Chapter 7 : Variable-rate management and whole-farm planning: hypothetically demonstrating with long-term modelling scenarios

7.1 Introduction
There is an increasing depth of research motivated by societal concerns about the environmental and social consequences of agriculture. Such concerns have provided the impetus for entire-system oriented research. This type of research asserts the need for analysis at multiple spatial (eg. field, farm and catchment) and temporal scales. This assertion is justified because management of a production system often involves tradeoffs between short-term profit maximisation and long-term investment in approaches towards sustainable production (Giller et al. 2006). Some examples of such analysis are goal-based farm modelling (Sterk et al., 2006), prototyping (eg. Vereijken, 1997), bio-economic farm modelling (Janssen and van Ittersum, 2007), life-cycle analysis (Haberl et al., 2004), agri-environmental indicators (van der Werf and Petit, 2002) and other integrated analytical frameworks.

Few of these examples incorporate spatial variability and much of the PA literature with an environmental focus does not consider entire farms. The majority of PA environmental research is limited to the side-environmental-benefit of waste minimisation from a single field while maximising yield using variable-rate fertiliser (Eg. Wang et al., 2003; Hong et al., 2004; Thrikawala et al., 1999).

However, a good example of the intersection between a system approach and PA is provided by Stoorvogel et al. (2004). These authors used prototyping to investigate a role for PA within a whole-production systems approach to agricultural research. The role of site-specific fertiliser and nematocide application on a Costa Rican banana plantation was investigated from a sustainability perspective. Crop productivity, soil and water quality and socio-economic acceptability were considered requirements for sustainability.

This research indicates a complimentary relationship between PA and system approaches to agricultural research. Some other PA research examples with a wide perspective provide further indication that this is the case. Some of these examples employ crop growth simulation modelling to integrate environmental and economic outcomes or to integrate management and environmental regulations. As well, some similar applications of PA technology have been reported in the literature under the term ‘precision conservation’ (Goddard, 2005).

Wong et al. (2005) undertook a site-specific assessment of financial and environmental outcomes at a field and at a farm scale. These authors used APSIM to simulate yield nitrogen recovery and nitrogen leaching under some different climate scenarios. A result of this work was the ability to identify areas on the farm that perform poorly from both a financial and an environmental perspective. van Alphen and Stoorvogel (2002) also used
modelling to identify areas across a farm where pesticide leaching would exceed a threshold value. Stull et al. (2004) looked at the use of PA for decisions regarding placement of filter strips to combat erosion. Bouma et al. (2002) used a modelling based approach to investigate relationships between environmental regulation and management. It was found that it is important to account for spatial variation when imposing regulations.

Some other landscape scale research in a similar vein has also been reported. For example, Castrignamo et al. (2007) with a salinity focus and Renschler and Lee, (2005) with a water quality and soil erosion focus.

This literature serves to emphasise the importance of continued research that analyses entire systems from a PA perspective. It is also evident that this type of research has not been exhaustively pursued. The sound basis of PA for analysing variability suggests that the integration of PA and whole-farm studies is a worthwhile avenue of research.

Consequently, this chapter will attempt to meet the fourth aim of this thesis which is to apply modelling scenarios across some farms and consider management benefits from a whole-farm planning perspective (ie. to consider both production and environmental outcomes). Three specific aims will be addressed; (i) to develop a framework to enable integration of crop yield potential, soil carbon sequestration potential and nitrogen leaching potential across farms at a high spatial resolution; (ii) to investigate the value of variable-rate management for integrated management of crop yield, soil carbon sequestration and nitrogen leaching and; (iii) to locate parts of a farm that might be suitable for alternative land uses.

