2011 3rd International Conference on Machine Learning and Computing (ICMLC 2011)

A Multi-agent (MA) Cellular Automata (CA) Framework for Grapevine Growth and Crop Simulation

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***Abstract*—The paper describes a multi-agent (MA) cellular automata (CA) model framework for simulating grapevine growth and crop in Chardonnay cultivated in northern New Zealand. Estimating or projecting crop (quantity of grapes in tons per hectare (ha) and berry quality in Brix i.e., sugar content) is an extremely complex task as the crop depends on many factors that interact with each other at varying degrees over different time intervals in a "chaotic" manner. These "deterministic" factors could be classified as relating to grapevine variety, climate (year-to-year variability in weather conditions) that in turn determines grapevine phenology, and then finally vineyard operations, all of which impact on the vigour in vine growth and ultimately on the outcomes. The deterministic factors and their influences are modelled using CA rules, MA behaviour and interactions. The key phenological events pertaining to grapevine growth such as budburst, flowering, veraison, berry ripening are simulated using CA lattices and rules. The major vineyard operations such as pruning, irrigation, spraying, trellising, canopy manipulation and harvest are incorporated into the MA architecture. Meanwhile, the outcomes classified as frost damage and over/ under cropping are simulated using CA lattice structures and rules at both individual vine and field (vineyard) scales using daily temperature, vine canopy structure and vineyard yield data of Chardonnay from northern New Zealand. Results of statistical tests, such as discriminate analysis and regression techniques ran using yield and climate data, as well as domain expertise are used to develop CA and agent rules. NIWA's climate data captured at Henderson River Pk metrological station (36.85539S, 174.62383E), and obtained via NIWA's web portal (http://cliflo.niwa.co.nz) is used in the study. Finally, the paper presents the conclusions drawn from the initial investigation so far conducted, frameworks designed and visualisation formats produced for this multi-agent cellular automata approach to simulating and visualising the climate effects using rules developed with a mix of vineyard observations, meso and macro scale data on daily weather conditions (probability and cumulative frequency distributions). The research and results achieved thus far show potential for simulating vine growth and yield in different grape varieties from New Zealand's major wine regions and from that of world's in ways which that have not been explored previously.**

Keywords-component; climate effects; yield; vineyard

I. INTRODUCTION

Obtaining a nearly accurate as possible estimation of grapes in quantity (tons/ha) and quality (sugar, aroma and other colour phenol contents) is an extremely complicated task yet it has operational and economic significance to viticulturists and vintners (1) (2). Traditionally, vineyard yield and must composition are measured in terms of tons per hectare (ha) and Brix (and some occasions with pH and acidity) respectively. Over the years, there have been formulae developed to estimate the crop with vines/ha, clusters/vine, buds/vine and cluster/ berry weight values (sampled averages) for different varieties and the paper gives an outline on some basic formulae currently in use. Meanwhile, in any approach inconsistencies between a vineyard's estimated and real crop figures are considered to be coming from two factors;

(1) 70% of the variation from year-to-year variability in the number of clusters and
(2) 30 % of it from the variability in cluster weight.

From the initial introduction of Van Neumann neighbourhood rules in the 1950s (3) (4) to recent satellite imagery grid quantification research (5) clearly depict the significant advances made in the development and application of CA and other related hybrid approaches to simulating spatial and temporal changes in a wide spectrum of disciplines. The second section of the paper briefly outlines a few CA frameworks specially developed for vegetation dynamics simulation. Consequently, details of a multi agent CA framework being developed for simulating grapevine growth and yield in *Chardonnay* cultivated in northern New Zealand are presented.

II. CROP ESTIMATION ISSUES IN VITICULTURE

Adverse consequences of inaccurate grape crop estimation and related issues are well-known among viticulturists and vintners all over the world, and this has led to increased demand for improved techniques to better estimate the crop (6). Currently used conventional methods are:

- Destructively harvesting whole vines or segments of vines or
- Randomly sampling and weighing bunches and then combining these with bunch counts.

