Certificate of Originality

I hereby certify that the text of this thesis contains no material that has been accepted as part of the requirements for any degree or diploma in any university nor any material previously published or written unless the reference to this material is made.

James A. Taylor

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Acknowledgements

"Is this the real life,
Is this just fantasy......"

For the past ten years my life has been intertwined with the Faculty of Agriculture, and more specifically the Australian Centre for Precision Agriculture, at the University of Sydney, firstly as an undergraduate and then a postgraduate student. Unfortunately nothing last forever and my days as an "eternal" student have come to a juddering halt (much to the relief of my parents). Along the way I have had help from more people that I can recall and my Oscars acceptance speech would go something like this........

Firstly I would like to thank my peers and supervisors within the ACPA. My supervisor Alex for providing the opportunity and inspiration for my studies. Over the past 5 years we have probably spent more time apart on different continents than at University however he has always made his time available when it is required and I'd like to thank him personally for that. To my peers in soil science, Budiman, Brett, Damien, Odeh, Johnny and particularly, Matt, Tommy, Tamara, Craig, Dick and Raphael, thank you for the invaluable assistance you have provided along the way both professionally and socially. It seems inconceivable that mine is the last of our theses to be submitted and that we are now spread far and wide around the globe. I am sure out friendship will endue (even if communication lapses from time to time).

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In proverbium cessit, sapientiam vino adumbrari.

Pliny the Elder (Caius Plinius Secundus), Historia Naturalis

Objectives

As stated in the title, the work presented here is an investigation into the application of production-orientated information technologies to the Australian viticultural industry. In particular the research is aimed at:

i) quantifying the amount of variability within Australian viticultural production (with a particular focus at the moment on yield) to determine if site-specific management is practical,

ii) incorporating new technologies and methodologies with existing vineyard soil survey protocols to improve the resolution of vineyard soil and environmental mapping,

iii) utilising the derived soil and environmental information to predict "digital terroirs" at a sub-vineyard scale to ensure that vineyard design is optimised, and

iv) developing a decision support model to assess "total" grape quality to assist viticulturists with selective harvest strategies.

Prior to the research chapters three literature review chapters are presented that provide a background to the concept of Precision Agriculture (Chapter 1), the factors that influence vineyard site selection and methods of selecting vineyard sites (Chapter 2) and new and emerging technologies available to the viticulture industry (Chapter 3).

Synopsis

Digital terroir is a relatively newly coined phrase and one that may raise the eyebrows and perhaps the ire ofthe more traditional wine-loving people in the world. The Prologue is a short explanation of what is meant by "digital terroir", how it differs to the traditional concept of terroir and why it is necessary in modern viticulture.

Following the Prologue, the first three chapters are reviews of existing literature. In Chapter 1, the philosophy and ideals of Precision Agriculture are related to the viticultural industry. Since its inception Precision Agriculture has been primarily the domain of annual broadacre cropping industries. In recent years this has been expanded to other cropping areas e.g. horticulture/viticulture and even livestock with the concept of fenceless farms. The application of Precision Agriculture to perennial crops, like grapevines, requires a slight modification of thinking. More importance is attached to initial site-selection and vineyard design as initial mistakes will be propagated for 30 or more years. There is a greater opportunity to value-add to production information due to the higher level of vertical integration in the wine industry. Finally the emphasis on quality is much stronger in viticulture thus more attention must be given to yield-quality interactions.

