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Expert Systems Modeling for Assessing Climate Change Impacts and Adaptation in Agricultural Systems at Regional Level

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ABSTRACT

Australian agriculture is very susceptible to the adverse impacts of climate change, with major shifts in temperature and rainfall projected. In this context, this paper describes a research methodology for assessing potential climate change impacts on, and formulating adaptation options for, agriculture at regional level. The methodology was developed and applied in the analysis of climate change impacts on key horticultural commodities—pome fruits (apples and pears), stone fruits (peaches and nectarines) and wine grapes—in the Goulburn Broken catchment management region, State of Victoria, Australia. Core components of the methodology are mathematical models that enable to spatially represent the degree of biophysical land suitability for the growth of agricultural commodities in the region of interest given current and future climatic conditions. The methodology provides a sound analytic approach to 1) recognise regions under threat of declines in agricultural production due to unfolding climatic changes; 2) identify alternative agricultural systems better adapted to likely future climatic conditions and 3) investigate incremental and transformational adaptation actions to improve the problem situations that are being created by climate change.

Keywords: Climate Change; Expert Systems; Analytic Hierarchy Process; Land Suitability Analysis; Chilling; Adaptation Actions

1. Introduction

The Earth's climate has changed in the past, is changing now, and will continue to change in the future. There is nevertheless extensive scientific evidence that the observed rapid warming of the Earth since the Industrial Revolution has been caused by human-induced climatologically phenomena interacting with natural climate processes. The enhanced (anthropogenic) greenhouse effect is a consequence of modifications to the Earth's atmosphere from gases emitted by industrial, transportation and agricultural activities—termed Greenhouse Gases (GHG)—and variations in the land surface reflectivity caused by deforestation, cropping and irrigation. The impacts are likely to become more serious over coming decades as global warming is projected to accelerate, with an increasing risk of drastic changes to natural and human systems [1-3].

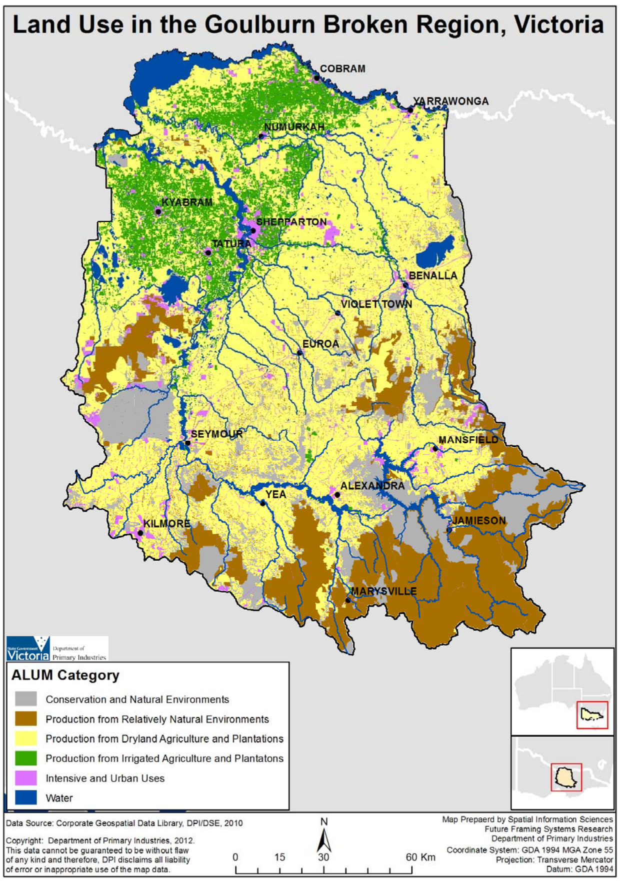
Reducing the vulnerability of coupled socio-ecological systems (including human settlements, biodiversity, land and water resources, and economic activities) to the impacts of climate change by means of adaptation is therefore critical. "[Planned] adaptation involves changes in socio-ecological systems in response to actual and expected impacts of climate change in the context of interacting non-climatic changes. Adaptation strategies and actions can range from short-term coping to longer-term, deeper transformations." [4]

Australia is likely to be one of the most adversely affected countries in the world with respect to potential climate change impacts on economic activities, especially possible declines in agricultural production [5-7]. Production must nevertheless increase in the future to feed and clothe the Earth's growing population—the world population is expected to increase from approximately 6.9 billion people to over 9 billion by 2100 (based on United Nations 2009 medium world population forecasts). However, without major adaptations to the unfolding climatic changes, agriculture in Australia will struggle to even maintain current production levels [7,8].

In this context, this paper describes a research methodology developed for assessing potential climate change impacts on, and formulating adaptation options for, agriculture at regional level in Australia. It is explained by its application in the Goulburn Broken catchment management region (hereafter "Goulburn Broken") in the State of Victoria, Australia; see **Map 1**.

The Study Area—Goulburn-Broken, Victoria

Goulburn Broken covers an area of approximately 24,800 square kilometres, or about 10.5% of the state's total area; the region is part of the largest river basin in the country—the Murray Darling Basin (MDB). It is home to over 190,000 people, with around 40% of the population living in rural areas. Cities and rural towns in Goulburn Broken are shown in **Map 1**. The regional landscape comprises low lying floodplains along the Murray River in the region's north and mountainous areas in the south, including Mount Buller with an elevation of 1806 metres above sea level. The main waterways are the Goulburn and Broken Rivers, whilst Lake Eildon is a major water storage. Groundwater is also an important source of water for irrigation within the region.



Map 1. Land use in Goulburn Broken, State of Victoria, Australia, according to the ALUM (Australian Land Use and Management) classification.