7.2 Method

The method for this chapter can be divided into six distinct steps:

(i) Simulating 50 hypothetical yield years under uniform management;
(ii) Simulating 50 hypothetical yield years under variable-rate management;
(iii) Calculating soil carbon inputs for the above-mentioned 50 years;
(iv) Calculating a nitrogen leaching potential for the above-mentioned 50 years
(v) Classifying the 50 year outcomes in terms of potential performance
(vi) Using the resultant potential performance classes to simulate another 50 hypothetical yield years under uniform management and variable-rate management

Consistent with the preceding chapters, the methods are applied across “Merinda” and “BrookPark” (refer to Chapter 2 for study site descriptions). Outcomes from the preceding two chapters define which fields on each of the farms that this modelling can be undertaken. Refer to Chapter 5 for the names and locations of the fields. “Grandview” is excluded because only one field was available for scenario modelling and this is considered inadequate.
7.2.1 Crop yield simulations

50 years of historical climate data were used. Years 1920-1969 were chosen to represent possible future climate variability including a drought period. Two yield simulation scenarios were considered; uniform management and; variable-rate management. All of the remaining analysis was undertaken for both management scenarios.

Uniform management – Scenario one

50 years of yield data was simulated for the fields on a ten metre grid that were available for each farm using the across-farm models finalised in Chapter 6. One difference was that for this chapter the estimated hydraulic properties used were based on all the available years of data rather than excluding a single year for model validation. Notably, this modelling has ignored management in terms of fertiliser rates. As a result this scenario implies uniform management for 50 continuous years.

Variable-rate management – Scenario two

The above yield simulations were altered to simulate a hypothetical variable-rate nitrogen fertiliser scenario (based on some simple assumptions about the relationship between nitrogen fertiliser and yield response). Three management classes were delineated using fuzzy k-means classification (Minasny and McBratney, 2002) within each of the fields. The data used was mean yield calculated from 50 years of uniform-management, EC_a (if available) and elevation data. This approach is consistent with current commentary in the literature about which spatial information is useful for delineation of fields into potential management zones (Whelan and McBratney, 2003). The important difference is that 50 years of yield data is being used.

Centroids for each of the classes were observed and the classes were ranked in terms of yield such that ‘class one’ contained the highest mean yield, ‘class two’ contained the second highest mean yield, etc. It was assumed that the points falling in ‘class one’ would receive relatively more fertiliser (relative to scenario one); the points falling in ‘class three’ would receive relatively less fertiliser and; the points falling in ‘class two’ would receive the same amount of fertiliser. Based on these assumptions it was then assumed that the yields in ‘class one’ would increase by 15% each year, the yields in ‘class two’ would not change and the yields in ‘class three’ would decrease by 15% each year. The variable-rate management yields were calculated accordingly from the uniform management yield predictions.

7.2.2 Calculating annual soil carbon inputs

The amount of soil carbon in the top 30cm of the soil profile was calculated for each simulated yield year using Equation 7.1. This equation is an adaptation of the two compartment model proposed by Henin and Dupuis (1945) that allows for different carbon inputs, and rate constants between years (Jenkinson et al. 1990).

Equation 7.1 Carbon content of the soil

\[ C_{t+1} = C_t e^{-k} + \frac{fA_e (1 - e^{-k})}{k} \]
In this equation C is the organic carbon content of the soil, \( A_c \) is the annual input of plant carbon, \( f \) is the quantity of plant carbon that will decompose and \( k \) is the annual rate of decomposition. For each of the farms, soil carbon to a depth of 0.3 metres was considered. \( C_0 \) values were estimated from the soil sampling results reported in Chapter 2. The mean soil carbon values from each of the sampling strata in Chapter 2 were used for the points that fell into those strata.

\( A_c \) was derived from the crop yield with knowledge of the harvest index (HI) and a shoot-root ratio (SR) using Equation 7.2 where \( Y \) is the yield (t/ha) and the carbon concentration of all plant parts is assumed to be 0.45g/g. HI was assumed to equal 0.4, SR was assumed to equal 0.5.

**Equation 7.2 Annual input of plant carbon (above and below ground)**

\[
A_c = \left\{ \frac{Y(1-HI)}{HI} \times 0.45 \right\} + \left\{ \frac{Y(SR \times HI)}{HI} \right\} \times 0.45
\]

The quantity of plant carbon that will decompose \( (f) \) was varied by the compound topographic index (CTI) that was calculated across each farm in Chapter 2. CTI was scaled to equal between 0.3 and 0.4 so that in the moister areas of the farms a larger fraction of the plant carbon decomposes quickly to form carbon dioxide (ie. 70% as opposed to 60% in the dryer areas).