Both methods require adequate sampling and data interpretation for more accurate crop estimation however vineyard management is seen to be understandably unwilling to commit sufficient resources during the busy harvest season. This unwillingness to allocate more resources during

978-1-4244-9253-4 /11/$26.00

harvest for proper sampling has been described to be a major impediment with these conventional methods. The present situation of course, clearly indicates that there is a pressing need for less demanding methods in terms of resources for crop forecasting.

A. Conventional methods of crop estimation

Two commonly used conventional crop estimation methods are outlined herein based on (1):

1) Traditional Method: For this method an average cluster weight of a season is obtained for use in the consequent harvest and the formula used for this is as follows:

$$PY = (ANV \times NC \times CW) / 2000 \tag{1}$$

Where,

PY = predicted yield (tons per acre)
ANV = actual number of vines / acre
NC = number of clusters per vine
CW = cluster weight (in pounds)

2) Lag Phase Method: This method uses cluster weights collected during the "lag phase" which refers to a period when seeds begin to harden and this occurs about 55 days after first bloom or corresponds to the accumulation of 1000-1300 growing degree days (GDD) or heat units. During this period berry growth slows temporarily and it is considered that at this lag phase the berries have reached about 50% of their final weight. Based on this theory, the cluster weight at harvest could be predicted by multiplying the lag phase weight by an "increase factor" of 2. However, the multiplier varies among varieties and seasons hence advised to determine an own multiplier for each variety/ vineyard. Furthermore, GDD required for calculation with the lag formula, could be obtained from any nearby meteorological station. The formula used for this method is as follows:

$$PY = (ANV \times NC \times Lag\ CW \times 2) / 2000 \tag{2}$$

Where,

PY = predicted yield (tons per acre)
ANV = actual number of vines / acre
NC = number of clusters per vine
Lag CW = cluster weight at lag phase (in pounds).

3) More elaborative method: This method includes average values for all possible variations from vine/ ha down to berry weight, both inclusive as described in (7).

Predicted yield = vines / ha x buds / vine x shoots/ bud x bunches / shoot x berries / bunch x berry weight

III. CA FRAMEWORK IN VEGETATION DYNAMICS SIMULATION

CA framework designs developed and implemented for vegetation dynamics simulation over the last six decades continue to gain popularity due to their ability to provide new information on the likely patterns in the spatiotemporal changes of complex natural habitats. Increasingly, new knowledge gained via CA models is described as detailed enough for management decision making in certain specific problem domains. Spatial patterns and trends over time in the dynamics of forest tree population (8), alpine tundra vegetation (9), rain forest species composition (10) and weed population (11), are among some useful simulations in this domain and the publications described how CA rules relating to a micro scale i.e., individual plant could be applied to simulate changes at meso/macro scales influenced by different factors and at varying degrees i.e., field under current and future scenarios as elaborated below.

In (12) authors simulated the effects of future climate change scenarios under different greenhouse gas emissions and then estimated future irrigation requirements for vineyards in Spain by combining global circulation and crop models. The scenarios for different greenhouse gas emissions were produced by perturbing the water generator based on Canadian climate change model (CGCM2) results for selected areas studied in the north east corner of the Iberian Peninsula. The "LARS-WG" weather generator was ran with historical data covering a 42 year period to generate some 100 possible local weather scenarios corresponding to years 2010, 2015 and 2025 for the simulation. Meanwhile, CropSyst was used to simulate vineyard water balance. The crop simulation for 2005 reflected the FAO-56[1] crop co-efficiencies and even though the weather model suggested early spring and hastened harvest, interestingly this was concluded to be causing lesser burden on future irrigation requirements than earlier anticipated.

IV. MULTI AGENT CA FRAMEWORK FOR SIMULATING GRAPEVINE GROWTH AND CROP

This section presents details of a multi agent CA framework with two different sets of lattices and rules for simulating an individual vine growth and *Chardonnay* grape yield in a vineyard.

A. CA lattice for grapevine growth

At this initial investigation, an individual vine growth, divided into 1) budburst, 2) leaf growth, 3) clusters of inflorescence initiation, 4) flowering, 5) berry formation, 6) development and 7) ripening stages, is simulated using a $l \times l$ set of lattice and individual vine growth rules. In this vine simulation, major growth factors (soil quality, water stress and exposure to solar radiation) and triggers, (daily maximum, minimum and soil minimum temperatures, and GDD) are used to calculate a variable called "available energy" (AE), the driving force for vine growth (Fig. 1).