Goulburn Broken is considered the food bowl of the MDB with the main agricultural industries being horticulture, dairy, cropping, viticulture, forestry and grazing for sheep (both for wool and meat) and cattle (meat, dairy or both). The region also supports a large fruit and vegetable food processing industry centred on its largest city, Shepparton. The production of timber is also an important regional employer, and tourism is becoming increasingly significant to the region. Major land uses in Goulburn Broken include dryland agriculture (approximately 51%), irrigated agriculture (about 9%), native forests (27%), plantation forests (1%), urban uses (4%) and water bodies (2%).

In 2006-2007, the average area dedicated to irrigated horticulture in Goulburn Broken accounted for approximately 280 hectares. The main irrigated crops were pome and stone fruits (including apples and pears) and wine grapes. Irrigated horticulture farms in the region held an estimated 285 megalitres of water entitlements, comprised mainly of surface water rights. In 2006-2007, these farms used an average total of nearly 200 megalitres of irrigated water at an estimated rate of about 4 megalitres per hectare [9].

2. Methodology and Research Objectives

The complete methodology[1] developed is shown in **Figure 1**. The main research objectives (Phase 1 in the process) were the following. 1) To systematically investigate the climate change impacts on agriculture at regional level (through a generic approach that can be replicated elsewhere), 2) To understand the adaptation options available to agriculturalists in the region of interest. The focus in this paper is on the first objective, with some discussion of the second objective (Section 8, below). Furthermore, current research work in other regions of Victoria is exploring which combination of adaptation measures might be more beneficial according to different climate change scenarios. A future paper will explain this work.

At the core of the methodology there are mathematical models that enable to spatially represent (*i.e.* map) the degree of biophysical land suitability for the growth of agricultural commodities in the region of interest given

[1]As the word indicates, a methodology is a *logos* of methods; *i.e.* it is a structured set of principles which can be adapted for use in a way that suits the specific nature of each situation in which it will be used [10]. As methodology is essentially theoretical, we can accept a plurality of theories flowing into methodology, and hence a variety of methods and models can be seen as legitimate. Our methodology uses a Multiple-Criteria Evaluation *method*, climate change *models*, and Geographic Information Systems as a *tool* (and platform) for generating the products of the methodology.

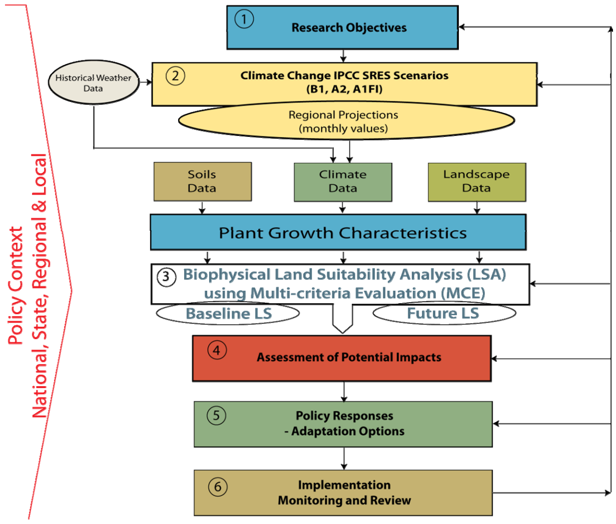


Figure 1. Methodology for assessing climate change impacts and adaptation in agriculture at regional level.

current and projected future climatic conditions (Phase 3 in the process). Land suitability is defined as a measure of how well the characteristics of a parcel of land match the requirements of a particular type of land use [11,12]. Modifications in land suitability likely to be caused by climate change can be assessed by comparing future suitability maps with current suitability maps. The sections below describe key components of the methodology.

2.1. Climate Change Projections

In Phase 2, global climate change scenarios derived from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios—SRES [13] were scaled down to the regional level. Model-specific monthly climate projection data were prepared by CSIRO Marine and Atmospheric Research for this phase. This included data of its latest global climate change model—termed CSIRO Mark 3.5—downscaled to a spatial resolution of only 5 square km grid (0.05˚) for nine key climatic variables: temperature (maximum, minimum and mean), rainfall, solar radiation, potential evapotranspiration, relative humidity (at 9 am and 3 pm), and wind speed [14,15]. Although information for three “marker” SRES scenarios (B1, A2 and A1FI) were generated for the years 2030, 2050 and 2070, reference to the A1FI (intensive fossil fuel) scenario and 2050 will mostly be made in this paper.

Climate data for historical observations were provided by the Department of Natural Resources and Mines (Queensland, Australia), together with the Australian Bureau of Meteorology (BoM) weather recordings, through their SILO program. These data are produced as text files which then can be presented in a map grid at the same spatial resolution as the climate change projections.

2.2. Biophysical Land Suitability Analysis

Multi-Criteria Evaluation in a GIS Environment—In order to define the biophysical suitability of an area for a specific land use (or activity), several criteria need to be considered simultaneously. For this purpose, the models developed in our research integrated a Multi-Criteria Evaluation (MCE) method with a Geographic Information System (GIS). MCE has been developed to investigate a number of alternatives (or choice possibilities) in the light of multiple objectives (or criteria) and conflicting preferences (or priorities) [16,17]. It is a very useful method when a set of alternatives need to be evaluated on the basis of conflicting and incommensurate criteria [18].

MCE has been utilised around the world for land suitability modeling where it is primarily concerned with how to combine the information from several criteria to form a single index of evaluation [19-24]. A “criterion” is a basis for a decision that can be measured and evaluated. “Factors” and “constraints” are the two types of criteria and they can pertain either to attributes of an individual decision or to an entire decision set. A “factor” is a criterion than enhances or detracts from the suitability of a specific alternative for the use, or activity, under consideration. It is generally measured on a continuous scale. A “constraint” serves to limit the alternatives being considered [25].

MCE is most commonly applied by one of two procedures. The first, deployed in traditional land suitability approaches, uses the Boolean aggregation method of constructing suitability indexes based on a rigid binary choice of acceptance or rejection. An example is the Most Limiting Factor (MLF) method that is based on the land capability classification of the US Department of Agriculture [26,27].