Three different values for \( k_{optimum} \) (at optimum moisture and temperature conditions) were investigated. These were 0.2yr\(^{-1}\), 0.3yr\(^{-1}\) and 0.4yr\(^{-1}\). The most appropriate single \( k_{optimum} \) value was chosen by observing the most realistic carbon modelling results.

Spatially \( k_{optimum} \) was held constant and temporally \( k_{optimum} \) was altered by empirical moisture and temperature functions (Equation 7.3). The moisture and temperature functions were taken from those used in the SOCRATES model (Grace et al. 2006a). The moisture function (MF) is described by Equation 7.4 where \( P \) is the annual precipitation (mm). The rate modifier ranges between 0.25 and 0.45, allowing for annual rainfall to range between 170 and 1400mm (Grace et al. 2006b). The temperature function is described by Equation 7.5 where \( T \) is the mean annual air temperature (ºC). This function is based on a Q10 relationship of two. The function equals one when \( T \) equals 25ºC and the relationship determines that the function is halved when the temperature is reduced by 10ºC (Parkin and Kaspar, 2003).

**Equation 7.3 Annual decomposition rate**

\[ k = k_{optimum} \times MF \times TF \]

**Equation 7.4 Moisture function**

\[ MF = 0.0598P^{0.279} \]

**Equation 7.5 Temperature function**

\[ TF = 0.177e^{0.069T} \]
7.2.3 Calculating nitrogen leaching potential

Leaching potential was calculated using Burns leaching equation (Scotter et al. 1993). In Equation 7.6 and Equation 7.7, $X$ is the fraction of N present on the soil surface leaching below depth $z$, $\theta$ is the moisture content at field capacity and $I$ is the effective rainfall (rainfall minus crop evapotranspiration). Crop evapotranspiration was assumed to equal 1mm per 20kg of crop yield (Rogers et al. 2007). For “Merinda” rooting depth was assumed to be 1.2 metres while rooting depth was assumed to equal 0.9 metres for “BrookPark”.

In some cases, particularly the variable-rate scenarios, the effective rainfall calculated was negative. In these cases, no further calculations were undertaken and the final leaching fraction was assumed to be zero.

Equation 7.6 Burns leaching equation

\[ X = \exp\left(-\frac{1}{I_s}\right) \]

Equation 7.7 Input for Burns leaching equation

\[ I_s = \frac{1}{z\theta} \]

7.2.4 Delineating potential performance classes

This analysis was undertaken across each farm with all the available fields together. First, some very simple classification rules were applied. Second, a more complex k-means classification was undertaken. These classifications provide a juncture for discussion about alternative management scenarios as they aid simultaneous visualisation of three different farm outcomes. First, comparisons between the simple and complex classification approaches were made. Second, comparisons between classification outcomes between the uniform rate scenario and the variable-rate scenario were made. Third, questions about this type of assessment prompting decisions to change land use in specific areas was addressed.

Simple classification rules

Arbitrary threshold values (or limits) were chosen that indicate minimum acceptable crop yield potential, minimum acceptable soil carbon sequestration potential and maximum acceptable nitrogen leaching potential. The indicator for crop yield potential was the 50 year mean and 2t/ha was considered the minimum acceptable yield. The indicator for soil carbon sequestration potential was the net change of soil carbon after 50 years. A net gain was considered acceptable and a net loss was considered unacceptable. The indicator for nitrogen leaching potential was the 50 year mean leaching fraction and the threshold value was 0.3.

These threshold values were used as criteria to determine each point in space as satisfactory or unsatisfactory with regards to potentially producing yield, potentially sequestering soil carbon and potentially leaching nitrogen to the ground water. A value of zero was allocated to the unsatisfactory points and a value of one was allocated to the satisfactory points. These three classifications were then combined by addition and a final
classification scheme containing values of zero, one, two and three was obtained. Values of three indicate points that satisfy environmental and production potential criteria under the hypothetical management practice. Values of zero indicate poor performance with respect to each of the criteria. Values of one or two indicate failings in two or one of the criteria respectively.

