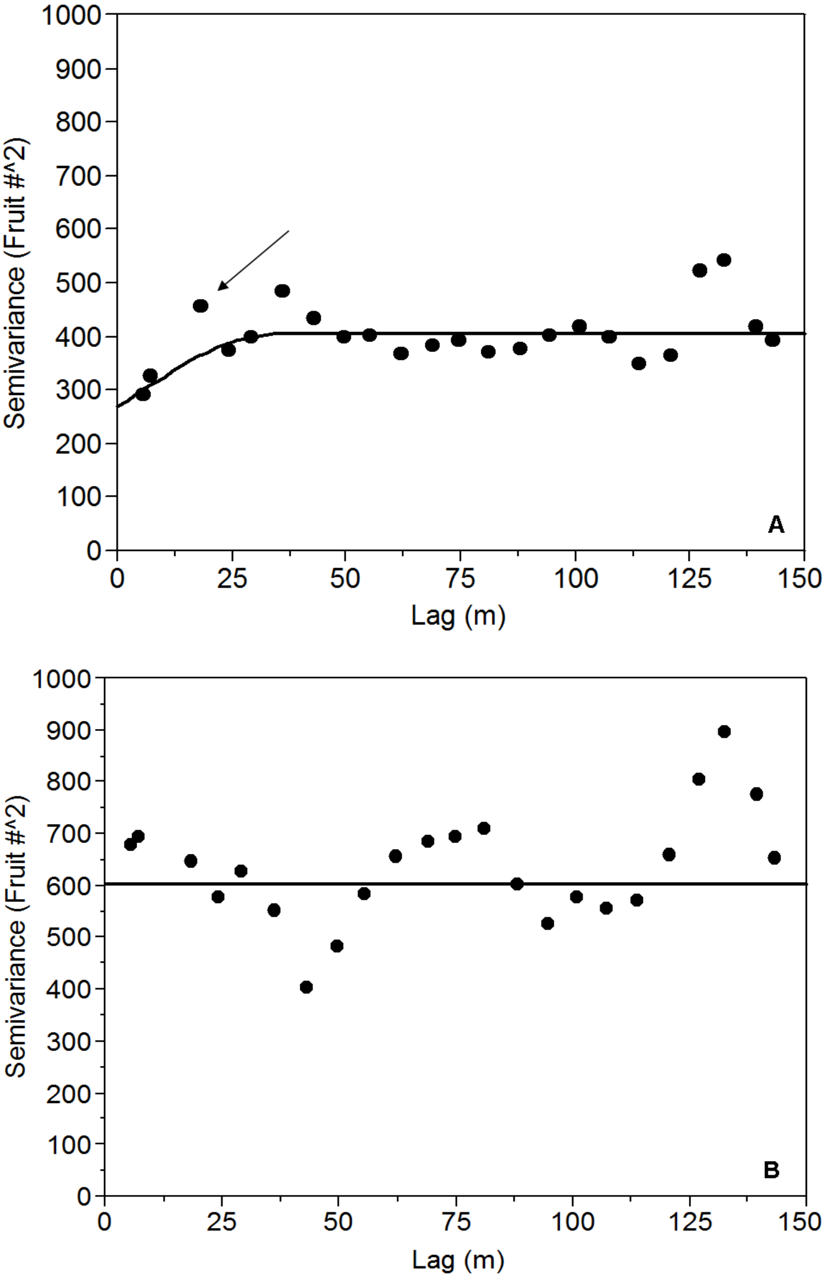


Fig. 2. Experimental variogram clouds and fitted theoretical spherical models for the crop load data pre hand-thinning (A) and post hand thinning (pre harvest) (B). The pre-thinning variogram (A) shows auto-correlation (less semivariance) between data separated by less than 35 m. The post hand-thinning variogram (B) shows no auto-correlation. The arrow indicates a lag variance with a low number of data pairs. This data point has been omitted from the theoretical variogram fitting.

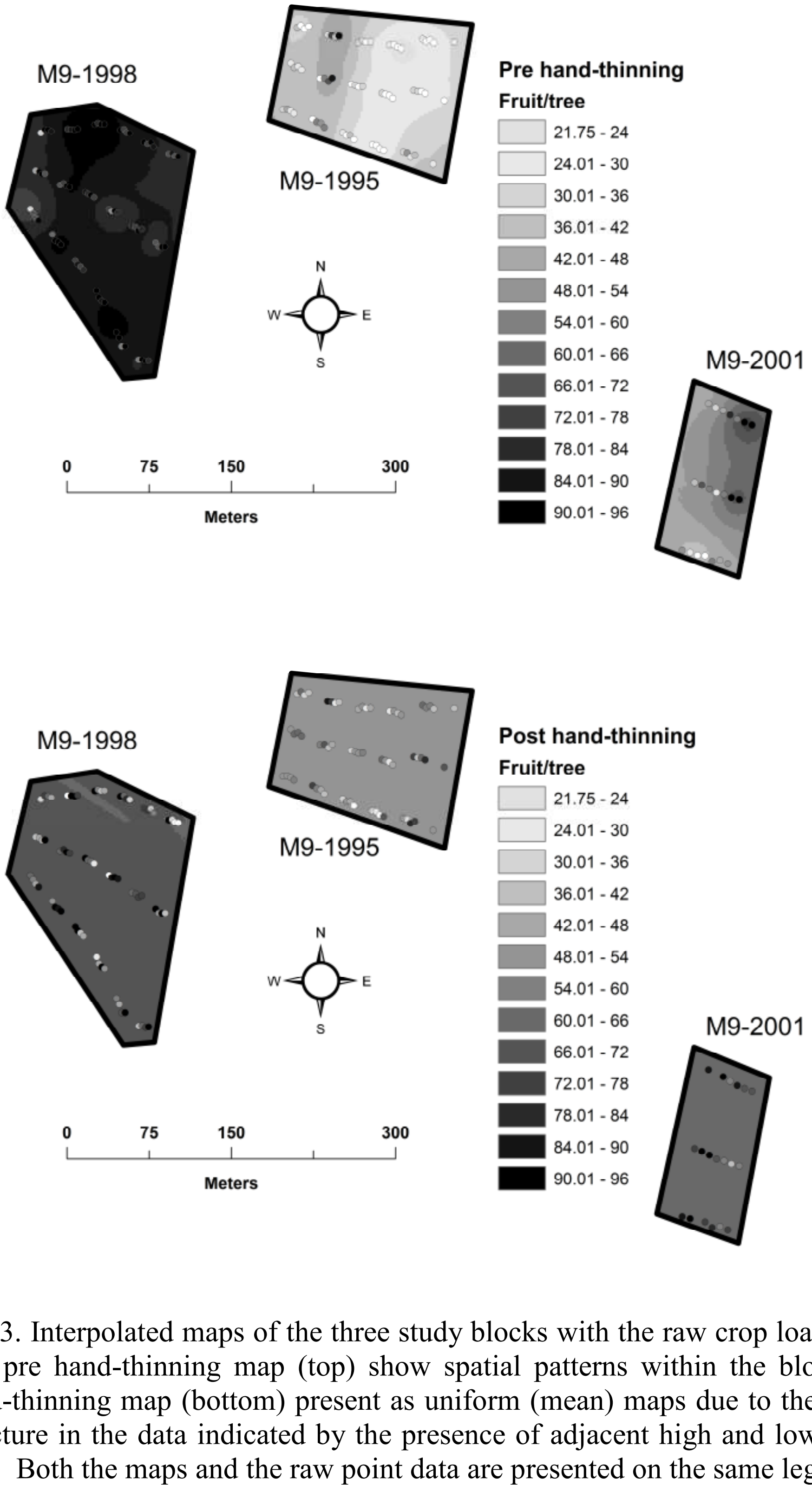


Fig. 3. Interpolated maps of the three study blocks with the raw crop load data overlain. The pre hand-thinning map (top) show spatial patterns within the blocks. The post hand-thinning map (bottom) present as uniform (mean) maps due to the lack of spatial structure in the data indicated by the presence of adjacent high and low raw crop load data. Both the maps and the raw point data are presented on the same legend.

Table 1: Non-spatial statistics and variogram parameters for the combined data from all three blocks and individual non-spatial statistics for each block for the pre hand-thinning (May, 2007) and post hand-thinning (September 2007) crop load estimations.

| Sampling time | Block ID | No. of data ($n$) | Mean Crop Load (fruit/tree$^{-1}$) | Crop Load Variance | CV | Nugget variance ($c_0$) | Sill Variance ($c_0$+$c_1$) | Range ($a$) (m) | Cambardella Index |
|---|---|---|---|---|---|---|---|---|---|
| **Pre hand-thinning (May, 2007)** | M9-1995 | 63 | 31.22 | 329.66 | 58.15 | | | | |
| | M9-1998 | 72 | 86.86 | 377.90 | 22.38 | | | | |
| | M9-2001 | 21 | 58.67 | 945.73 | 52.42 | | | | |
| | Combined | 156 | 60.6 | 1098.64 | 54.7 | 267.6 | 404.6 | 35.24 | 66.14 |
| **Post hand-thinning (September, 2007)** | M9-1995 | 63 | 50.57 | 250.41 | 31.29 | | | | |
| | M9-1998 | 72 | 68.02 | 920.46 | 44.6 | | | | |
| | M9-2001 | 21 | 84.98 | 792.31 | 33.12 | | | | |
| | Combined | 156 | 63.25 | 763.89 | 43.69 | 601.0 | 601.0 | 0.00 | 100.00 |

CV, coefficient of variation (%).

# CHAPTER 3

# MODELING AND INVERSE MODELING MANAGEMENT CLASSES TO VERIFY THE SPATIAL EFFECT OF ENVIRONMENTAL PROPERTIES ON APPLE PRODUCTION

## 3 Summary

Stratification of spatial data into management classes is a common way of interpreting and managing spatial variation. High-resolution environmental and crop production information was collected within a 2.2 ha apple orchard (cv. Gala) near Sydney, NSW, Australia. Classifying the block into management classes using the environmental data did not help to interpret crop spatial variation. An inverse model approach was subsequently undertaken, effectively analyzing whether the crop production explains environmental variation. The inverse modeling identified a very different spatial patterning. By segregating the inverse modeled classes into discrete zones there appears to be both an environmental and managerial effect on the fruit production in different sections of the orchards. The interaction of these two effects masked any response in the initial analysis. The inverse modeling approach significantly assisted the interpretation of spatial variation in the orchard and identified a previous unknown management effect.

## 3.1 Introduction

Spatial data sets are becoming increasingly available for agricultural management. With this comes a need to recognize that spatial data, particularly high resolution sensor-derived data, has inherently different properties to agricultural data derived from 'traditional' plot experimentation. Spatial data needs a spatial analysis. This means that spatial data often need to be pre-processed prior to analysis and the density of the data may often hide relationships. Increasingly, approaches using both modeling and inverse modeling techniques are being used to tease out relationships in these high density (high information) data sets (Ferreyra et al., 2006; Florin et al., 2008). Inverse modeling, as the name suggests, is simply a process of switching the dependent and independent variables in a model, usually a crop simulation model.