The second procedure is known as Weighted Linear Combination (WLC) which uses a soft or “fuzzy” concept of suitability in standard criteria [16]. Instead of the hard Boolean decision of assigning absolute suitability or unsuitability to a location for a given criteria, it is scaled to a particular common range where suitable and unsuitable areas are continuous measures. The WLC retains the variability of continuous criteria and allows criterion to trade-off with each other. A low suitability defined by one criterion may be compensated by a high suitability score in another criterion [25]. Trade-offs between criteria depends on weights assigned to them, and a wide variety of techniques exist for the development of weighting [28]. As depicted in the decision strategy space in **Figure 2**, the WLC model is a significant improvement over the Boolean approach by avoiding its extreme risk aversion (binary rejection) and extreme risk taking (binary acceptance) nature [25].

Analytic Hierarchy Process (AHP) and Experts’ Judg-

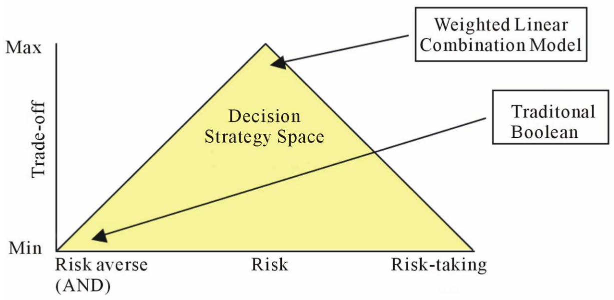


Figure 2. Decision strategy space. Source: [23, p. 17].

ment—In our research, the MCE was implemented using an Expert Systems Modeling—the Analytic Hierarchy Process (AHP) developed by Saaty [29,30]. AHP provides a framework that incorporates experts' participation in the decision-making process. Compared to empirical models based purely on the correlation amongst data, this Expert Systems Modeling incorporates the knowledge of experts who can address significant issues and have an understanding of the system of concern that may be relevant to the required decision-making. The method is also better suited when the availability of good data is limited.

As explained by Saaty [30], "basically the AHP is a method of breaking down a complex unstructured situation into its component parts; arranging these parts, or variables, into a hierarchical order [or decision tree]; assigning numerical values to subjective judgments on the relative importance of each variable; and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation. AHP incorporates both the qualitative and the quantitative aspects of human thought: the qualitative to define the problem and its hierarchy and the quantitative to express judgments and preferences concisely. The process itself is designed to integrate these dual properties." When AHP is integrated with GIS, it can deal with criteria that are interdependent, both from the effect on land and in the interaction between spatial units [31].

It is required when using a WLC in MCE that the weights sum to one. In the AHP, the weights are calculated by taking the principal eigenvector of a square reciprocal matrix of pair-wise comparisons between the criteria. All possible pairs of criteria are compared by experts on a 9-point continuous scale for their relative importance to determining the suitability of the stated objectives. The ratings are then introduced in a matrix to calculate the weights. The accuracy of the weight results at each level of the AHP hierarchy depends on the consistency of judgments in the pair-wise comparisons. A consistency ratio (CR) measures the logical inconsistency of judgments and enables the identification of possible errors in the matrix. If CR ≥ 0.10 the pair-wise comparison matrix must be reformulated [25,29,30].

3. Example of a Biophysical Land Suitability Model (LSA)

The methodology was developed and applied in the analysis of the potential climate change impacts on key horticultural commodities—pome fruits (apples and pears), stone fruits (peaches and nectarines) and wine grapes—in Goulburn Broken [30]. However, for illustration purposes, we explain only the LSA model for apples (Royal Gala variety—the most common in Australia).

This model was developed in a workshop-type situation held during approximately 6 hours with participation of a large group of experts including: land use and environmental planners, natural resource analysts/managers, climate and soil scientists, hydrologists, geographers, and agriculturalists involved in pome fruits cultivation. Relevant material was distributed prior to the workshop comprising information on the methodology, particularly on the AHP, climate, soil, topography, and scientific criteria for the growth of the crop being examined. At the commencement of the workshop, the agenda for the day was discussed, and explanations on the methodology and available data (including gaps and accuracy) were provided. A workshop Facilitator assisted in the development of the following steps in model formulation 1) construction of the AHP hierarchy, 2) making pair-wise comparisons and 3) calculating the priorities. To undertake these steps on-the-fly, we used a computer program developed by us. It is interesting to note that, in general, there was agreement in relation to weights and ratings, and, if there was disagreement, the experts with the greatest knowledge on the factor in question ultimately prevailed. Much discussion occurred in relation to the weightings at the top of the AHP hierarchy, especially between soils and climate; (as expected) the soil scientists argued that soil was the most important factor influencing pome fruits growth. A counter-argument was however put that climate, on account of its significant projected changes should be given a greater weight; and this position was finally accepted.

The apple LSA model was developed setting a goal to produce a yield within a range (as agreed at the workshop) of 30 to 60 tonnes per hectare per year (t/ha/y). These are desirable values on the assumption that the agricultural land is utilised to its maximum potential through Best Management Practices (BMP). Current yields, as reported by the Australian Bureau of Statistics (ABS), show that the average production of all current orchards in Goulburn Broken is at the lower range of the stated yields at around 33 t/ha/y. And **Figure 3** shows the overall structure of the model and the landscape branch's hierarchy. Because of its significance for this paper, of the other two branches of the LSA model—soil and cli-