**Fuzzy k-means classification**

A similar approach to that used by Whelan and McBratney (2003) for field classification into potential management zones was used. However, different variables were included in the classification. The same indicators as in the simple classification were used to represent a yield performance potential, a carbon sequestration potential and a nitrogen leaching potential. Fuzzy k-means classification (Chapter 2) was implemented with these three indicators across the farms. For this classification, the uniform and the variable-rate data was combined so that the classes could be compared between management types. The optimum number of classes was obtained (Chapter 2) and differences between these classes described.

Principle component analysis was also undertaken on the correlations between carbon, yield and nitrogen. This enabled location of the class centroids within the multivariate space and comparison between the uniform management data and the variable management data.

**7.2.5 Using potential performance classes**

Two final management scenarios (one uniform and one variable-rate) were simulated. These scenarios utilised the previously obtained potential performance classes for variable-rate management. Comparisons between the scenarios were made in order to evaluate long-term variable-rate management using classes obtained in this way.

50 years of daily rainfall and temperature data was generated, again to represent a possible future climate scenario. The Stochastic Climate Library (Srikanthan et al., 2006) was used and the modelling was based on a 200 year data-record (from the SILO DataDrill - see Chapter 4). Rainfall state (the presence of rainfall) is based on a second order Markov chain and the amount is generated from a gamma distribution. Daily climate data is then generated using a first order auto-regressive multivariate model conditioned on rainfall state. The daily model is nested in a monthly model which is nested in an annual model.

The variable-rate management scenario was set up in a similar way to the preceding variable-rate scenario. In this case, the management classes used were the potential performance classes derived from the previous variable-rate management scenario. Centroids for each of the classes were observed and the classes were ranked in terms of yield. Subsequent rules for modifying yield were derived from these rankings for the whole-farm rather than considering each field alone.
The management outcomes were calculated and evaluated in the same way as previously described. In this case, only the k-means classification for potential performance was undertaken.

7.3 Results
Figure 7.1 and Figure 7.2 display the annual rainfall that was used for the first two management scenarios across “Merinda” and “BrookPark” respectively. These figures demonstrate the range of high and low rainfall years used.

![Figure 7.1](image1.png)  
**Figure 7.1 Annual rainfall between 1920 and 1969 used for management scenarios across “Merinda”**

![Figure 7.2](image2.png)  
**Figure 7.2 Annual rainfall between 1920 and 1969 used for management scenarios across "BrookPark"**
7.3.1 Yield simulations

Figure 7.3 displays mean yield predictions calculated from 50 years of yield predictions across “Merinda” under uniform management. Figure 7.4 displays the management classes used for variable-rate management on each of the fields calculated using the uniform management data, elevation and EC<sub>a</sub>. Figure 7.5 displays the resultant mean yield predictions calculated from 50 years of yield predictions across “Merinda” under variable-rate management. Within-field and between-field variation can be clearly observed under both management scenarios. Comparison between these two figures demonstrates that variable-rate management results in greater spatial variability within fields.

Similarly Figures 7.6 to 7.8 display the results for “BrookPark”. The management classes within each of the fields were calculated using the uniform management data and elevation data for two of the fields. EC<sub>a</sub> was also available for the other two fields. Similar observations to those across “Merinda” in terms of within-field variation, between-field variation and between management scenarios can be made.

Figure 7.3 Mean wheat yield (t/ha) calculated from 50 years of uniform management across “Merinda”
Figure 7.4 Potential management classes for variable-rate management scenario across “Merinda”

Figure 7.5 Mean wheat yield (t/ha) calculated from 50 years of variable-rate management across “Merinda”
Figure 7.6 Mean wheat yield (t/ha) calculated from 50 years of uniform management across “BrookPark”

Figure 7.7 Potential management classes for variable-rate management scenario across "BrookPark"
7.3.2 Soil carbon decomposition modelling

Figure 7.9 and Figure 7.10 demonstrate the sensitivity of the carbon decomposition model to the $k_{optimum}$ value. These figures depict soil carbon across “Merinda” and “BrookPark” respectively after 50 years of continuous wheat under uniform management. In terms of realistic additions of carbon to a soil, the $k_{optimum}$ value of 0.3yr$^{-1}$ was chosen for “Merinda” and the $k_{optimum}$ value of 0.4yr$^{-1}$ was chosen for “BrookPark”. For “Merinda”, this decomposition rate provided that the maximum addition of soil carbon on the farm was 50tC/ha and the greatest loss on the farm was 25tC/ha. For “BrookPark” this decomposition rate provided that the maximum addition of soil carbon on the farm was 54tC/ha and the greatest loss on the farm was 10tC/ha.