Management classes (or zones) are often used in cropping (Taylor et al., 2007b) and viticulture systems (Paoli et al., 2007) to interpret spatial relationships between crop and environmental parameters. Recent advantages in sensor technologies, such as soil sensors, canopy sensors and yield monitors, provide many different layers to help derive management classes (zones). In many cases horticulture producers already have some of these data layers but have not applied them spatially to crop management strategies (Praat et al., 2001; Taylor et al., 2007a; Manfrini et al., 2009). Management classes are generally considered as a means of implementing differential (zonal) management, however they can also be used as an analysis tool to help interpret spatial relationships.

Experiences in dryland production systems in Australia have shown that within-field production variation is strongly influenced by within-field environmental variation, particularly edaphic variation (Kitchen et al., 2003). Similar experiences have been reported in irrigated viticulture systems, although these systems tend to be placed under water-stress during ripening thus emphasizing the effect of edaphic variation on production (Tisseyre et al., 2007). In horticulture crops where irrigation is non-limiting, the influence of soil type may be less obvious. Spatial relationships between crop and environmental parameters can be modeled (or inverse modeled) to assist in understanding correlations and casual effects in the data set. Usually inverse modeling techniques are done using complex crop models (Florin et al., 2008). However a simpler approach to help in the initial interpretation of spatial data is an inverse management class model. This inverse approach may help identify complex patterns where a dominant driver of production is absent. Such an approach has not been previously reported in the precision agriculture literature.

This study, an initial foray into precision horticulture (PH) in apple orchards in Australia, aims to identify if production variation is related to environmental variation, particularly soil type. The null hypothesis is that variation in soil type and micro climate are not major determinants of variation apple yield and quality at the *within* block level. The study is undertaken using the concept of management classes as a means of spatially organizing the data and using both a modeling and inverse modeling approach.

## 3.2 Materials and Methods

Site description and environmental data layers. The study was conducted during the season 2007-2008 in a commercial apple orchard located at Darkes Forest (near Sydney), NSW, Australia. The orchard was chosen for its ease of access and the existence of a priori environmental information. This a priori information consisted of a soil apparent electrical conductivity ($EC_a$) map (done with a Geonics EM38) and a high quality elevation map (from a carrier-phase receiver) collected commercially (Terrabyte, Wagga Wagga, NSW, Australia). This data was used to identify a 2.2 ha block of apples (var. Gala grafted on M26 rootstock) within the orchard, which exhibited a large variation in $EC_a$. Apple trees in the block were planted in 1995 and were trained as a vertical axis at a density of 667 $tree \cdot ha^{-1}$ (3x5 m). The block was approximately north-south oriented and every third row contained pollinator trees (either cv Granny Smith or Pink Lady®). In total there were 12 rows of Gala and 6 rows of pollinators. The pollinator rows were omitted from the analysis. The block was dissected north-west/south-east by an internal track for machinery. This split the block into two sections, with an approximate ratio of 1:2 between the south and north sections.

The elevation and $EC_a$ data were interpolated onto a square 2 m grid using the protocol of Taylor et al., (2007). Information on net solar radiation interception (NR) was modeled using the SRAD program (McKenney et al. 1999) and the interpolated digital elevation model (DEM). The northern and eastern edge of block is flanked by native Eucalyptus forest (~10 m high). The digital elevation model was modified to reflect this, i.e. to a digital surface model, to simulate the influence of the forest on the orchard before being run through the SRAD model. There was not a lot of information in the NR surface (Fig. 1) but it did show less radiation interception in the eastern and northern sections of the block from early morning shading. The three data layers ($EC_a$, Elevation and NR) were clustered, again using the protocol of Taylor et al., (2007), and the two cluster map chosen as a basis for the sampling scheme and initial analysis. The map highlighted two distinct classes in the field; the higher $EC_a$ and elevation 'hill' in the north-east corner and the remainder of the block. To avoid confusion with later analysis, these classes were labeled with the subscript "E". i.e. Class $1_E$ and Class $2_E$, to indicate classification based on environmental data.

### 3.2.1 Crop Production Data Layers

Initially, 89 samples were randomly allocated to trees across the orchard with a slight weighting to increase sample numbers in the smaller Class $1_E$. From these 89 samples, 15 were chosen randomly and the adjacent tree to the south of these 15 trees was also sampled. By pairing trees the sampling ensures that the short range stochastic variation is measured and can be accurately modeled in any spatial analysis. Therefore, in total there were 104 sample trees.

The selected trees were monitored for quantity and quality at harvest. Harvest was conducted over 5 days (12th, 14 th, 15 th, 19 th and 21st February, 2008). The initial trees were stripped picked. This corresponded to 19 trees in the most easterly row. Total crop load ((FN) number of fruit per tree) and total fruit weight (FW ($kg \cdot tree^{-1}$)) were measured and then the average fruit weight (MFW ($g \cdot fruit^{-1}$)) was calculated. After this first row, the harvest strategy was altered and only saleable (mature) fruit was picked during the first pass. Unripened fruit was left on the tree. Subsequent passes through the orchard were made over the next 10 days until all the fruit was removed. The same parameters (FN, FW and MFW) were measured. This approach also allowed the percentage of first pick fruit (FP%) to be calculated for the remaining 85 trees. This provides an indication of ripening within the orchard. All the harvest data is reported on a single tree basis. The trees were georeferenced with a stand alone Garmin GPS76 Global Positioning System (GPS) receiver. Post harvest, the trunk circumference (TC) 20 cm above the graft union was measured and recorded.

To complete the spreadsheet, the environmental data ($EC_a$, elevation and NR) was interpolated at the sampling points (tree locations) and the corresponding “E” class (Class $1_E$ or Class $2_E$) for each tree recorded.

Maps of crop production parameters were generated by punctual kriging with a global variogram using the Vesper freeware (Minasny et al., 2005). The interpolation was performed onto the same grid used for the environmental parameters. Surfaces of FN, FW, MFW and TC were kriged using all 104 points while FP% was kriged using only the 85 points where FP% was recorded. Maps were created in ArcGIS (ESRI, Redlands, Ca, USA) and are shown in Fig. 2. Since a common grid was used a spreadsheet was generated with the x, y coordinates of the grid points, the environmental interpolations and the crop parameter interpolations.

### 3.2.2 Preliminary Data Analysis

The primary hypothesis testing revolved around whether or not production variation is driven by an environmental variation. As a preliminary investigation, pearsons correlation coefficients were derived between the main harvest parameters, FN, FW, MFW and FP%, TC and the three environmental variables, $EC_a$, elevation and NR using the point data. Given that differential management is usually facilitated by adopting a management class approach, the second part of the analysis focuses on management class-based analysis rather than on the point data.

### 3.2.3 MC Analysis 1 – Harvest Data as the Independent Variable(s)

An ANOVA was performed in JMP 6.0 (SAS Institute) on the point harvest data (FN, FW, MFW) (n=104) using the two "E" classes as treatment effects. This investigates how the environmental variables explain the variation observed in the crop data. It is expected that the local environment will impart some influence on plant productivity at each individual site. This yielded no significant difference in harvest parameters between the two classes (see results for full analysis). A three cluster approach was also tried (map and results not shown) but again showed no significant difference in harvest parameters between classes.

### 3.2.4 MC Analysis 2 – The Inverse Approach with Environmental Data as the Independent Variable(s)

To verify the lack of relationship between the harvest and environmental data an inverse modeling approach was also performed i.e. do crop variables explain environmental variation? Obviously, it is not expected that crop variables will influence the local environment (at least not in a relatively young production system), however this inverse approach may provide alternative (different) information than Analysis 1, which may help explain the spatial response in the orchard. The inverse management class modeling was performed by clustering the interpolated crop data (FN, MFW and FP%), again using the protocol of Taylor et al., (2007). These management classes were labeled with the subscript "C" denoting that they are derived from crop parameters, i.e. Class $1_C$, to differentiate them from the "E" classes. The "C" two cluster map is shown in Fig 2. Statistical differences in the interpolated environmental data ($EC_a$ and elevation) between the two C classes were analyzed using the modified confidence interval of Cupitt and Whelan (2001). This statistic determines if the differences between the class means is greater (or less than) the mean error associated with interpolation. If the error is greater than it is possible for the difference in classes to be an artifact of the interpolation procedure. Standard comparisons of class means, such as the Tukey-Kramer test, can not be used on spatial data, especially interpolated data, where the assumption of independent data is not valid. In high density spatial data sets, neighboring points are generally auto-correlated thus the number of independent points does not equal the number of points. The modeled NR data could not be analyzed as it does not have a kriging variance, a limitation to the statistic of Cupitt and Whelan (2001).

The modified C.I. of Cupitt and Whelan (2001) is calculated as (after Taylor et al, 2007b);

$$95\%\ \boldsymbol{C.I.}=\mu\pm(\sqrt{\tilde{\sigma}^{2}_{krig}}\bullet 1.96$$

where $\tilde{\sigma}^{2}_{krig}$ is the median kriging variance, and for statistically different classes

$$\left|Y_{zone_x}-Y_{zone_w}\right|\geq\left(\tilde{\sigma}_{krig}\bullet 1.96\right)\bullet 2$$

where $Y_{zone_x}$ is the mean of Class/Zone *x*, $Y_{zone_w}$ is the mean of Class/Zone *w* and $\tilde{\sigma}_{krig}$ is the median kriging standard deviation.

## 3.3 Results and Discussions

### 3.3.1 Preliminary Data Analysis

The results from the multivariate correlation analysis are shown in Table 1. The fruit yield parameters (TN, TW and MFW) showed no correlation with the individual environmental parameters. The maturity indicator (FP%) was slightly negatively correlated with $EC_a$ (r = -0.49) and slightly positively correlated with net radiation (r = 0.44). There was a weak negative correlation between $EC_a$ and trunk circumference (r = -0.38). From this information no distinct relationships for the production data can be identified.

### 3.3.2 Description and Discussion of the Crop Attribute Maps

The kriged maps for the measured crop parameters and TC are represented in Fig. 2 and show an independent pattern to the initial environmental clustering map (Fig. 1). A high productive area (FW > 60 $kg \cdot tree^{-1}$) is visible in the south-western side of the orchard while a lower productive area (FW < 50 $kg \cdot tree^{-1}$) is located in the central north-eastern section of the orchard (Fig. 2). The FN map follows a similar pattern. The MFW map (Fig. 2) shows the same pattern but inverted with larger fruit (> 126 $g \cdot fruit^{-1}$) in the areas with lower FW and FN and smaller fruit (< 115 $g \cdot fruit^{-1}$) where FW and FN are higher.

To evaluate changes in the maturity patterns, a map of FP% was produced. The FP% map shows distinct spatial patterns that differ from the other fruit maps. There is an obvious effect of slow maturing fruit (low FP%) along the eastern edge, probably associated with morning shading. The south-western section of the orchard is also slow maturing and aligns with the higher FN and FW area. Late maturity in this area is likely due to the larger ripening load placed on the tree. These yield and maturity maps concur with accepted physiological apple tree behavior (as described by Palmer et al., (1991) and Wünshe et al., (2000)) and illustrate that these physiological relationships exist at the within field scale.

The TC map also describes a quite clear pattern: trees on the north east side of the orchard show a larger trunk circumference while the north-west and the south seems to have a smaller size. The trend in TC in the northern section of the orchard follows the spatial trend exhibit by the $EC_a$ and elevation maps (Fig. 1). This, along with the slow maturing eastern edge effect, are indicators that environmental factors are influencing tree growth.