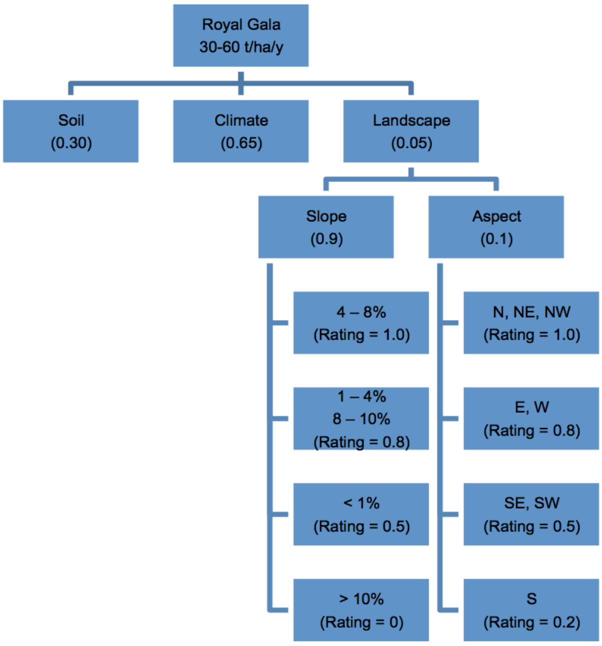


Figure 3. Apple land suitability model—overall structure and landscape hierarchy.

mate—**Figure 4** depicts only the latter.

The AHP hierarchy shows that Climate is the most influential factor with an assigned weight of 0.65, followed by Soil (0.30) and Landscape (0.05). These main branches are further divided down the model; each with their own weighting factors. For example, if one progresses down the Climate branch, shown in **Figure 4**, the temperature is the most influential factor with a weight of 0.45. Down this division, temperature at flowering is the most important with a weight of 0.70. Overall, branches with a higher weighting will have a large influence on the model output, whereas branches with smaller weightings will have a lesser impact. The GIS model-based on the AHP tree was developed using ArcGIS (ArcGIS 9.3, 2008) and PyScripter for Python 2.5 (PyScripter 1.9.9.7, 2008). The model was then populated with necessary data. For comparative purposes, climate data were generated taking the average historical values of the key climatic variables for a 10-year period from 1996 to 2005; *i.e.* five years either side of 2000. To simplify the explanation, we will refer to 2000 as the "baseline" year. Through the use of a decade baseline, any (relatively infrequent) climate events, such as extreme weather, are smoothed out and an even spread of climate data are generated.

Calculation of Chill Units—an interesting factor included in the Climate branch of the model is "chill units" (CU). Deciduous fruit plants, including pome, stone and grape trees, develop their vegetative and fruiting buds in the summer. As winter approaches, the already formed buds go dormant in response to both shorter day lengths and cooler temperatures. This dormancy, or sleeping stage, protects buds from the effects of cold weather. The buds remain dormant until they have accumulated sufficient chilling, or vernalisation, to break the dormancy [32]. As long as there has been enough accumulated chilling, the flower and leaf buds would develop normally. One chill unit is accumulated per hour when temperatures are between defined limits. Maximum chilling tends to occur between 6˚C - 8˚C, with very little chilling accumulated below 2˚C or above 12˚C - 14˚C [33].

A modified version of the widely used Utah Vernalisation Model [34] was employed in our research. In the Modified Utah Model, proposed by Linvill [35], CU are accumulated in the following steps:

$$\text{CU} = 0 \text{ when } T(t) \le 0^\circ\text{C} \quad (1)$$

$$\text{CU}=\sin\left(\frac{2\pi T(t)}{28}\right) \text{ when } 0 < T(t) \le 21^\circ\text{C} \quad (2)$$

$$\text{CU} = -1 \text{ when } T(t) > 21^\circ\text{C} \quad (3)$$

where: CU is chill units and *T(t)* is temperature at time "*t*" hours.[2]

When this model is plotted over a range of temperatures from −5˚C to 25˚C, a smooth curve is formed where chilling becomes positive after 0˚C, peaks at 1 CU at 7˚C, reaches negative chilling after 14˚C and strikes −1 CU at 21˚C (**Figure 5**).

For Goulburn Broken, chilling accumulation was calculated for each individual grid point in the 5 square kilometre grid, where climate information was available for the present and the future. A GIS-based version (using ArcGIS and Python 2.5) of this model was used to convert daily mean temperatures into CU from the start of autumn to the end of spring (*i.e.* from March to November). The calculated CU for each day were then consecutively added together (e.g. day 1 + day 2, day 1 + day 2 + day 3, and so on) to form an accumulated chilling curve for the entire study region over that nine month period. This procedure was repeated for the three future years (2030, 2050, 2070) using the IPCC emission scenario and mean temperatures. See **Figure 5**.

In this figure, chilling starts on March 1st (Day 0), declines during early autumn due to relative warm conditions, increases once the cooler weather begins during late autumn and winter, and declines again in late spring as the temperature increases. Stone, pome and grape trees enter bud dormancy when they discern the cooler wea-

[2]For the calculation of CU in this model, hourly temperatures are required. Also, the observed temperature used for this step should be determined based on time of day and length of day. For example, minimum temperatures should be used during night time and maximum temperatures during daylight hours. For our research, only daily mean temperatures were available; therefore, to estimate hourly mean temperatures the value was multiplied by twenty four.

ther, or when positive chilling begins. [Some other species respond to day/night length]. The annual chill accumulation is hence defined as the largest section of the curve with a positive gradient, *i.e.*, the difference between the maximum value and the minimum which precedes it [33].

For Goulburn Broken, in the baseline, the positive chill begins at the end of March and continues to the end of October and the start of November. The accumulated chilling value is 2723 CU where the minimum is −179.7 CU on day 30 (relative to March 1st) and the maximum is 2543.8 CU on day 250; this reflects a chilling period of about 220 days.

When the baseline curve is compared with the future years of 2030, 2050 and 2070, a noticeable decrease in accumulated chilling over the nine month period occurs. For example, 2050 has an accumulated chilling of 1690.6 CU (maximum of 1193.1 CU, minimum of 497.1 CU). Accompanying this decrease, accumulated chilling shows a delay in the start of the period when positive accumulation occurs. Thus, 2050 has a starting point for positive chilling on approximately day 60 (relative to March 1st) compared with day 30 for the base years. There is also a shortening of the chilling period.