Chapter 2 is a review of site factors that affect the yield and quality of grapevines. A discussion on the influence of climate, soil and landform on winegrapes is followed by a review of current and previous indices used to determine vineyard site suitability. The majority of these indices are designed for application at a regional level and are based on climatic variables. This reflects the notion that climate is the dominate influence on grape yield and quality. In the past decade attempts have been made to scale down these indices and incorporate other environmental data e.g. soil type, geology, and landform attributes. These new approaches to predicting "digital terroir" are still quite broad and aimed at a region or district level. No literature on digital terroir delineation was found at a sub-vineyard level. The current methods for surveying prospective vineyard sites are discussed

Chapter 3 examines the new and emerging technologies available to viticulturists to measure their production systems - both from a crop and environmental point of view. The evolution of the grape yield sensor is documented. Current equipment and the future opportunities for variable-rate technology are reviewed. The main section of the chapter deals with the rapid adoption of remote sensing technologies in viticulture and the applications, advantages and limitations of remotely sensed data. In particular the adoption of canopy imaging and soil electrical conductivity surveys which are now commonly acquired data layers in viticulture. The types of decision support available to viticulturists and Australian suppliers of spatial information are reviewed before future site-specific information needs for Australian viticulture are discussed.

Chapter 4 is the first of the research chapters and investigates the amount of variability currently being recorded by new yield sensors. A specific aim of the chapter was to publish some geostatistical data on winegrape yield. For site-specific management to be effective there must be a certain magnitude of variation and spatial structure to the variation. The suboptimal use of classical statistics in describing spatial variation is discussed and investigated. In particular problems with the commonly used coefficient of variation statistic are highlighted. Alternative spatial statistics are discussed and the yield data collected over the past 4 years is analysed. The amount of yield variation within a block is highly variable and not all blocks appear to be suitable for site-specific management. It is important to identify the most suitable blocks to ensure that the effort put into site-specific management produces the greatest return. Many blocks did exhibit yield variation and this variation often occurred over distances smaller than the current standard soil survey grid used to delineate vineyards. While viticultural yields tend to be higher than broadacre crops the effective magnitude of variation was smaller. A brief geostatistical investigation of winegrape quality parameters is presented. This data is derived from hand sampled surveys as a commercial quality sensor is currently unavailable. From the analysis different quality attributes have different ranges over which they vary and maps of individual quality attributes show little similarity among themselves. This will have implications for quality management and is discussed in more detail in Chapter 8.

Chapters 5, 6 and 7 flow on from one another and are aimed at identifying a protocol to map digital terroirs at a sub-vineyard level. Chapter 5 presents a protocol for conversion of existing point source soil survey information into continuous raster maps using pedotransfer functions. This displays the data in a form that is easier to interpret and also produces data layers that can be easily modelled within GIS or statistical software.

Soil surveys are generally constrained by cost to 75 m -100 m grids. Analysis of yield data indicates that considerable variation can occur at scales <75 m. In recent years it has been common to conduct soil electrical conductivity surveys prior to vineyard design. This provides a layer of information at a much finer scale and may identify features not evident from the broader conventional soil survey. While this information is often collected no protocol for incorporating the EC_a or elevation information into soil property maps exists. Chapter 6 examines the potential of regression kriging to utilise both the conventional and ancillary data to produce more accurate and detailed maps of soil properties. Finally Chapter 7 presents a local site index (LSI) that may be employed to map vine suitability at a sub-vineyard scale. The usefulness of the LSI is discussed with reference to crop response (yield and imagery data) in certain parts of the trial vineyards. The use of regression kriging did not statistically improve the predictions of soil properties. However when incorporated into the LSI the regression kriged data produced a map that was more coherent with crop response. Despite the lack of statistical response, soil maps appear to benefit from the regression kriging approach. The LSI is being proposed here for the first time and is still open to amendment and validation at other vineyard sites.

Chapter 8 investigates real-time grape quality sensing and the issue of "total" winegrape quality versus the quality of individual grape juice parameters. The first part of the chapter is a literature review of how individual grape quality are measured and the opportunities for on-the-go sensing. The second part is a research paper to develop a fuzzy logic model to predict "total" grape quality from individual grape quality properties. In Chapter 4 it was observed that individual must quality properties such as sugar content, pH and titratable acidity exhibit spatial patterns. To manage this a grower needs a decision support tool to determine how this variation is affecting the final output. The model developed here is aimed at providing this decision support. A "total" grape quality map was derived from the merging of sampled grapes and expert knowledge within the fuzzy logic model. The model presented was applied retrospectively to the vintage however an opportunity exists to trial it for a selective vintage.