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[1] Even though 56 (FAO-56) co-efficient is expected to provide a universally consistent methodology for obtaining reliable estimates of crop evapotranspiration it has its own limitations (13)

The AE calculated using formula (3) and (4) is in turn utilised for growth in five vine organs, namely trunk, bud, shoot, leaf and cluster, depending on the "stage" of the vine growth (1-7). A term "priority" is used to define the growth stage in the vine CA cycle. In modern day viticulture, annual grapevine growth cycle is divided into the seven growth stages (used in this study) based on temperature/day length/ growing degree days (GDD/ heat units) hence, temperature and GDD are used in the vine CA cycle to define the priority and stage. Energy not used in the current cycle will be stored in trunk as SE.

$$AE = ((GDD/DS) \text{ x } AW \text{ x } (TPV)) + SE \qquad (3)$$

Where,

AE =*Available energy*
GDD = *Growing Degree Days*
AW =*Available water (1.0-0.0)*
DS =*Day segments (morning, noon, twilight and night)*
TPV =*Total photo synthesis value*
SE =*Stored energy*

$$TPV = (ALC \text{ x } (A^2 \text{ x } L) / LA^2 \qquad (4)$$

Where,

ALC =*Active leaf cover in cell*
CA^2 =*Cell area* ^{2} *(in centimetre*^{2}*)*
L =*Light (1.0-0.0)*
Cells =*Cells in grid*

Vine organ initiation, growth, maturity and death vary based on the type of organ and are simulated using rules in the vine CA cycle. For example, organ "leaf" grows into become a full leaf since unfolding from a "shoot". The leaf growth continues until it reaches maximum leaf blade length, stays alive for several weeks producing energy via photosynthesis and then eventually dies off; similarly, each organ has its own growth phases and rules in the vine CA cycle (see Fig. 3 for bud growth rules).

B. CA lattice for grape crop (field) simulation

The grape crop simulation (field CA) displayed on a *L x L* set of lattice has its own set of rules. The field CA rules are applied to selected key parameters from the vine simulation along with environmental parameters whereby yield and related outcome/s at larger scales i.e., within a vineyard, are simulated. The key vine parameters used in the CA cycle are: vine canopy structure (buds/ vine, clusters/ vine, cluster weight). Meanwhile, random values are generated for environmental factors, such as soil quality, availability of water and solar radiation, temperature and humidity, to introduce "within-field" variability, for the field CA cycle, run with CA rules to produce vineyard displays (Fig. 2).

C. Agents for vineyard operations

Vineyard operations, such as pruning, fertiliser application, spraying (pesticide/ fungicide), irrigation and harvest are incorporated through agents. The agent rules are used for implementing vineyard operations and to define their potential outcomes; loss of foliage, nutrient increase.