### 3.3.3 Results and Discussion of Approach 1 - Effectiveness of MCs Based on Environmental Variables

The $Cluster_E$ map, derived from analysis of the environmental data, is shown in Fig. 1 and the mean response of both the environmental data and crop harvest parameters for the 2 clusters are shown in Table 2. The environmental data, on which the clustering was performed, clearly shows a delineation between the high elevation and high $EC_a$ north-east corner of the block and the remainder of the block.

However, the ANOVA showed that there was no statistical difference in mean crop production responses between the two E classes. The harvest parameter maps show strong spatial patterns but these don’t visually correlate with the $Cluster_E$ map (Fig. 1). The statistical results indicate that stratification based on environmental data does not help explain the observed production variation i.e. management classes derived from $EC_a$ and elevation do not seem to be an appropriate method of management.

### 3.3.4 Results and Discussion of Approach 2 - The Inverse Modeling Approach

To verify the results from Approach 1 an inverse model was tried. The Cluster$_C$ map, derived from cluster analysis of the FN, FW and FP% parameters, is shown in Fig. 2. However, although this is a 2 class map, Class 1$_C$ is separated into 4 discrete zones whilst Class 2$_C$ is contiguous. This contrasts with the Cluster$_E$ map which has 2 classes and 2 zones. The first obvious feature of the Cluster$_C$ map is the zone in the north-east corner that corresponds to the area of high EC$_a$ response (and Class$_E$ 1). The second is that the large southern zone in Class 1$_C$ encompasses the area in the block south of the internal machinery track. There is a small zone of Class 1$_C$ in the north-west corner of the block associated with several trees with a low MFW and FP%. The smallest zone in Class 1$_C$ (mid-eastern side) does not contain a sampling site and is probably too small to be considered as a management unit. It is ignored for subsequent analysis and discussion.

The class means and comparisons are given in Table 3 The classes derived from the clustering of crop production data do not yield significant differences in the environmental data response. This reflects the results found in Analysis 1. However, the spatial patterns in Cluster$_C$, particularly the north-eastern and southern zones, indicate that there may be more to the data.

To further investigate this, the output for Class 1$_C$ has also been restructured to give the means for the two largest zones (north-east and south). The block can therefore be effectively described as having three zones – north-east, centre and south. The centre zone is equivalent to Class 2$_C$. When the means comparison is done on the zones, rather than the classes, a distinct pattern emerges. The clustering algorithm identifies Class 1$_C$ as areas with higher FN, but lower MFW and FP%. When this class is broken into its two main zones, north-east and south, environmental differences are observed. The north-east receives less sunlight (NR) but has a significantly higher $EC_a$ response, which is indicative of heavier, more clayey soils. Elevation is significantly different between the north-east and south zones, however this is unlikely to a direct causal agent of the production differences (although it may be correlated to another unidentified agent).

The $EC_a$ and NR response of the south zone is not significantly different from the center zone (Class $2_C$), hence both these areas being joined in the original $Cluster_E$ approach (Fig. 1). However, the crop response between the centre and south zones is significantly different for all three parameters (FN, MFW and FP%). There is an unidentified effect(s) in the centre zone that is reducing FN, which produces larger earlier ripening fruit. While this effect may be environmental, an observation of the patterning in the cluster map indicates that it is more likely to be managerial. The boundary between the centre and south zones follows the internal track. This can be considered a strong fit given that the cluster map (and inverse modeling approach) is derived from the low density 104 sampling points, making boundary locations uncertain.

Sources of the managerial effects on production may be diverse and could range from different treatments between the two sections during block establishment, different management within this season or possibly different management in previous seasons. With perennial systems it is possible for management effects to linger for several years, for example, a different pruning strategy in year 1 will impact on canopy and fruit development in year 2. This in turn impacts on pruning at the end of year 2 which could influence fruit development in year 3 and so on. Although the grower believes the two sections are uniformly managed, further consultation is needed to identify likely sources of the spatial pattern in the block. This is a key part of any spatial analysis and the next step in developing a spatial management strategy for the orchard.

Therefore, the environmental differences between the north-east and south zones offset each other and hide the differences between Class $1_C$ and Class $2_C$. The inverse $\text{Cluster}_E$ modeling approach yielded a different spatial structure, which, on first analysis again, yielded no statistical differences. However, interpretation of the results on a zonal, rather than class, basis indicated that the management classes (zones) are segregating crop variation and maybe useful as a means for future investigations. If the analysis was restricted to the preliminary multivariate correlation analysis and management class model then the conclusion for this block would be that $EC_a$, elevation and NR are not indicators (or drivers) of production variation. The inverse modeling revealed that the environmental parameters do impact on production, however the relationship is complex and probably influenced by management. To understand this spatial relationships better, further information on crop management is needed.

Over time temporal and spatial changes could provide effective feedback for precision horticulture and for growers on how persistent and responsive are the patterns within an orchard depending on management treatments and environmental conditions. If normally treatments are planned as homogeneous, it is rather common to find zonal pattern in a field. That may indicate an environmental implication or not consistent managing treatments.

## 3.4 Conclusions

The aim of this investigation was to investigate if the spatial variation was driven by environmental factors. A typical non-spatial analysis was undertaken but showed low or no correlation between environmental and production/quality parameters within the Gala orchard. A conventional (forward) management class model also showed no spatial relationships. However, an inverse modeling approach, coupled with some local knowledge, identified relationship between the production, managerial and environmental conditions.

Spatial variation does exist in apple orchards and there may be differential management options available to growers who are aware of this variation, to increase their potential to respond to market demands of higher quality fruit at a lower cost. However, the size and density of spatial data sets often hides these spatial relationships. Different approaches are often needed to uncover relationships and modeling and inverse modeling of management classes using environmental and crop parameters is one tool for achieving this.

## 3.5 References

Cupitt, J. and B.M. Whelan. 2001. Determining potential within-field crop management zones. In: G. Greiner and S. Blackmore (eds.). Proceedings of the Third European Conference on Precision Agriculture, June 18-20, 2001, Montpellier, France. Pp. 7−12.

Ferreyra, R.A., J.W. Jones and, W.D. Graham. 2006 Parameterizing Spatial Crop Models with Inverse Modeling: Sources of Error and Unexpected Results. Transactions of the ASAE 49(5): 1547−1561.

Florin, M., A.B. McBratney, and B.M. Whelan. 2008. Inverse meta-modelling of yield monitor data for estimation of soil available water capacities at a spatial resolution of 10 metres across farms. In: Proceedings of the 1st Global Workshop on High Resolution Digital Soil Sensing and Mapping. ACPA, Sydney, Australia, p. 10.

Kitchen, N.R., S.T. Drummond, E.D. Lund, K.A. Sudduth, and G.W. Buchleiter. 2003. Soil electrical conductivity and topography related to yield for three contrasting soil-crop systems. Agron. J. 95:483–495

Manfrini, L., J.A. Taylor, and L. Corelli Grappadelli. 2009. Spatial Analysis of the Effect of Fruit Thinning on Apple Crop Load. European Journal of Horticultural Science. In press.

McKenney, D.W., B.G. Mackey, B.L. Zavitz. 1999. Calibration and sensitivity analysis of a spatially-distributed solar radiation model. Int. J. Geo. Inf. Sci.13: 49–65.

Minasny, B., A.B. McBratney, and B.M. Whelan. 2005. VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW. 2006. <www.usyd.edu.au/su/agric/acpa>.

Palmer, J.W., Y.L. Cai, and Y. Edjamo. 1991. Effect of part-tree flower thinning on fruiting, vegetative growth and leaf photosynthesis in “Cox’s Orange Pippin” apple. J. Hort. Sci. 66(3):319–325.

Paoli, J.N., O. Strauss, B. Tisseyre, J.M. Roger, and S. Guillaume. 2007. Spatial data fusion for qualitative estimation of fuzzy request zones: Application on precision viticulture. Fuzzy Sets Sys. 158(5): 535–554.

Taylor, J.A., J.P. Praat, and A.F. Bollen. 2007a. Spatial Variability of Kiwifruit Quality in Orchards and Its Implications for Sampling and Mapping. HortScience.42:246–250.

Taylor J.A., A.B. McBratney, and B.M. Whelan. 2007b. Establishing management classes for broadacre agricultural production. Agron. J.99:1366–1376.

Wünsche, J.N., J.W. Palmer, and D.H. Greer. 2000. Effects of crop load on fruiting and gas-exchange characteristics of ‘Braeburn’/M.26 apple trees at full canopy. J. Amer. Soc. Hort. Sci.125: 93–99.

## 3.6 Figures and Tables

Table 1. Correlations between environmental parameters and crop production parameters from the 104 sample sites.

| Environmental Parameter | Trunk Circumference | Total Weight | % First Pick[^] | Total Number | Mean Fruit Weight |
|---|---|---|---|---|---|
| **Elevation** | -0.32 | 0.05 | -0.25 | 0.02 | 0.11 |
| **$EC_a$ (EM31)** | -0.38 | -0.02 | -0.49 | 0.01 | -0.08 |
| **Net Radiation** | 0.05 | 0.03 | 0.44 | -0.06 | 0.29 |

[^] sample size (n) = 85 for the FP% data

Table 2. The mean response per class for the environmental variates used in the initial cluster analysis and the corresponding mean crop production parameters based on hand sampling within the two clusters (zones).

| | **Environmental data*** | | | **Crop production data** | | |
|---|---|---|---|---|---|---|
| | **Elevation** | **$EC_a$** | **Net Radiation** | **Total Weight** | **Total number** | **Mean fruit weight** |
| **Class $1_E$ (N= 41)** | 397.09 | 48.54 | 103.99 | $55.90^a$ | $461.98^a$ | $121.95^a$ |
| **Class $2_E$ (N= 63)** | 394.38 | 33.99 | 105.32 | $56.35^a$ | $465.65^a$ | $121.64^a$ |

*Significant differences between the crop production means was assessed by ANOVA with $p< 0.05$

Table 3. The mean class and zone response of the interpolated crop production environmental data from the $\text{Cluster}_C$ analysis. The first two rows represent the class responses while the bottom three rows represent the zone responses where Class $1_C$ has been split into two zones. Class $2_C$ and Zone center are identical.

| | | Crop production data* | | | Environmental data^ | | |
|---|---|---|---|---|---|---|---|
| **ID** | **N** | **Fruit Number** | **Mean Fruit Weight (g)** | **First Pick%** | **$EC_a$** | **Elevation** | **Net Radiation** |
| **Class $1_C$** | 51 | $487.2^{1}$ | $118.7^{1}$ | $60.2^{1}$ | $36.49^{1}$ | $394.26^{1}$ | 106.96 |
| **Class $2_C$ / Center** | 53 | $442.1^{2,b}$ | $124.7^{2,a}$ | $81.8^{2,a}$ | $34.32^{1,b}$ | $394.93^{1,b}$ | 107.80 |
| **North-East** | 27 | $468.6^{ab}$ | $121.7^{ab}$ | $65.1^{b}$ | $50.05^{a}$ | $397.45^{a}$ | 104.36 |
| **South** | 21 | $485.2^{a}$ | $119.2^{b}$ | $64.6^{b}$ | $32.28^{b}$ | $393.23^{b}$ | 107.91 |

Different superscript numbers indicate significant differences between classes whilst different superscript letters indicate significant differences between zones.