This pattern of delayed start to the beginning of the positive chilling period and its shortening resulting in lower accumulated chilling becomes more pronounced in each following future year. For example, by 2050 the maximum accumulated chilling occurs at about day 210 giving a chilling period of roughly 150 days. By 2070, the maximum chilling occurs at around day 213 with a total chilling period of about 122 days.

4. Biophysical LSA–Model Robustness and Results

The execution of the LSA model produces a composite map that ranks areas in terms of suitability for the growth of apples; it has an index range of 0 to 1, where 0 means a site which is deemed to have no potential for growing apples and 1 represents a site deemed ideal for growing apples (*i.e.*, 100% suitability). The production of a particular area can be estimated by multiplying a value in the yield range defined at the top of the AHP hierarchy by the suitability index. For example, in an area with a suitability of 0.8 (or 80%) we could expect, other things being equal, a yield of (0.8 × 30 t/ha/y = 24 t/ha/y).

Model Robustness—the resultant suitability map was sent for validation purposes to the same group of experts that participated in the development of the LSA model. If inconsistencies were perceived by any of the experts, weights and ratings in the model were adjusted and a new suitability map was generated. This process was repeated until every participating expert was satisfied with the output map. The model was also examined in relation to its robustness through two (desk-top) methods: climate sensitivity analysis and Pearson's product-moment correlation coefficient.

Analysis of the sensitivity of the LSA model to climatic variables, as per the former method, is important because if the model does not respond as expected, its predictive capacity is low and it is not fit-for-purpose. Due to the strong influence that climate has in the AHP hierarchy, there should be a response to seasonal variability in the suitability ratings produced by the model. Sensitivity analysis hence focused on examining the impacts of maximum and minimum temperature and total annual rainfall, as these variables have a heavy weighting in the LSA model. LSA outputs were developed for several seasons and the influence of each season on the land suitability was then assessed. It was seen that shifts in the climate patterns caused concomitant modifications in the suitability of the land resource for grape production. The results thus showed that the biophysical land suitability model for apples behaved in a responsive fashion and was sensitive to the climatic changes.

The Pearson's product-moment correlation coefficient is a measure of the correlation, or linear dependence, between two variables. It gauges the strength of the relationship between two variables and gives a value in the range of −1 to 1. A strong negative or positive correlation would typically have a value near to the upper (+1) or lower maximums (−1) of the range, whereas no correlation would have a value close to, or at, 0. For validation purposes, the two variables analysed were 1) change in land suitability due to climate, landscape and soils and 2) change in grape production in terms of yield. The values of the LSA model were compared with actual production figures provided by the ABS. The application of this method showed that there was a strong positive relationship between land suitability and actual apple production in a given year: as land suitability in a particular area increased or decreased, apple production was seen to increase or decrease in response. This result confirmed that LSA model outputs correlated well with actual production figures.

It should be noted that existing land uses are the consequence of many factors, including past and current market conditions and tradition, whilst the LSA maps primary reflect biophysical conditions.

Results—The desk-top validation confirmed the LSA model performed as expected. Land suitability was then ascertained using widely diverging climate change scenarios to cover a broad range of plausible futures. The set of resultant maps illustrate where and how the suitability of the land resource is likely to alter if climatic changes unfold as projected by the IPCC SRES scenarios considered. The metrics of the model are assumed to remain constant. As previously mentioned, only the results from the IPCC SRES A1FI scenario are discussed in this paper.