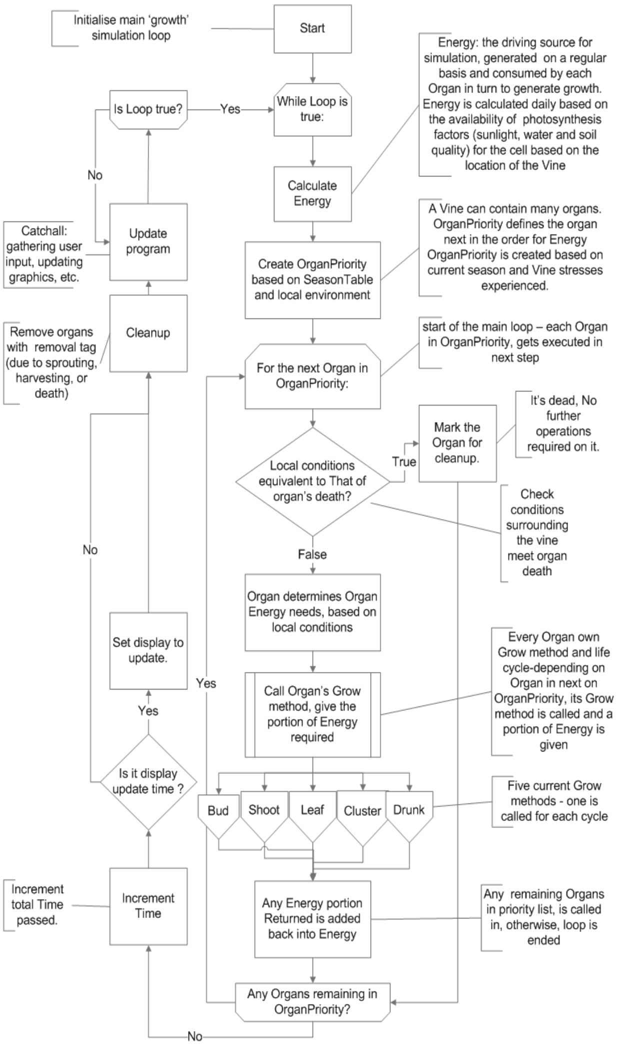


Figure 1. Schematic representation of the main processes relating to individual vine CA cycle. Each vine growth is displayed by a *l x l* lattice simulated by vine rules.

V. RESULTS

The initial results of this research on a multi-agent CA framework being developed for simulating perennial crop (Figs 3-5), show how grape crop simulation at meso/macro scales, such as a vineyard, could be achieved using expertise represented by rules, and available data on factors pertaining to micro scale issues (individual vine growth).

The vine CA lattice simulates growth in vine organs (as explained in section IV) beginning with budburst, leaves, clusters (fluoresce and berry) to produce grapes for both, in a vine (in berry weigh and berries/ cluster) and in a vineyard (in terms of grapes (tons/ha), Brix, p^H and acidity). The user interface has buttons, tabs and scroll bars to set/ change critical parameters relating to individual vine growth, such as buds/ shoot, shoots/ vine, clusters/ shoot, berries/ cluster and berry size. These parameters could be used to change values based on the grape variety being simulated.

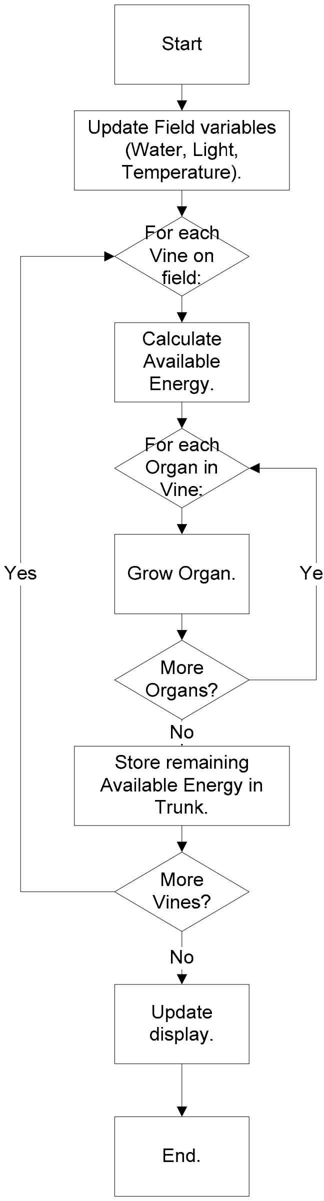


Figure 2. Schematic representation of the main processes on the crop simulation cycle displayed by $L \times L$ lattice based on vineyard rules

At this initial implementation, even without agents to simulate vineyard operations, such as pruning, fertiliser application or pesticide/ fungicide spraying, the results thus far achieved with CA lattices and rules (vine and field) show potential for crop prediction in different grape varieties and at varying scales. By changing an individual vine growth parameters, such as buds / vine x shoots/ bud x bunches / shoot x berries / bunch x berry weight, users are able to predict the different outcome from a single vineyard, such as grapes in tons/ ha under different climate change scenarios. The ability to change vine parameters could be used for predicting crops in different grape varieties, such as *Pinot Noir* and *Pinot Gris*. By changing field variables soil quality, availability of water and light (solar radiation), temperature and humidity, it is possible to create within-field variability for the CA cycle and this is useful in creating within and among vineyards (different sites).