^The confidence interval of Cupitt and Whelan was used to determine significance with the environmental data. C.I. for $EC_a$ and Elevation were 3.94 and 0.94 respectively.

*Significant differences between the crop production means was assessed by Tukey means comparison with $p<0.05$.

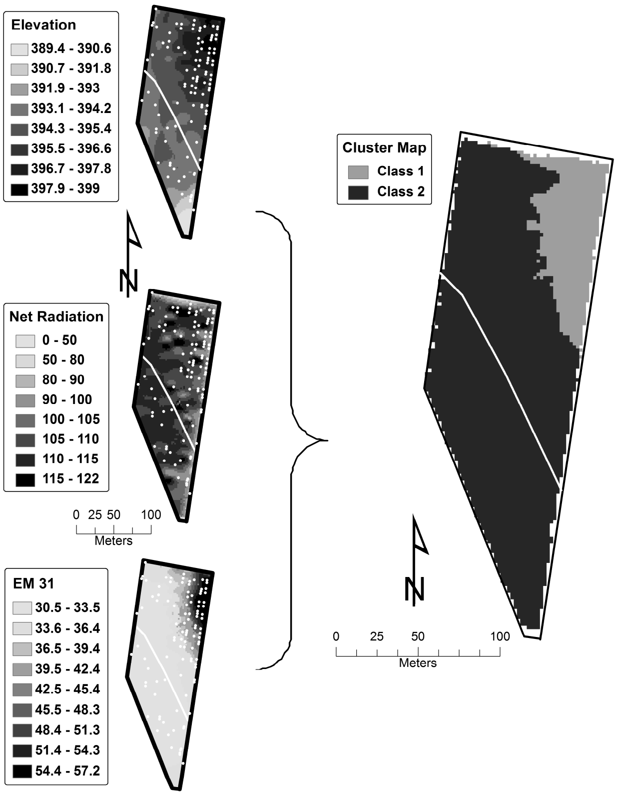


Fig. 1. Maps of the *a priori* environmental data for the study site on the left hand side (from top to bottom Elevation, apparent soil electrical conductivity (EM31) and net radiation) compressed into a two cluster management class map (Cluster$_E$) using *k*-means clustering (right-hand side).

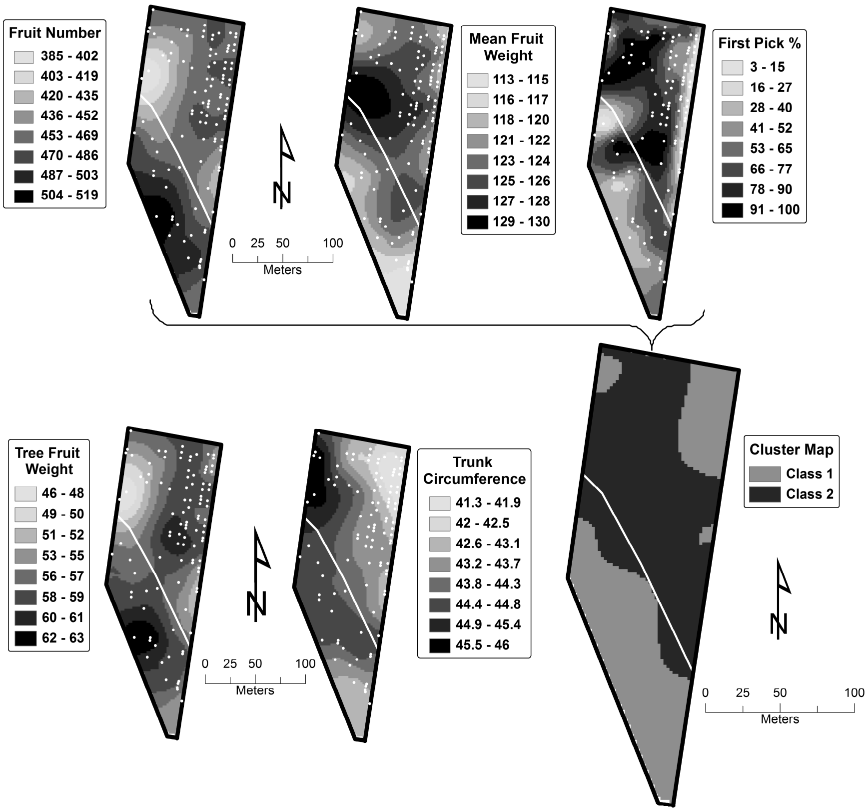


Fig. 2. Production maps derived from the manual sampling. Clockwise from top left maps are number of fruit per tree, mean fruit weight (g·fruit$^{-1}$), first pick %, total fruit weight per tree (Kg), trunk circumference (cm) and the Cluster$_C$ map derived from the MFW, FP% and FN data.

# CHAPTER 4

# THE DRIVING FORCE OF NUMBERS - HOW TO COLLECT AND INTERPRET DATA ON WITHIN SEASON VARIATION IN APPLE PRODUCTION

## 4 Summary

Precision horticulture is a new technological area aimed at reducing production costs while improving crop performance and environmental quality. This concept is still hardly integrated in fruit growing operations worldwide. Currently, information on the crop performances of fruits along the season are lacking, and this can cause considerable losses due to insufficient fruit quality at harvest time. This paper analyses field information recorded along the season in two commercial orchards, that was used to provide assistance in management decisions taken by the growers and/or the consultant throughout the season. The goal was to assist the growers in improving the efficacy of crucial management decisions, to help ensure high production levels of high quality fruit.

Data are first interpreted by mean block statistics at whole block level. Since these tools are easily applied, a relatively dense spatial data set has been constructed. Geo-referencing the data allowed us to undertake a simple spatial analysis and to illustrate the potential for this type of information to apply site-specific management strategies.

The work presented is also intended as a proof of concept of this methodology, whose satisfactory results signal that it may not be far from large-scale adoption.

## 4.1 Introduction

The concept of sustainable agriculture has become widely accepted by growers, consumers, and policymakers as an important guide for the future directions of fruit production systems. This idea is also integrated into the newer concept of precision horticulture (PH). The precision agriculture philosophy embodies the notion that decisions on orchard management should be economically viable, environmentally sound, and socially responsible. Unfortunately unanswered questions on the within season variation in crop status often make the seasonal production system difficult to read and therefore difficult to respond to in a timely manner in regards to these three objectives.

In many horticultural systems there is a lot of unused or hidden data on the crop and the environment that are collected by a grower and are available at a field or sub-field scale. These data are an important source of information for the growers. For example, there are parameters that are, or can be, recorded regularly through the growing season such as fruit diameter (Morandi et al., 2007), leaf fluorescence (Losciale et al., 2008) and fruit fluorescence (Merzlyak et al. 2008) and fruit chlorophyll content (Ziosi et al., 2008), and production parameters recorded at harvest  such as fruit counts, yield and mean fruit size. However, even with this knowledge and recent advances in technology, real effective data monitoring systems within fields are not common and management is usually performed using subjective practices.

Growers need within season information for many issues related to crop status. In apple production systems, growers routinely apply plant growth regulators to remove excess fruitlets to improve fruit size and quality (Marini et al., 1999). However there is often no or little information collected about how to use orchard-specific information to determine the intensity of chemical thinner needed or any real time feed back of the efficacy of chemical thinning post application. Moreover, no information is collected on the intensity required for the subsequent manual thinning practices and the effect that these practices have on the fruit development (Link, 2000). In other words many of the field activities related to production and quality are not checked or submitted to a quality control process to assess their usefulness before the harvest time.

A key reason for the lack of a quality control system for the thinning process is the absence of quick, effective indicators of thinning efficacy that can be easily implemented in a commercial production system. Monitoring needs to be timely and accurate to be effective. Thus the principal aim of this paper is to present some approaches that may help fill this knowledge gap. The intention is to help both the grower and the consultant, to get the feedback needed for decision making at critical times of the season and to provide information to help packing-houses to better plan harvest logistics. A brief discussion on the suite of tools to be used and rationale for their use is presented first. This is followed by some case studies where these tools have been applied to apple orchards in Italy. The interpretation of the data will initially be performed at the whole block level, using mean block statistics. This is the level of management that most growers currently operate at and a key target for the application of the monitoring tools. Since these tools are relatively quick and easy, a relatively dense spatial data set has been constructed during the project. Geo-referencing the data permits a simple spatial analysis to also be undertaken to illustrate the potential for management at a sub-block level.

## 4.2 Materials and Methods

### *4.2.1 The Suite of Tools to be Used and Rationale for their Use*

Growers require information that relates to both the quality and quantity of the crop and expected values at harvest. The first key parameter to determine for most apple production systems is the final production target. Yield is an important factor to manage given the bi-annual bearing nature of trees (i.e. in cv Fuji). Growers need to achieve a balance between the high and low bearing alternate years to obtain a more uniform crop, and more uniform income stream. Given this, there is a need for within-field tools that allow the grower to follow and asses the spatial and temporal variation and development of yield throughout the season.

The main approach to controlling yield in apples is through managing thinning treatments, both chemical and manual, so that the crop load target is achieved with a given degree of confidence. In high-quality apple production systems, manual refinement of chemical thinning is a must, but growers lack a method of assessing the efficacy of previous thinning treatments for future management decisions.

The work proposed here is innovative in that our field data recording starts with the collection of the natural flower drop and connected information on the chemical thinning treatment to adopt. Consequently the efficacy of the chemical thinning can be assessed by single tree fruit counting which also allow to determine the manual thinning pressure and its efficacy. For assessing further decision on the manual fruit thinning and other managing practices (i.e. irrigation) also the fruit growth was monitored. A late count, because the bigger fruits allow a more precise count, is also suggested to inform the growers on the final yield and, in the case of excessive fruit verified, apply an additional thinning treatment. These information coupled to the final production parameter allow also to map at block and within block level the two orchards to inform the grower on possible better strategy to adopt in the following seasons.

Yield is determined by the number of fruit and the size of fruit at harvest. Therefore to assess and monitor yield potential during the season information on fruit set is required. Prior to thinning applications, fruit set is strongly influenced by the number of flowers retained. Information on crop load can therefore be garnered by monitoring the flower drop early in the season and then monitoring the actual fruit load during the season. Constantly monitoring is required as there are several natural phenomena that result in either flower or fruit drop apart from any management intervention by the grower.
Prediction of harvest quantity (weight) and quality (diameter) can therefore be derived from simple measurements of flower drop, fruit counts and fruit diameter measurements. The following section provides greater detail of field protocols to collect this information.

### *4.2.2 Orchard Characteristics*

The study was conducted during the 2008 growing season in 2 commercial apple orchards located near Ferrara, Italy. Data were collected from 2 blocks of the cultivar Fuji, indicated as Ghelfi and Guberti of 0.65 ha and 0.95 ha, respectively. The orchards differ in age, having been planted one year apart (2002 and 2001, respectively), but are fully mature and quite comparable for all other traits: both are grafted on M9 rootstock, solaxe trained at a density of 2857 trees $ha^{-1}$ (3.5 X 1 m), and are managed following standard procedures. The pollenizer cultivars are Pink Lady at Ghelfi and Granny Smith at Guberti, in a ratio of 1:10, planted at regular intervals in the orchards. Both the orchards have an approximate North-South orientation.