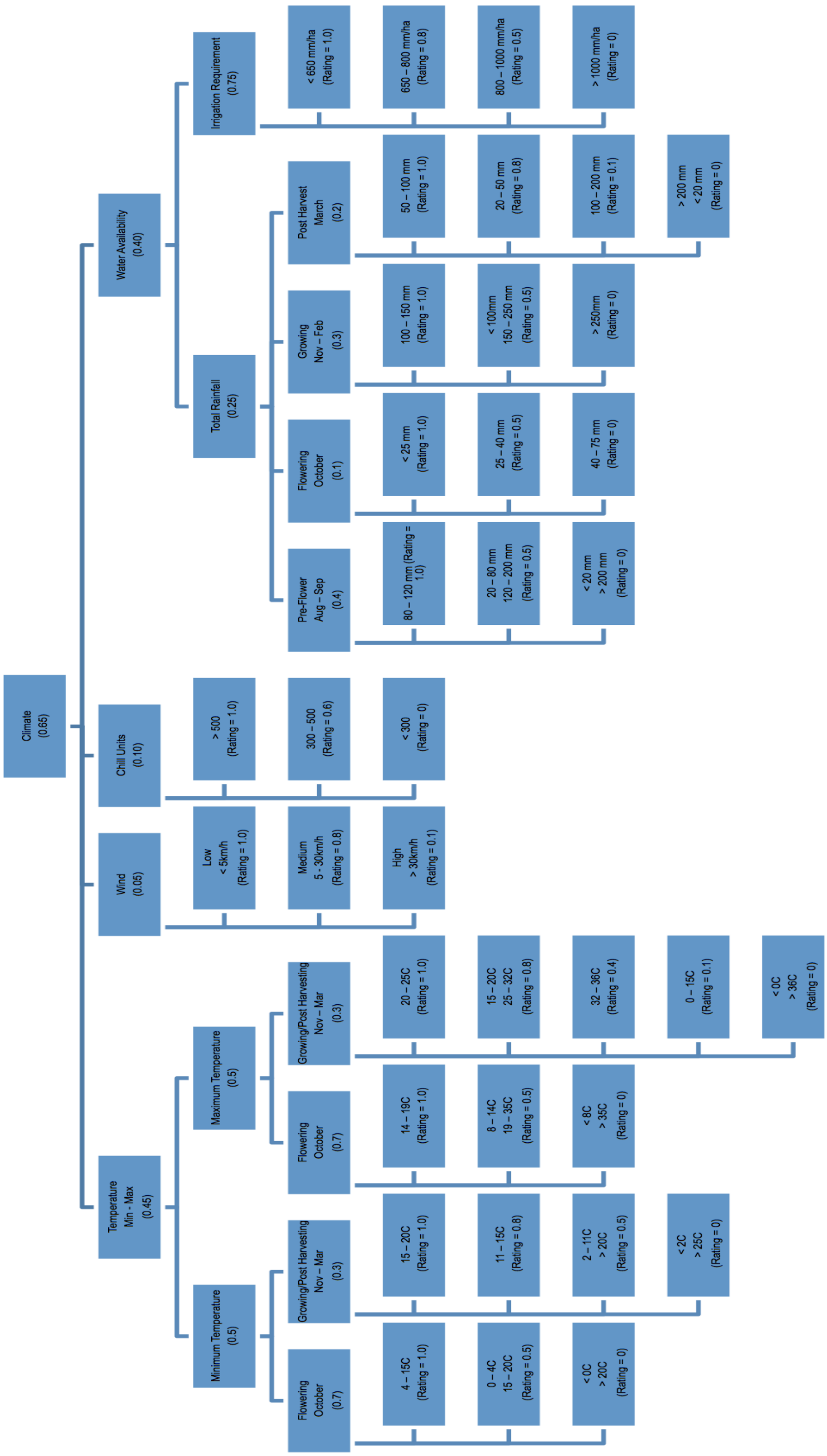


Figure 4. Apple Land Suitability Model—climate hierarchy.

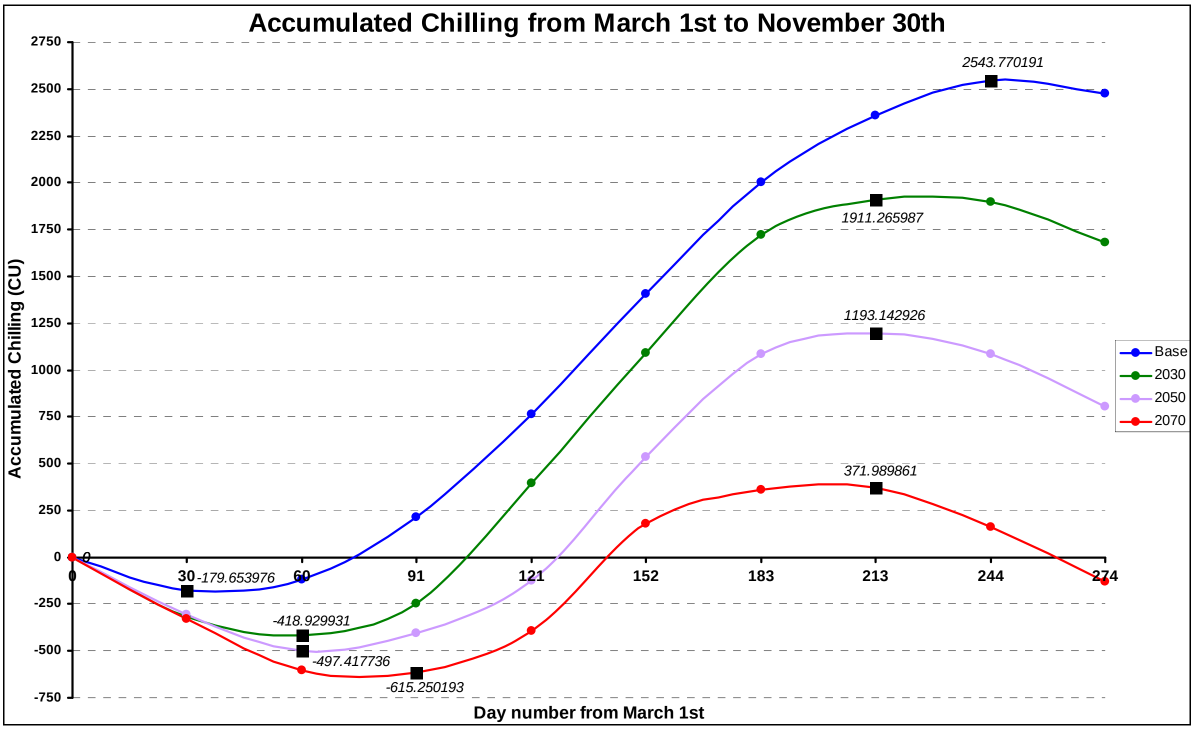


Figure 5. Accumulated chilling from March 1st to November 30th. CU refers to chill units; Base refers to the years 1996 to 2005.

Maps 2-4 show, respectively, the results of LSA for the baseline (average climatic conditions in the period 1996-2005; noted as year 2000), year 2050 and the change in land suitability between these two years. Red, orange, yellow and green colours in Maps 2 and 3 and associated legends represent, respectively, very low (0% to 10%), low (20% to 40%), moderate (50% to 70%) and high (80% to 100% suitability) ranges. A large area in the south (shown in grey colour in the maps) and portions of the northwest and east of the region are restricted to protect native vegetation and other natural landscapes.