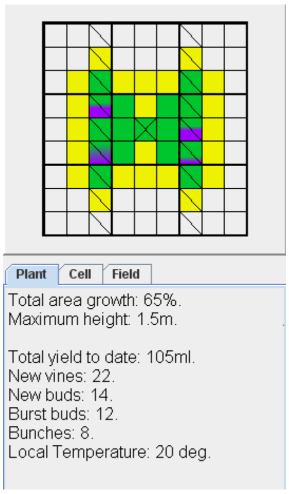
```
All Organs
Variables:
Death Threshold = 0°C

Standard Organ death rule:
IF Local Temperature < Death Threshold
        Organ is dead.
Bud rules
Variables:
Frost Threshold = 2 degrees centigrade.
Flower Daylength Threshold = 12 hours
Flower Temp Threshold = 10 degrees centigrade

Death:
IF Local Temperature < Frost Threshold
        Decrement Remaining Buds
IF Remaining Buds == 0
        Bud is dead
ELSE IF Local Temperature < Death Threshold
        Bud is dead.

Growth:
Add Growth to Total Growth
IF Total Growth >= Burst Threshold
IF Day Length > Flower Daylength Threshold AND Local
        Temperature > Flower Temp Threshold
Bud is dead
        Cause Vine to spawn new Shoot at Bud's location.
Remove any excess Total Growth beyond Burst Threshold, return to
        Growth
Return any remaining Growth
```

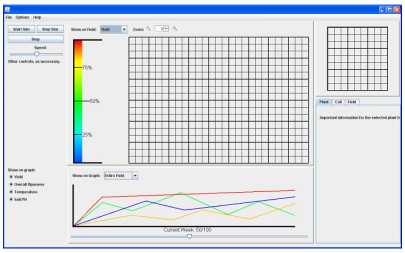
Figure 3. *Field CA rules for budburst, death and growth*



Total area growth: 65%.
Maximum height: 1.5m.

Total yield to date: 105ml.
New vines: 22.
New buds: 14.
Burst buds: 12.
Bunches: 8.
Local Temperature: 20 deg.

Figure 4. CA simulation showing vine growth with various grapevine organs that are incorporated in the vine CA cycle.



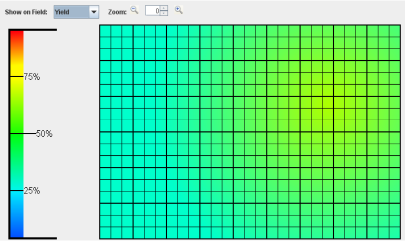
Show on Field: Yield

Show on Graph: Entire Field

Current Week: 50/100

Important information for the selected plant h

Figure 5. CA simulation of grape vine growth and yield at larger scales, such as vineyard, region. By changing the vine and field parameters it is possible to simulate growth and yield in diffident grapevine varieties, such as Chardonnay, Pinot Noir and Pinot Gris.



Show on Field: Yield

Figure 6. Screen display showing the CA simulation of grape crop. The variability in yield within a vineyard is simulated based on variations generated in soil, availability of water, nutrients, solar radiation, temperature and humidity created with random number generators.

VI. CONCLUSIONS

The paper described the initial investigation so far conducted on simulating vine growth and vineyard yield in *Chardonnay* cultivated in northern New Zealand. Even without the vineyard operations designed to be incorporated by means of multi-agents, the preliminary results of CA simulations (vine and field) are promising. It is believed that on full implementation of the multi-agent based CA framework with an interface, the approach will enhance viticulturists' ability to better predict their outcomes under different scenarios, such as pruning decisions; number of buds/ shoot to allow for full growth for that season, future climate change and at different scales. The major benefit with the approach is that it provides an alternative method to estimating yield without incurring any additional cost as this approach could be simulated with historic and other model prediction data. As far as we are aware, this is the first attempt to contribute to 'precision viticulture' (14) through the use of cellular automata that take into account detailed information concerning both resources (energy, water) as well as important botanical features (leaves, buds, etc).