### *4.2.3. Production Target Calculation*

For Fuji apples the target size for premium market price is the 80/90 mm size class. A fruit diameter of 82.6 mm equates to a mean fruit weight of 230 g/fruit. For these orchards a historic long term annual production of 65 t/ha is considered sustainable. With this information, individual fruit weight (230 g/fruit), target yield production (65 t/ha) and tree density (2857 trees/ha) the optimum average fruit number per tree can be derived (99 fruit/tree).

### *4.2.3 Method of Data Collection*

All the harvest data are recorded on a single tree basis. The trees were georeferenced with a stand alone Garmin GPSII plus (GPS) receiver.

#### 4.2.3.1 Flower Drop Monitoring

Flower monitoring began on April 11 when the trees had reached the full bloom stage;10 clusters (each containing 6 flowers) were tagged on 15 randomly chosen trees within each orchard. These tagged clusters were monitored on the 23rd, 26th, 28th of April and the 2nd, 5th, 8th and 21st of May and the number of remaining flowers/fruitlets in each cluster counted. These counts were used firstly to assess the natural flower drop, to help determine the initial rate of chemical thinning and then the rate and timing of subsequent thinning procedures. The last count (May 21st) provided a final indication of fruit set. Chemical thinning treatments were applied as following: at Ghelfi thinning was performed on the 1st and 7th of May using a mix of 1.5 kg/ha of Sevin

(Carbaryl), 1.5 kg/ha of mineral oil and 1.5 kg/ha of Exilis (6-Benzyladenine at 20% concentration); at Guberti thinning treatments were applied on the same days (May 1st and 7th) with a mixture of 1.5 kg/ha of Sevin (Carbaryl) and 1.5 kg/ha of mineral oil. A third treatment was applied on the 11th of May using a mix of 1 kg/ha of Sevin (Carbaryl), 2 kg/ha of mineral oil and 1.5 kg/ha of Exilis (6-Benzyladenine at 20% concentration). The third treatment was applied independently by the grower to increase fruitlet drop and decrease workload during subsequent manual thinning.

The average flower drop in each orchard was calculated at any single date as the percentage of flower lost over the total number of 900 flowers (15 trees by 10 clusters by 6 flowersper cluster) tagged at the start of the monitoring.

#### 4.2.3.2 Fruit Counts

Fruit counts for the estimation of fruit tree load were performed on 30 randomly chosen trees, indicated by row and tree number. Counting was done using the protocol described in Chapter 2. The counted " tree window" adopted was one meter because of the distance between the trees along the row. Every tree was counted in both orchards three different times (June 11th, July 21st and August 4th ) during the season by either 2 or 4 counters and their counts were averaged to obtain a single count/tree.

#### 4.2.3.3 Fruit Growth Monitoring, Final Fruit Weight, Class Distribution and Productivity Forecast

The maximum diameter was measured on 10 fruit from the same 30 randomly selected trees counted above, for a total of 300 fruit per orchard . Measurements were taken on June 11th , July 3rd and 21st and August 4th and 20th. From fruit diameter data, fruit weight was calculated following a standard conversion equation, and these data were entered in an algorithm that allows to calculate fruit size at a specific date of harvest. This information was used to evaluate the current status of the crop and its potential to reach the target yield parameters of fruit size and total yield per orchard. The 300 measured fruit were then divided into size categories, according to the commercial standards, which increase by 5 mm, starting from 70 mm. The percentage distribution of the fruit in these size categories was used to obtain a forecast of the size distribution at harvest. The gradient, m, of the linear diameter model was also calculated on a per tree as well as per block basis.

On 16th October a further evaluation of the fruit maturity (on the second pick fruit – see below) was assessed by a DA-meter. This sensor measures the chlorophyll content (CC) in a single fruit. This is assumed to be a good descriptor of the advancement of the maturation process. Measurements were taken on a sample of 5 fruit/tree for the 30 sample trees generating a total of 150 fruit measured per block. For each fruit the sensor was used to take 2 measurements on both the blush and the ground color sides of the fruit, and the 4 measurements were averaged.

#### 4.2.3.4 Harvest Schedule, Quality and Quantity Data Collection

Fruit were harvested in 2 passes, following the commercial strategy of the orchard, which aims to minimize the number of poorly colored and small fruit. Only larger, more colored fruit are picked during the first pass. At Ghelfi, picks were on the 2nd and 15th of October while at Guberti on the 7th and 23rd of October.

Total crop load (FN: number of fruit per tree) and total fruit weight (FW: kg/tree) were recorded and the average fruit weight (MFW: g/fruit) was calculated. All these parameters were calculated using the combined data from the two passes. The percentage of the fruit picked (FP%) in the first date was also calculated to evaluate the fruit maturation within the orchard.

#### 4.2.3.5 Post Harvest Measurements

After harvest was complete, the trunk circumference (TC) of each tree was measured 20 cm above the graft union and recorded.

### *4.2.4 Whole Blocks Analysis*

The evolution of flower drop was analysed by plotting the percentage of retained fruit against time (day of the year) for both orchards using the mean of the 30 trees (fig.1).

The results of the fruit counting are shown in tabular form (Table 1). An ANOVA was performed to compare the means at different times (days of count) and against the final harvest count. The prediction of crop development was assessed by comparing each others the mean prediction response (Table 1) and also the distribution of predicted and actual fruit size at harvest (fig 2).

The forecast of distribution of fruit in size classes was analysed by plotting the percentage of each forecast size class against the results from a commercial grading machine that measured all the fruit delivered to the packing house.

### *4.2.5 Spatial analysis*

#### 4.2.5.1 Map Production

Maps of crop production parameters were generated by punctual kriging with a global variogram using the Vesper freeware (Minasny et al., 2005) on a common grid.

Surfaces of FN, FW, MFW FP%, TC, m and the mid season fruit counts (June, July and August counts) were kriged. Variograms were generated using the 60 points from the two orchards but interpolation was done individually for each orchards by limiting the neighborhood to a maximum of 30 points. Maps were created in ArcGIS (ESRI, Redlands, Ca, USA) and are shown in Fig. 3, 4 and 5. The two fields are geographically displaced by ~800 m. The fields have been realigned as neighbors for the purposes of mapping after the interpolation.

## 4.3 Results and Discussion

### *4.3.1 Whole Orchards Level*

#### 4.3.1.1 Flower/Fruitlet Drop

The natural flower drop (from 11th till 28th April) showed a different pattern between the two orchards (Fig. 1). For Guberti, the flower drop was more intense after the third measurement day, Ghelfi showed a smoother flower drop pattern. That Guberti had larger drop may be attributable to the fact that more flower clusters were likely present on these trees, as is attested by the fact that, although there was a similar final fruitlet count on May 21st, the fruit counts per tree at harvest were higher in Guberti. The results of the initial counts provided the basis to suggest a stronger chemical thinning treatment was applied on Ghelfi (by incorporating BA into the treatment as well as Sevin) to try to reduce the fruitlet per cluster.

#### 4.3.1.2 Fruit Counts

The initial production target calculation indicated that the desired number of fruit per tree number is 99. The first count (June 11th) indicated a higher than desired average fruit number in both orchards; the Guberti orchard was particularly high and required a further reduction of ~ one-third of the fruit set. Ghelfi, on the other hand, had only a few fruit more than the target (112) suggesting a quite light thinning treatment (tab.1). Given the experiences and results from Chapter 2, there is a high probability that these counts are under-estimations due to the difficulty in locating and counting fruit within the canopy at this stage of production. The results from the June counts indicated both orchards required manual thinning, with a more severe thinning required in Guberti.

The early fruit counts support the previous data and hypothesis regarding the higher total and percentage flower/fruitlet drop in Guberti (compared to Ghelfi). After the first manual thinning (second half of June) another fruit count was performed on July 21st to verify the efficacy of the manual thinning . These results indicated that the fruit load in the Guberti orchard was still too high (136 fruit/tree) and subsequent fruit thinning was required. In the Ghelfi orchard, because the mean fruit count (109) was close to the target number (99), no other thinning treatments were recommended or applied. This decision is supported by the data on the fruit growth pattern (see next section) which forecasted a mean final fruit size between 82.2 and 85.2 mm (Table 1), which is considered optimal for marketing. A third count (August 8th), was performed to again verify the effect of the Guberti second manual thinning. This indicated that there was still a high fruit load and further additional thinning would be helpful. However, based on the forecasted mean fruit size (again see next section for details) which indicated an optimal fruit weight and diameter at harvest, the decision was made to leave the remaining fruit on the trees. The count in Ghelfi, as expected, showed a fruit number/tree similar to the previous count.

Harvest counts, which are definitive, showed that the mid-season fruit counts were highly underestimating the real tree load (Table 1). Significant differences between the harvest measurement and the counts along the season were observed for both early and late season counts.

The fruit counting technique still needs improving. The main causes of error are likely to be attributed to the tree shape and training system. Even if the “solaxe” trellis should not facilitate bias because it promotes fruit production on the external part of the canopy, there is a problem regarding fruit set at the top of the tree with this system. The pruning operations associated with this trellising induce a natural high quantity of flower buds on the tree top and promotes high amount of canopy development at the top of the tree that hides the fruit (Lauri and Lespinasse, 2000). Of course bias may be addressed to counters. Studies on the differences found between counters have been undertaken but they will not be reported in the thesis.

The two Ghelfi counts did not show any statistical difference between each other even though a manual thinning was performed between the first and the second count (as already indicated it was very light). The thinning intensity was minimal, just eliminating doubles on some of the clusters. That may have varied the average number count but not the variance between the counts. The count repetition between July and August returned similar numbers indicating that, even if they differ from the number at harvest, it might be possible to find a correction factor to improve the fruit number forecast.

In Guberti the fruit counts decrease at all measurements but their number at harvest was still too high, a clear indication that, although thinning was done, it was not as strongly as suggested (more than 40 fruit to remove per tree). Aside from the considerations on the strategy adopted by the farmer (who didn't obviously follow the advice provided), our efforts to achieve a high precision were frustrated somehow, as the difference between estimated and observed was quite high (124 Vs 175.7).

#### 4.3.1.3 Fruit Growth Monitoring and Forecast Size Distribution

The initial information collected on fruit growth highlights the excessive fruit load in both orchards. A very slow fruit growth (1.2 g/day) was observed in both the orchards, (Table 1) which translated in a forecast of small fruit size at harvest. In response, a manual thinning treatment was undertaken to reduce the carbon sinks on the tree and to partition the tree resources among a smaller number of fruit per tree (Lakso et al., 2006). The response to thinning can be seen in the second measurement in Ghelfi, with the growth rate rising in late July to the high value of2.6 g/day), giving a good diameter prediction (average of 85.2 mm/fruit) at harvest. This indicates the usefulness of the thinning treatment (Table 1). In subsequent dates, the prediction remains relatively constant, and above the optimum size range, even though the growth rate drops towards the end of the season. For Guberti, even after the initial manual thinning, the growth rate in late July still shows unsatisfactory growth, as thinning was ineffective to increase fruit growth enough to obtain a good fruit size prediction at harvest (predicted mean diameter of < 80 mm/fruit, Table 1). This observation led to the recommendation of a second thinning to further reduce fruit load per tree, following which fruit growth rate increased (> 2 g/day in early August) and remained high till the last measurement. At this growth rate, even with a high fruit load (> 120 fruit/tree, Table 1) the model indicated that the fruit diameter at harvest would fall into the optimum range.