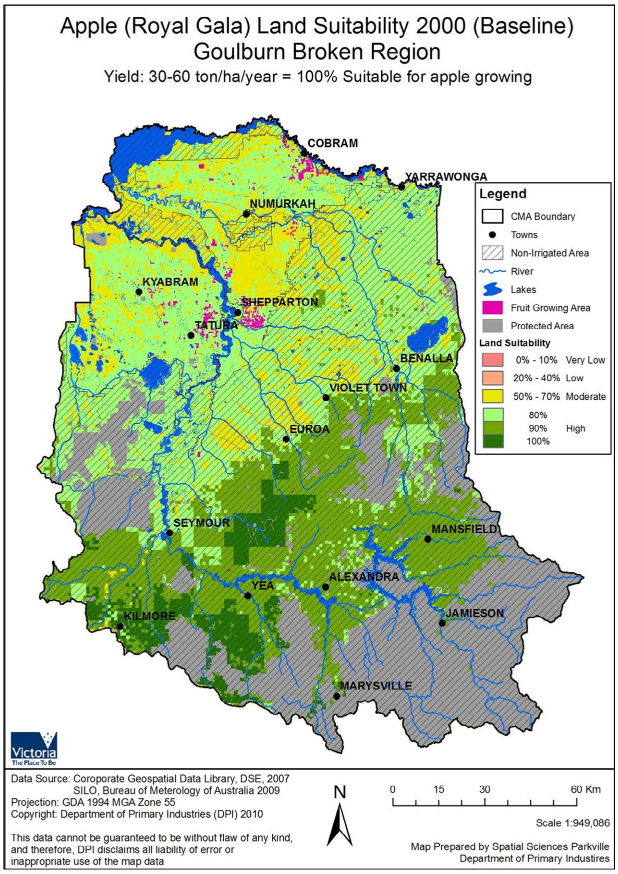
Map 2 shows that most areas in Goulburn Broken are currently high in suitability to produce 30 - 60 t/ha/y of apples. Only a small scattering of areas show a moderate suitability; in particular, areas between Numurkah and Shepparton and north of Kyabram display this ranking. **Map 3** for 2050 depicts a large change in the land suitability for apples from the high to the moderate categories. The northern regional areas (north of the town of Euroa) have shifted from a high land suitability category to moderate land suitability ranges. In the southern regional areas, land suitability has changed from the high suitability categories of 90% and 100% to the high suitability category of 80%. These changes are largely a consequence of the projected increases in temperature and concomitant decreases in rainfall across the region.

In the comparison between the baseline and 2050 (**Map 4**), a decrease indicates that there has been a 10% change from a higher suitability class to a lower suitability class (e.g. from 90% to 80%); similarly an increase indicates that there has been a 10% change from a lower class to a higher class (e.g. from 80% to 90%). A high increase denotes that there has been a 20% change from a low suitability class to a higher suitability class and a high decrease indicates that there has been a 20% reduction from a higher suitability class. No change means that there has been no variation between the baseline and the year of the comparison. Therefore, from the baseline to the year 2050 changes are quite pronounced with over half of the region displaying a decrease in land suitability. This is primarily seen in the areas south of the town of Euroa.

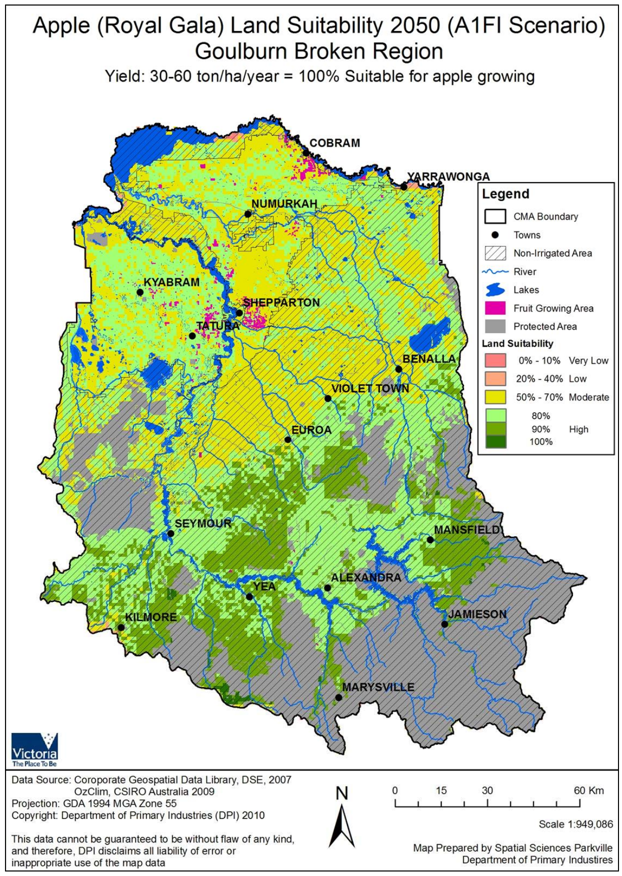
If a new variety of apples (or any commodity) is better adapted to the likely future climatic conditions, a new LSA model can be developed and parameterised with new weights (based on the new data) to investigate whether an anticipated improvement in performance will actually occur.

5. Discussion

The integration of MCE methods, particularly the AHP, with GIS is fairly well established in theory and practice in the analysis of land uses [18-24]. The linking of the AHP with climate change projections to determine possible changes in agricultural land suitability as a consequence of potential climate change, we believe, a novelty of the methodology outlined in this paper. It proved



Map 2. Apple (Royal Gala) land suitability for Goulburn Broken Region—2000 (Baseline).



Map 3. Apple (Royal Gala) land suitability for Goulburn Broken Region—2050 (A1FI Scenario).