With the inclusion of a wine quality module vintage ratings as well could be predicted under different possible weather and other atmospheric conditions.

ACKNOWLEDGMENTS

The authors wish to thank Michel Brakavich, Kumeu River Wines. Prof Philip sallis and Peter Sumich of AUT are acknowledged for their continuous support.

REFERENCES

[1] Dami, Imed. Methods of Crop Estimation in Grapes. [Online] 2010. [Cited: 27 9 2010.] http://www.oardc.ohio-state.edu/grapeweb/OGEN/07262006/CropEstimation06.pdf.

[2] Trought, Mike. Yield Management and Prediction. http://www.wineresearch.org.nz/. [Online] Marlborough Wine Research Centre, 2009. [Cited: 10 09 2009.] http://www.wineresearch.org.nz/projects/SR06-01aYieldManagmentPrediction.pdf.

[3] Bandini, S, Mauri, G and Serra, R. 2001 Cellular automata: From a theoretical parallel computational model to its application to complex systems. www.elsevier.com/locate/parco, 2001, Vols. Parrallel Computing 27 (2001) 539-553.

[4] Geertman, S, Hagoort, M and Ottens, H. 2007 Spatial-temporal specific neighbourhood rules for cellular automata land-use modelling. 21: 5 547-568, London, UK : Publisher Taylor & Francis, 2007, Vol. International Journal of Geographical Information Science.

[5] Espínola, M., Ayala, R., and Leguizamón, Saturnino 2008 Classification of Satellite Images Using the Cellular Automata Approach [Eds] M.D. Lytras et al. Springer-Verlag Berlin Heidelberg, 2008, The Open Knowlege Society. A Computer Science and Information Systems Manifesto Communications in Computer and Information Science, 2008, Vol. 19, 521-526, DOI: 10.1007/978-3-540-87783-7_66 .

[6] Dunn, Gregory M and Martin, Stephen R. 2004 Yield prediction from digital image analysis: A technique with potential for vineyard assessments prior to harvest. Australian Journal of Grape and Wine Research 10, pp196-198.

[7] Keller, M, Tarara, J M and Mills, L J. 2010 Spring temperatures alter reproductive development in grapevines_105. Wiley Onlie Library, 2010, Australian Journal of Grape andWine Research Vol. 16, 445–454, 2010.

[8] Stamatellos, G and Panourgias, G. 2005 Simulating spatial distributions of forest trees by using data from fi xed area plots. Institute of Chartered Foresters, 2005, Vol. Forestry, Vol. 78, No. 3, 2005. forestry.oxfordjournals.org doi:10.1093/forestry/cpi028.

[9] Zhang, A Yanqing, et al. 2008 Cellular Automata: Simulating Alpine Tundra Vegetation Dynamics in Response to Global Warming. Arctic, Antarctic, and Alpine Research Volume 40, Number 1 / February 2008 pp256-263.

[10] Alonso, David and Sole´, Ricard V. 2000 The DivGame Simulator: a stochastic cellular automata model of rainforest dynamics. Ecological Modelling 133 (2000) 131–141.

[11] Zhang, A. Y., Peterman, M. R., Aun, D. L., and Zhang, Y., 2003 Using CA model to obtain insight into mechanism of plant population spread in a controllable system: annual weeds as an example. Ecological Modelling 166 (2003) 277–286.

[12] Marsal, Jordi and Utset, Angel. Vineyard Full Irrigation Requirements under Climate Change Scenarios for Ebro Valley, Spain. [book auth.] Valladolid, Spain) Angel Utset (ITACyL. Climate Variability, Modeling Tools and Agricultural Decision-Making 978-1-60692-703-8 261 pages. Nova Publishers, 2009, pp. 119-126.

[13] Hunsaker, D J, Pinter, P J and Cai, H. Alfalfa basal crop coefficients for FAO-56 procedures in the desert regions of the southwestern U.S. [Online] 2002. ISSN 0001-2351.

[14] Best, S, León L and Claret, M. 2005. Use of precision viticulture tools to optimize the harvest of high quality grapes. Information and Technology for Sustainable Fruit and Vegetable Production (FRUTIC 05), 249-258,