As well as generating block mean forecasts, the fruit growth monitoring on August 20th was extended to every single fruit monitored on the trees (300 fruit per orchard) to build a fruit size class distribution (Fig. 2). In both orchards, the error between estimating in August and harvest (6-8 weeks later) is low, and can be considered informative for the purpose of giving packing house managers and marketing experts a reliable information about the make-up of the crop at orchard level. For Guberti the error of prediction of the percentage of fruit within each size class is > 5%. In Ghelfi, although prediction in the optimum class (80/90 mm) was good, there was a shift in the distribution, with an overestimation of the smaller fruit in the 75/80 mm class and an underestimation of the larger fruit in the > 90 mm class. That is due to a sampling bias by the measurer: it is likely that a person may imputable to the wrong fruit selection among the trees. The eye in fact tend to always select average fruit instead of the extreme sizes. It should be stressed that a certain error is to be expected as the algorithm employed uses a reference harvest date, which is different, by much in some cases, from the actual one. This variation can be both in advance or delay. Ghelfi for example started picking before the reference date of Oct. 15th, while Guberti was one day earlier in one orchard, and one day late in the other. Also, the model assumes non-limiting meteorological growing conditions, which in 2008 did not occur, as the weather was particularly adverse during harvest.

### *4.3.2 Single block*

#### 4.3.2.1 Maps Description and Discussion

The kriged maps for the mid-season fruit counts are shown in Fig 4 and the maps of the harvest measurements are shown in fig. 3.

The count maps (fig. 3) start very spotted and undefined in June and become more defined with the next measurements. The July and August count patterns seem to be closer to the FN and FW maps (fig.3) underlying a higher production area in the southern part of Guberti and a low productive area in the eastern side of Ghelfi.

An alternative estimation of the spatial pattern of the fruit load was assessed by mapping the gradient of the linear growth regression equation (*m*) coming from the single trees average fruit growth. The *m* maps showed a positively related pattern to the MFW maps putting an accent on the theory that bigger fruit tend to grow faster and ripen earlier (Wünshe et al., 2000). This pattern is also supported by the two FP% and fruit chlorophyll content (FCC) block maps. In fact the block where the fruit were smaller, that correspond to greener in the FCC map, a later maturation occur and vice versa.

The harvest parameter maps confirm earlier findings (Chapter 3 of this dissertation). The areas with higher indicated fruit number (> than 201) correspond to areas with higher tree productivity (more than 43.7 kg/tree; i.e. south of Guberti, south and east side of Ghelfi). Confirming earlier observations (Chapter 3, this dissertation), trees with higher loads have a tendency to produce smaller fruit, as shown in the MFW map where the south and east zone in Ghelfi register larger fruit (more than 248 g/fruit).

It is also a well known physiological behaviour that fruit of bigger size, belonging to lower load trees tend to grow faster (Palmer et al., 1997). This "advance" is reflected in the productivity maturation and fruit growth maps. In fact bigger fruit were found in the southern and eastern area of Ghelfi (< than 248 g/fruit), in combination with a low chlorophyll content (< than 1.13 DA value), an indication they were closer to maturation. Moreover, the same areas in the LR map show a higher value (> than 2.02) indicating faster growth.

Even though a superficial analysis of the maps shows a coinciding pattern between the fruit production and size, some non-typical results can be observed in Guberti upon closer analysis (fig. 3). In fact in the south-west zone a high production area (in fruit number and weight per tree)can be found, to which a large fruit (< 248 g/fruit) also corresponds. The TC map can explain this: in that area, larger trees (according to trunk size, more than 18.3 cm) can be found, probably stronger in providing the fruit with assimilates (Westwood et al., 1970), allowing to support higher load of bigger sized fruit.

Within the Guberti block a maturation pattern was found showing a higher FP% the north decreasing to the south (Fig. 4). The chlorophyll map exhibited the inverse pattern. This is a good indicator that the sensor data is giving good information on fruit maturity. The cause of the pattern is probably due to the different soil texture of the two areas. The north side is in fact a more clayey soil, rich in organic matter while the south area is more sandy.

### *4.3.3 General Discussion*

Monitoring procedures based on georeferencing and geostatistical analysis appear to yield valuable information for the management of fruit orchards. This promises to bring innovation to fruit growing, in the form of more sound, fact-based decision making. This chapter illustrates how information on the intensity of the post bloom natural flower abscission has led to orchard-specific formulation and execution of chemical and manual thinning, and how subsequent monitoring of fruit growth parameters can be utilized to further steer the crop management strategies implemented by the grower to obtain higher fruit quality. Without our intervention and suggestions, a very mild thinning treatment would have been adopted, based on the experience of the previous season . 2007, contrary to all expectations, had proven to be a very low cropping year . Without the information provided through our monitoring, the grower would have left (according to his consultant) a higher quantity of fruit on the trees, in order not to not risk another low crop season. As a result of the recommendations issued, satisfactory results were achieved, although better result could be obtained with more precise fruit count, which would have been particularly beneficial in the case of Guberti (better fruit size and lower chance of inducing biennial bearing in the orchard. Although fruit size forecasts can be improved (for example integrating in the model environmental parameters), the results of such a simple and rapid assessment of crop status appear to already merit the growers' attention, because they definitely point to existing problems in the orchard during fruit growth.

## 4.4 Conclusions

The overall objective of the present dissertation was to assess the possibility of adopting precision approaches towards the goal of achieving real-time, cost-effective control of the fruit growth process in apples. The desirability of such goal lie in the need for Italian (and other advanced economies) fruit growing to maintain a technological advantage over competitors, in order to remain economically viable. There are of course many examples of precision agriculture applications, in field crops and, more recently, in viticulture, but not much progress has been made in recent years in fruit growing. Most applications in fruit crops deal with remote sensing of tree status, with some exceptions in New Zealand, particularly for kiwifruit.

That fruit crops pose specific problems, at a species level, was one of the early findings of this thesis, and has been remarked throughout its course: the shape and depth of apple trees in modern, efficient orchards, coupled to the small size and the greenish colour of the fruitlets make for an imprecise result of the counting, which is essential in many of our monitoring practices. How to overcome this difficulty is probably the major unanswered question in this work, but future steps could be taken in the direction of better error-controlling statistical procedures. Also, technical improvements in cameras, ground-positioning devices and software might allow if not to solve, to alleviate this difficulty.

Despite this difficulty, however, it has been found in this work that monitoring, even in its present “infancy” can already provide the grower with useful information, that can guide him/her in management decisions. Quite typically, in fact, in a few instances the grower or the consultant involved in our activities did not fully believe our recommendations, admitting later to this, and in those instances we have found the larger discrepancies between expected and observed results. Providing the grower with real-time information on the flower abscission intensity at the time of chemical thinning or with the information of how many fruitlets to remove from each tree to achieve optimum fruit load, is certainly a great step forward, even with the errors indicated above, in particular because we found a tendency to underestimate the real fruit load of a tree. This means that a recommendation for fruit removal tends to be less than really necessary, thus allowing to minimize the consequences of such counting errors.

Great progress was found when applying appropriate georeferencing and geostatistical approaches to data collection and analysis.

The analysis of maps of orchard and fruit characteristics has given us confidence in our approach, as it is apparent that the traits studied form a coherent, self-explanatory picture of orchard performance. These maps indicate that, contrary to expectations, there can be parts of an orchard where higher crop loads per tree are not conflicting with the tree's capacity to produce large fruit and earlier in maturation. This can be explained with different “environmental” characteristics (mostly restricted to soil, very likely) that growers aren't used to factor in their management strategies.

After three years of work on the topic, the ground has certainly been broken, yet more work lay ahead, as can be expected. The accumulation of accurate orchard data is needed to give the density maps more solid groundings, while completing the maps with accurate georeferencing of yield (collected via technology-already available-allowing to know the location of a bin when it was filled), and of other parameters that can be easily measured on each fruit in the sorting lines, will propel the fruit growing of a near future into a new dimension of precision, better and more respectful use of resources, and an overall more sustainable form of fruit growing.

## 4.5 References

Lakso, A.N., Robinson, T.L. and Greene, D.W. 2006. Integration of environment , Physiology and fruit abscission via carbon balance modeling – Implications for understanding growth regulator responses. Acta Hort. (ISHS) 727:321-326

Lauri P.E., Lespinasse J.M., 2000. The vertical axis and solaxe systems in France. Acta Hort. 513: 287-296

Link H. (2000) Significance of flower and fruit thinning on fruit quality. Special issue: Abscission and thinning of young fruit - from molecular to applied aspects. Plant Growth Regul 31: 17-26

Losciale, P., Oguchi, R., Hendrickson, L., Hope, A. B., Corelli-Grappadelli and Chow, W. S. (2008) A rapid, whole-tissue determination of the functional fraction of Photosystem II after photoinhibition of leaves based on flash-induced P700 redox kinetics. Physiologia Plantarum. 132: 23-32.

Manfrini, L., J.A. Taylor, and L. Corelli Grappadelli. 2009. Spatial Analysis of the Effect of Fruit Thinning on Apple Crop Load. European Journal of Horticultural Science. In press.

Marini, R.P. 2003. Fruitlet size and position within the cluster influence apple fruitlet susceptibility to chemical thinners. J. Hort. Sci. & Biotechnology 78:813-820

Merzlyak MN, Melø TB, Naqvi KR. Effect of anthocyanins, carotenoids and flavonols on chlorophyll fluorescence excitation spectra in apple fruit: signature analysis, assessment, modelling, and relevance to photoprotection. Journal of Experimental Botany (2008) 59:349–359

Minasny, B., A.B., McBratney and B.M., Whelan 2005. VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A05, The University of Sydney, NSW. 2006. <www.usyd.edu.au/su/agric/acpa>.

Morandi, B, Manfrini L, Zibordi M, Noferini M, Fiori G, Corelli Grappadelli L. 2007. A low-cost device for accurate and continuous measurements of fruit diameter. HortScience 42, 1380–1382

Palmer, J.W., R. Giuliani and H.M. Adams. 1997. Effect of crop load on fruiting and leaf photosynthesis of 'Braeburn'/M.26 apple trees. Tree Physiology 17:741-746.

Westwood, M.N. and Roberts, A.N., 1970. The relationship between trunk cross-sectional area and weight in apple trees. J. Am. Sot. Hortic. Sci., 95: 28-30.

Wünsche, J.N., J.W. Palmer, and D.H. Greer. 2000. Effects of crop load on fruiting and gas-exchange characteristics of ‘Braeburn’/M.26 apple trees at full canopy. J. Amer. Soc. Hort. Sci.125: 93–99.

Ziosi, V, M. Noferini, G. Fiori, A. Tadiello, L. Trainotti, G. Casadoro, G. Costa. 2008. A new index based on vis spectroscopy to characterize the progression of ripening in peach fruit,. Post harvest Biology and Technology. 49 (3): 319-329.