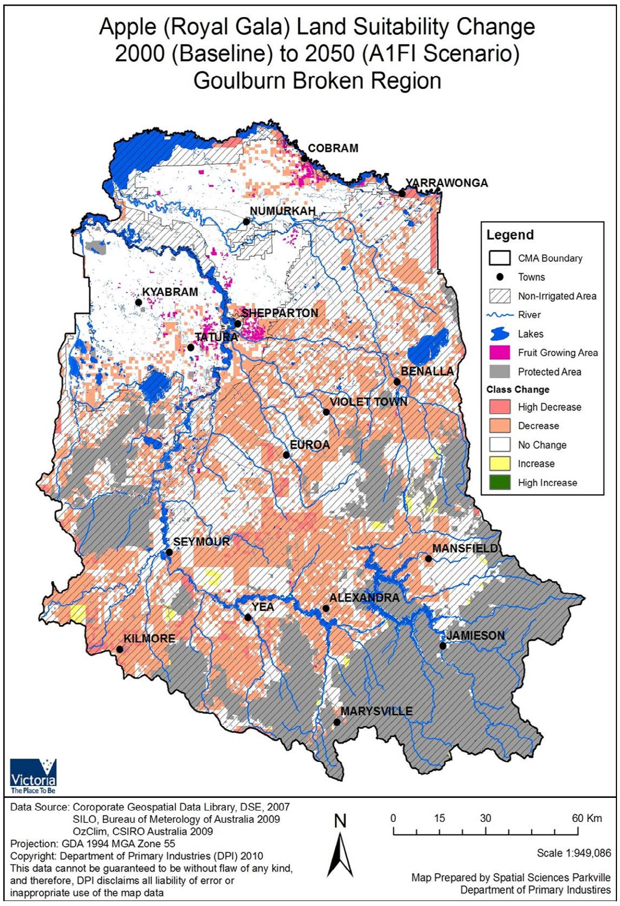
to be particular useful in assessing likely biophysical impacts in the future according to a multiplicity of scenarios (*i.e.* possibilities). The methodology was applied to examining the climate change impacts on the production of several horticultural commodities in Goulburn Broken. The following general comments hence refer to the results of the application of the methodology to all the commodities analysed in that region—pome fruits (apples and pears), stone fruits (peaches and nectarines) and wine grapes [36].

The assessment indicated that these horticultural commodities will be impacted in various ways by projected climatic changes.

Biophysical land suitability will likely change for all of the modeled commodities; in particular, there will be reductions and shifts in the areas most suitable for growing these crops. Increased temperatures will bring forward the timing of crop developmental stages with likely effects on flowering, pollination and harvest dates. This will be especially important in wine grapes cultivation, where a warmer climate could accelerate the progression of phenological stages of the vine—budburst, flowering and veraison so that ripening occurs earlier in the season [37]. Modifications in both the total amount of rainfall and periods in which rain falls, combined with changes in evapotranspiration, are likely to reduce water runoff to storages and affect soil moisture. The possible increase in water demand combined with reduced water availability indicates that the efficient use of water resources will be a major consideration for horticultural industries in the future.

Australia's agricultural industries have always experienced highly variable climatic conditions. Nevertheless, projected climate change will pose new and major challenges. For moderate levels of climate change (e.g. below 1.5˚C), incremental adaptations or adjustments to existing agricultural systems could lessen impacts and enable producers to take advantage of opportunities. Importantly, there are many adaptation actions of this type; they include:

1) Crop management: reduced sunburn, improved colour and elimination of bird damage can be achieved through hail netting, which was found to be particularly suited in high-yielding, intensive apple orchards systems [38] and in table grape production [39]. Strategies to protect grapevines during heatwaves (*i.e.* a prolonged period of excessive warm conditions) include a) maximise transpirational cooling with, for example, the use of



Map 4. Apple (Royal Gala) land suitability change Goulburn Broken Region—2000 (Baseline) to 2050 (A1FI Scenario).

sprinklers, and b) minimise incoming radiation intensity (or bunch exposure) by natural shading provided by the canopy or through new orientation (applicable to new vineyards) [40].

2) Varietal selection—introduction of breeding varieties of the horticultural crops that may be more suited to the new climatic conditions will assist in reducing some of the impacts mentioned above [6,41].

3) Water management: improve water application efficiency and minimise water loss by adopting the most efficient water saving techniques will assist growers to cope with the limiting supply of water. For example, a study by O'Connell and others [42] in Goulburn Broken on the responses of fruit trees to reduced irrigation in micro-irrigated, high-density apple and peach orchards demonstrated that better matching of water application to the evaporative surface of the orchard canopies (*i.e.* effective canopy cover—ECC) can substantially reduce irrigation water use in that region without compromising yield and fruit quality.

4) Weed, pest and disease management: several ecological approaches now exist for this purpose; they are based on integrated practices that affect pest population shifts and management rather than the complete "control" of a particular organism [43].

There are however limits to the effectiveness of the types of incremental adjustments that have proven useful in maintaining or increasing agricultural production in the highly variable Australian climatic conditions [6].

Climate change will probably expose existing agricultural systems to conditions which are likely to be outside the coping ranges of incrementally adaptive management practices and technologies. As the comprehensive definition of adaptation [4] highlights, adaptation also encompasses far-reaching change: "longer-term, deeper transformations". Therefore, a range of non-incremental, or transformational, adaptations must also be considered. Transformational adaptations of agriculture were recently recognised as a priority by the Australian Primary Industries National Adaptation Research Plan [http//piarn.org.au/about-piarnn/national-adaptation-research-plan; accessed on 2 March 2012] and is an emerging field of research [44,45]. Transformational adaptations could involve changes from existing activities to production systems or products that have been previously rare or unknown in the region of interest (*i.e.* changes in purpose), or transferring a production system and/or agriculturalists to another region that has (or will become) more suitable (*i.e.* changes in location). The latter could be however costly for established agricultural systems such as pome and stone fruit orchards and grapevines yards.

Agricultural research organised along traditional disciplines seems increasingly inadequate to address the growing complexity, uncertainty and risk brought about by climate, and other powerful drivers of, change. Such research needs to be holistic and trans-disciplinary in developing systems of adaptive governance and be undertaken through inclusive and participatory processes [46,47].

6. Concluding Remarks

The Earth's climate is changing and further changes seem unavoidable in the foreseeable future, even if appropriate actions are taken to reduce GHG emissions. For agricultural industries to continue to thrive in a complex, uncertain and risky future, we need to anticipate the likely changes and develop and implement adaptation strategies now. The methodology described in this paper provides a sound analytic approach to 1) recognise regions under threat of declines in agricultural production due to unfolding climatic changes, 2) identify alternative agricultural systems better adapted to likely future climatic conditions and 3) investigate incremental and transformational adaptation actions to improve the problematic situations that are being created by climate change.

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