The final chapter, Chapter 9, presents some conclusions to the aforementioned objectives and discusses areas for future research for the mapping of digital terroir and the adoption of precision viticulture

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List of Abbreviations

ACPA	Australian Centre for Precision Agriculture
AHP	Analytical Hierachy Process
AOC	Appelation d'Originie Controlee
ART	Adaptive Resonance Theory
AWBC	Australian Wine and Brandy Corporation
AWC	Available Water Content
AWRI	Australian Wine Research Institute
CDA	Catchment Decision Assistant
CLORPT	Climate Organism Relief Parent material and Time
CRCV	Cooperative Research Centre for Viticulture
CSIRO	Commonwealt Scientic and Industrial Research Organisation
CSTARS	Center for Spatial Technologies and Remote Sensing
CV	Coefficient of Variation
CVa	Areal Coefficient of Variation
DAW	Deficit Available Water
DC	Direct Current
DGPS	Differential Global Positioning System
DIPNR	Department of Infrastructure, Planning and Natural Resources
DTM	Digital Terrain Model
ECa	Apparent Electrical Conductivity
EM	Electro magnetic
EMI	Electro Magnetic Induction
ENFET	Enzyme Field Effect Transistor
ENSAM	École Nationale Supérieure Agronomique de Montpellier
ERIC	Environmental and Research Consortium
FPI	Fuzziness Performance Index
FVT	Free Volatile Terpenes
GA	Genetic Algorithm
GAM	Generalised Additive Model
GCP	Ground Control Point
GDA	Geodetic Datum of Australia
GI	Geographical Indications
GIS	Geographical Information Sysem
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GRAPES	Grapevine Remote-sensing Analysis of Phylloxera Early Stress
GWRDC	Grape and Wine Research and Development Corporation
HPLC	High Performance Liquid Chromatography
INRA	Institut National de la Recherche Agronomique
ISFET	Ion-Selective Field Effect Transistor
LAI	Leaf Area Index
LSI	Local Site Index
LTI	Latitude Temperature Index
MLR	Multiple Linear Regression
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPE	Modified Partial Entropy
MTWM	Mean Temperature of Warmest Month

NASA	National Aeronautics and Space Administration
NDVI	Normalised Differences Vegetation Index
NFS	Neuro-Fuzzy Systems
NIR	Near Infr-Red
NIRS	Near Infra-Red Spectroscopy
NNA	Neural Network Analysis
NNA	Neural Networks
OK	Ordinary Kriging
Oi	Opportuniy Index
PA	Precision Agriculture
PCA	Principal Components Analysis
PCD	Palnt Cell Density Ratio
POK	Punctual Ordinary Kriging
PPR	Plant Pigment Ratio
PSD	Particle Size Distribution
PTF	Pedotransfer Function
PV	Precision Viticulture
PVR	Photosynthetic Vigour Ratio
PVT	Potential Volatile Terpenes
QCM	Quartz Crystal Microbalances
RAW	Readily Avaiolable Water
RBF	Radial Base Function
RK	Regression Kriging
RMSE	Root Mean Square Error
RTK-GPS	Real Time Kinematic Global Positioning System
RVI	Relative Vegetation Index
S	Spatial Structure
SCORPAN	Soil, Climate, Organisms, Relief, Parent material, Age and Space (N)
SI	Site Index
SLR	Stepwise Linear Regression
SOM	Self Organising Maps
SSC	Soluble Sugar Content
SSCM	Site Specific Crop Management
TA	Titratable Acidity
TAW	Total Available Water
UVV	Unité Vigne et Vin
VDQS	Vin Délimité de Qualité Supérieure
VRI	Variable Rate Irrigation
VRT	Variable Rate Technology
WGS84	World Geodetic System 1984
UTM	Universal Transverse Mecator