## 4.6 Figures and Tables

Table 1. Fruit size forecasting parameters (growth rate, predicted diameter and predicted fruit weight),fruit count and production derived calculation, actual measurement variables at harvest (fruit number/tree, Mean fruit weight mean diameter yield) for the two orchards. The hypothetical harvest date was October 15th. The expected and obtained fruit production per ha was calculated considering a tree density of 2857 tree/ha. The first measurements day(June 11th) report only data on fruit counts because it's the first of the two needed values to obtain the forecast.

| Orchard | Day of Measurement | Growth Rate (g/day) | Predicted Diameter (mm) | Predicted Weight (g) | Average Fruit/Tree | Average Fruit Size (g/fruit) | Average Fruit Diameter (mm) | Production (t/ha) |
|---|---|---|---|---|---|---|---|---|
| Ghelfi | **11/6**[§] | . | . | . | 112b | 230 | 82.6 | 73.6 |
| | **03-lug** | 1.2 | 75.9 | 179.1 | | | | |
| | **21-lug** | 2.6 | 85.2 | 252.1 | 109b | 230 | 82.6 | 71.89 |
| | **04-ago** | 1.9 | 86.5 | 263.3 | 107b | 230 | 82.6 | 70.31 |
| | **20-ago** | 1.1 | 85.1 | 251 | | | | |
| | **Harvest** | | | | 130.9a ° | 239.9 | 83.8 ° | 89.8 ° |
| Guberti | **11/6**[§] | | | | 146b | 230 | 82.6 | 96.16 |
| | **03-lug** | 1.2 | 75.2 | 174.6 | | | | |
| | **21-lug** | 1.7 | 79.1 | 202.5 | 136bc | 230 | 82.6 | 89.15 |
| | **04-ago** | 2.1 | 80.9 | 215.9 | 124c | 230 | 82.6 | 81.25 |
| | **20-ago** | 1.5 | 81.3 | 219.7 | | | | |
| | **Harvest** | | | | 175.7a ° | 199.5 | 78.7 ° | 100.2 ° |

*Significant differences between the days of fruit counts means and harvest count were performed by ANOVA with $p < 0.05$ while means separation was evaluated thanks to SNK $\alpha = 0.05$ ..

[§] The first measurement day (June 11th) report only data on fruit counts because the first of the two needed values to obtain the forecast.

° refers to measured not predicted data

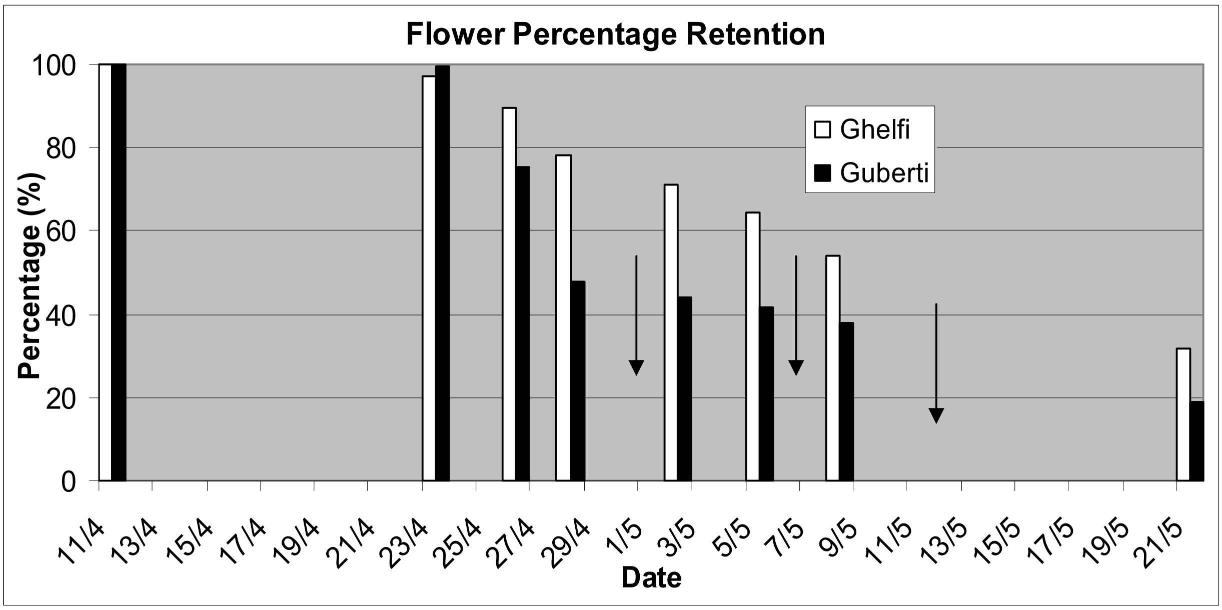
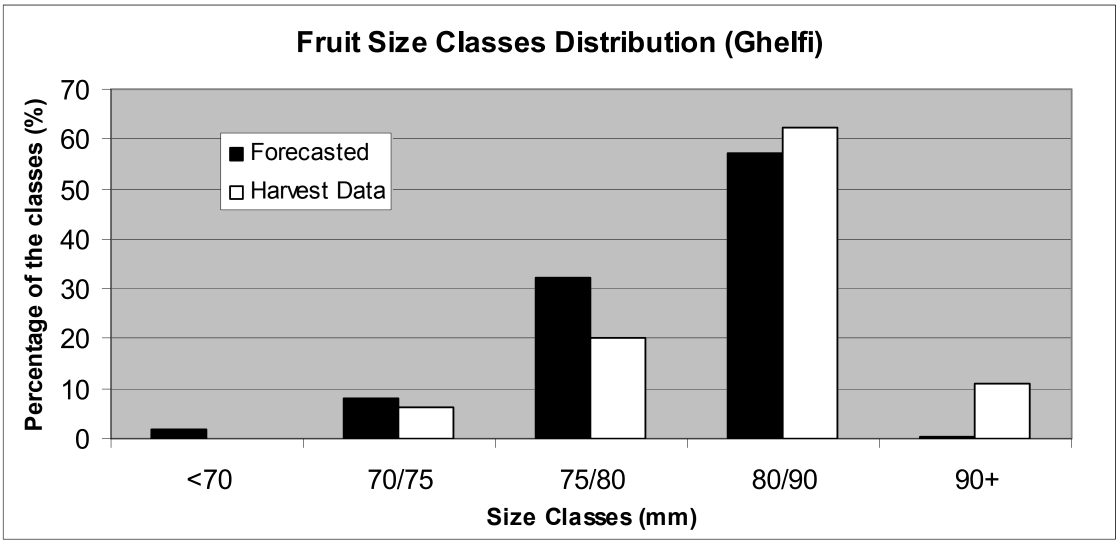


Fig.1. Percentage of flower retain in Ghelfi and Guberti orchards before and after the chemical thinning treatment The arrows indicate the chemical thinning treatment days. The first two arrows indicate treatments applied at both Ghelfi and Guberti, the third only at Guberti.



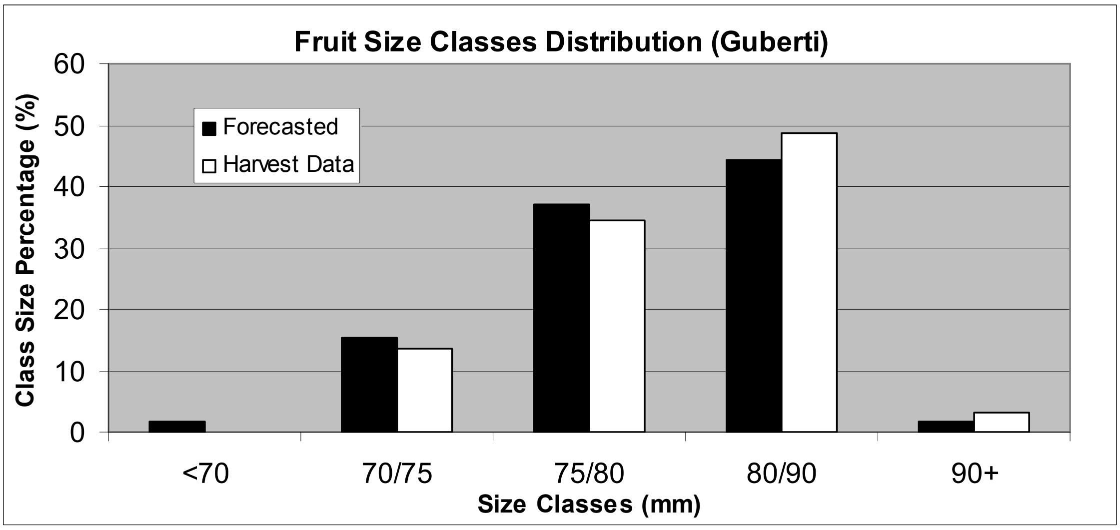


Fig 2. Harvest and predicted (on August 20th) fruit size class distribution (%) at Ghelfi and Guberti orchards.

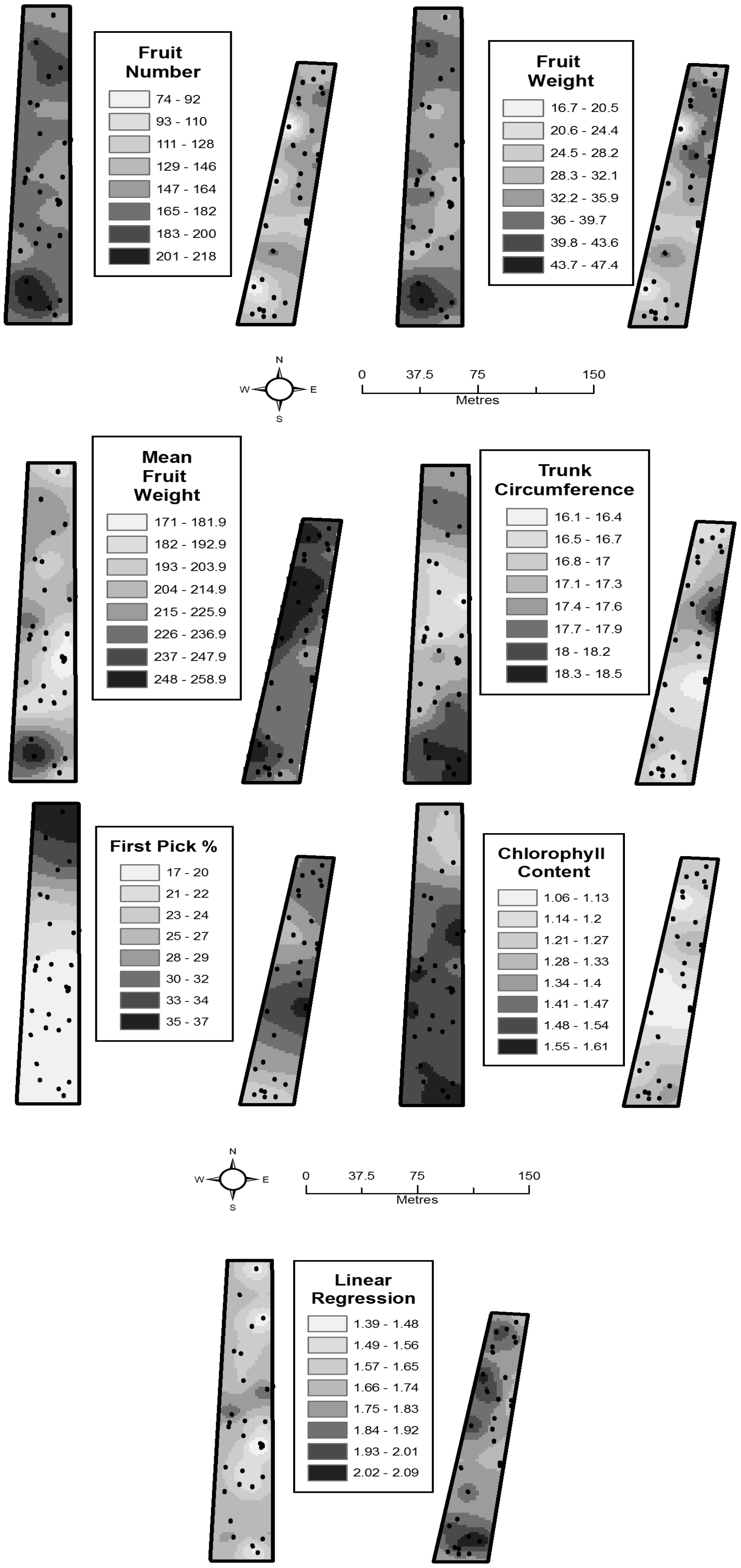


Fig. 3. Production, trunk circumference and maturity/growth maps. Maps derived from manual samplings. From the top left maps are: number of fruit per tree, total weight of fruit per tree (kg/tree), mean fruit weight (g/fruit), trunk circumference (cm,) percentage of fruit harvested in the first picking day, fruit chlorophyll content and the linear regression of the fruit growth.

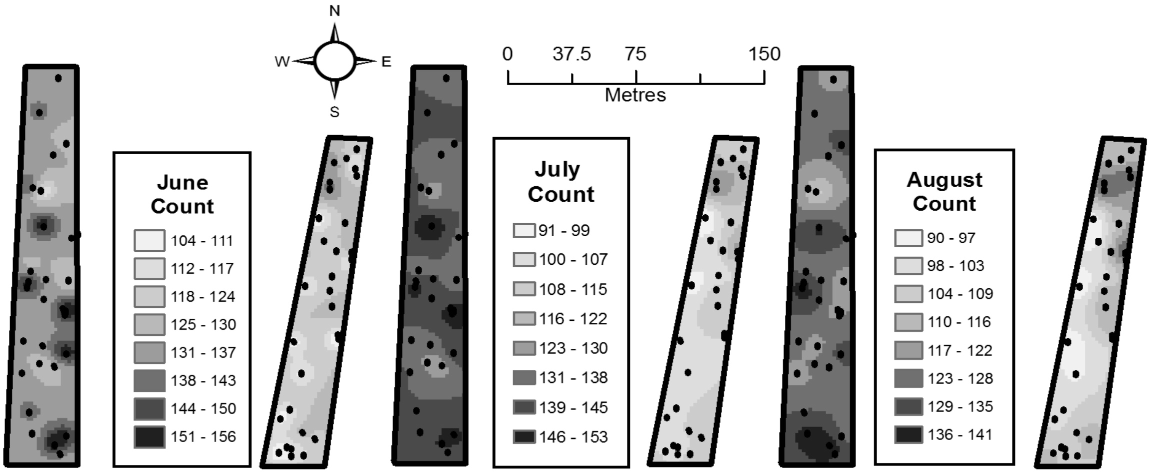


Fig. 4. Counts maps (number of fruit per tree) derived from the manual sampling along the season. Maps refer from the left at June, July and August counts.

# CHAPTER 5
# CONCLUSION AND FUTURE PERSPECTIVE

## 5 Aim of The Thesis

*Verify and quantify the variation magnitude, sources and distribution of quality-quantity and environmental parameter within apple orchards to discover/define opportunities for managing and exploit this variation. The final aim would be to build up a management protocol for assessing growers, consultants, and PH developers to render their activity more effective.*

Precision horticulture and spatial analysis applied to orchards is a new technological area of precision agriculture which aims to reducing production costs by continuously monitoring orchard-derived information. It takes advantage of the synergy between geostatistical analysis and point-data mining to implement management decisions at the single orchard level. Potential applications range from the opportunity to check in real time the effect of cultural practices, to the possibility of optimizing the whole orchard management, including the analysis of field data that can impact the post harvest handling of the fruit. This Dissertation has focused on some of the parameters that can provide the most information with the least amount of effort needed to collect them, and it has developed techniques for the data analysis aimed at the control of quality, production and environmental characters in apple orchards.

The prospects for precision horticulture are of increasing development by researchers and consequently uptake by growers. For researchers, the notion is arising that it is possible to devise monitoring schemes that can be implemented in the field, at reasonable cost, and that can largely improve the value of the crop by increasing its quality and uniformity. For the growers, adoption of precision horticulture appears inevitable if they are to maintain profitability of their operations vis-a-vis competition from emerging countries with different economic dynamics and lower production costs. Furthermore, increasing pressure towards respectful and reduced use of natural resources, one of the fundamental tenets of sustainable agriculture, will also represent a driver pushing for the adoption of this technology. At present, however, the acceptance of precision fruit growing suffers from a lack of trust from the growers, and this has impacted this Dissertation in a few instances when the growers have not followed precisely the recommendations that were formulated after the analysis of the data gathered.

The potential for PH to deliver innovation is high, and it is to be expected that research into this field will increase, with beneficial consequences on its uptake by growers. As this will not occur overnight, dissemination of results and demonstration of monitoring, georeferencing, analyzing will be necessary. These technologies promise a new approach to the management of orchards that will coherently respond to environmental variations in the orchard (e.g. soil characteristics), after having revealed them. Knowledge alone will not be enough, though, therefore this Dissertation has been conducted in commercial farms to obtain interaction with growers, as a means of learning how to deal with them in term of their acceptance of this type of far-reaching management system. This type of implementation has been the an important objective during the development of this thesis project.

### 5.1 What has Been Found at Orchard Level?

To date, information on the spatial variability in the orchard of apple fruit load has never been clearly described. It is important to underline that this crop has different characteristics and management strategies compared to field crops thus new methodologies for data capture and analysis had to be studied and developed. The three dimensional shape of the tree, the perennial behavior, the need for irrigation , that for hand harvesting, and the pre-harvest techniques impact on crop quality are just a few of the variables to be optimized in a correct management approach.

Experimentation from both data collection during the growing season (chapter 2 and 4) and from harvest/postharvest data (chapter 3 and 4) were used to assess labor, resource and other management information input.. These investigations indicate that spatial variation does exist in orchards and support the possibility of differential management options for growers, and scientists. This can have a far-reaching impact in improving the overall quality of production without increases in cost of production. For example, a discussion is given in Chapter 2 on fruit size distribution and variability within the season. Decisions on practices such as thinning are often made based on the assumption of uniformity in the orchard, which is probably rooted in the minds of the growers since every effort is made to achieve such uniformity, and because such assumption justifies a simplified execution of such practices. The realization that variations exist within an orchard perceived as uniform is important for the grower, who should learn to identify and treat differently sites within the orchards which are different and require more attention. Along the same lines, knowledge of prior yields can guide the grower in the management of harvest logistics, as well as assist the packing-house manager to better plan his activities. In Chapter 3 a PH approach coupled to traditional statistical analysis has been undertaken to correlate environmental parameters to production/quality parameters within an orchard. A first analysis didn't provide a sufficient explanation. Consequently an inverse modeling approach was taken, which allowed to extrapolate a quite strong relation between the field disposition and the environmental conditions. This investigation points out again that spatial variation does exist in orchards and there can be the opportunity of differential management. In Chapter 4 a preliminary methodology to manage cultural practices on the base of the information coming from the field was assessed. After defining an initial production target by analysing the orchard characteristics, an analysis of field information recorded within the season and at harvest, as flower drop, crop load, fruit growth, maturity parameters was performed. The analysis was undertaken in order to assist the growers in managing operations for better quality/quantity control. Data interpretation was initially performed at whole block level using mean block statistics then georeferenced data allowed a simple spatial analysis to highlight the potential for differential management adoption. This work clearly indicated that the possibility exists of providing information in real time for critical management operations.

These chapters are an initial stone to begin multi-facial precision management in orchards and assist growers and consultants with their activities.

The overall objectives of this Dissertations have been met, as it has been shown that not only can management decisions be based on data collected and analysed in the orchard, but that relatively simple monitoring techniques have a great potential for both current season management, and to construct long-term information tools that can streamline the management to the environmental conditions in the orchard. Further work will be needed as many interesting questions arise from the realisation of the potential of this approach.

## 5.2 Future Works and Perspectives

Options and possibilities for working in PH in the future are copious. This is because PH is an exciting subject for researchers to increase their knowledge on spatial data analysis and crop studies at an orchard level. Areas of particular need for PH to progress included a better understanding of spatiotemporal variation, the relationship between spatial and temporal crop, managerial and environmental parameters at a sub-field level, overcoming methodological/agronomical challenges on how to apply this knowledge for optimizing the crop management applications and developing new modeling and analysis strategies for PH.

From a PH angle there is scope to challenge the conceptual basis of current uniform management in terms of its of applicability. More specifically, to examine and identify processes and methodologies used in horticulture that are not able to capture spatial variation at a within-field scale. In fact, because PH scale is more variable and difficult to model than uniform systems, the research for the most useful balance between a complex analysis scheme and a simple one is an important future pursuit and probably the most important from a horticultural perspective. Furthermore, the development of models, either simple or complex, must also consider practical aspects of modeling, such as the cost of the modeling exercises, emphasizing the exchange between crop modeling skills and skills in spatial statistics.

A further practical research issue that requires future work is identifying the correct relevant model inputs required within the context of PH. There is scope to continue the development of strategies that efficiently capture the information required for PH analysis and it is worthwhile to continue the pursuit for PH across and within orchards to evaluate possibility of VRT and create newer and more useful networks of knowledge.

The potential and the initial aim of this thesis is to enhance the data analysis, reading it as “numbers from nature” in a place, the orchard, through modeling and PH approaches that provide new skills and technologies for horticulture. An interesting aspect of future work would be to incorporate some more environmental outcomes such as maturation rate or other quality parameters linked to the environmental conditions during the season. This could give consultants the power to predict the crop/fruit behavior and provide growers with better information and safety on their work, making it less stochastic and more certain. Moreover, a more confident answer of the temporal variation is required, to asses and reinforce the approaches in this thesis described. This suggest that future work about measuring and modeling ecophysiological outcomes at a high spatial resolution would be of great value. It would also be useful to evaluate economic outcomes over the long term. Integrating the environmental outcomes with the economic outcomes using an economic framework is a possibility that warrants further work.

Finally, inclusion of social outcomes due to different management approaches to orchard managing should also be considered. With respect to the evaluation of PH, a point of departure for further investigation is why certain orchards across a farm are more suited to PH than others. This question relates back to continuing research about spatio-temporal variability as well as how to evaluate spatial variation. To ensure that PH developers make this philosophy of study a relevant part of the horticultural world, it is a must that research continues to focus on broadening ideas about how PH can contribute. To this side an important, always increasing, subject within agricultural research, producers and consumers is sustainability. The opportunities exist for innovative horticultural systems using the PH structure to reinforce sustainability.

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