Figure 7.11 and Figure 7.12 shows changes in soil carbon over time for the individual fields on “Merinda” and “BrookPark” respectively. These plots of the median soil carbon for each field demonstrate that new equilibriums are reached over the course of the 50 years. It is interesting to note the direction of change between fields. Comparison between the two management scenarios demonstrates that the differences in terms of field-medians are not significant for most of the fields.

Figure 7.13 and Figure 7.14 demonstrates the initial soil carbon values across “Merinda” that were based on soil sampling results. Greater differences in soil carbon between the management scenarios can be seen in the maps of soil carbon across the farm at 50 years (Figures 7.15 to 7.18). Greater spatial variation in soil carbon within fields due to the variable-rate management can be observed on both the farms.
Figure 7.9 Soil carbon (0-30cm) after 50 years of continuous wheat cropping across “Merinda” calculated using different $k_{\text{optimum}}$ values. (a) $k=0.2$, (b) $k=0.3$ and (c) $k=0.4$
Figure 7.10 Soil carbon (0-30cm) after 50 years of continuous wheat cropping across “BrookPark” calculated using different $k_{\text{optimum}}$ values. (a) $k=0.2$, (b) $k=0.3$ and (c) $k=0.4$
Figure 7.11 Median (across each field on “Merinda”) soil carbon versus time under variable and uniform management; (a) ‘Kilrosewood’; (b) ‘Rosewood1-3’; (c) ‘Hol1-3’ and; (d) ‘Kilhouse’
Figure 7.12 Median (across each field on “BrookPark”) soil carbon versus time under uniform and variable management; (a) ‘Quarry’; (b) ‘House’; (c) ‘Clothier’ and; (d) ‘Griegs’
Figure 7.13 Initial soil carbon content (0-30cm) across “Merinda”

Figure 7.14 Initial soil carbon content (0-30cm) across "BrookPark"
Figure 7.15 Soil carbon (0-30cm) across "Merinda" after 50 years of uniform management

Figure 7.16 Soil carbon (0-30cm) across "Merinda" after 50 years of variable management
7.3.3 Nitrogen leaching potential

Figure 7.19 and Figure 7.20 display the mean nitrogen leaching fraction across “Merinda” calculated from 50 years of simulated data under uniform and variable-rate management respectively. Figure 7.21 and Figure 7.22 display the respective results for
“BrookPark”. Some difference due to the management scenarios is evidenced in these maps, however, the differences are not as stark as those are for soil carbon and crop yield.

Figure 7.19 50 year mean N leaching fraction under uniform management across “Merinda”

Figure 7.20 50 year mean N-leaching fraction under variable management across “Merinda”
7.3.4 Delineating potential performance classes

Simple classification scheme

Figure 7.23 demonstrates delineations across “Merinda” under both management scenarios for each of the criteria separately. Figure 7.24 and Figure 7.25 illustrate an integration of the three properties into a single classification for the uniform and the
variable-rate management scenario respectively. The main difference that can be observed between the management scenarios is enhanced loss of soil carbon due to variable-rate management in the field ‘Kilrosewood’. The number of points on the ten metre grid allocated to each of the simple classes is displayed in Table 7.1.

In the light of the comparison between the simple classification scheme and the fuzzy k-means classification scheme across “Merinda” only the k-means classification was undertaken across “BrookPark”.

**Fuzzy classification scheme and principle components analysis**

Evidence (Chapter 2) suggested that eight classes were most appropriate for k-means classification across “Merinda” and seven classes were most appropriate across “BrookPark”.

Figure 7.26 and Figure 7.29 are plots of the first two principle components derived from the classification data for “Merinda” and “BrookPark” respectively. In these plots, the red points represent uniform management and the blue points represent variable-rate management. Locations of the centroids from the fuzzy classification schemes are also identified in these plots. Table 7.2 and Table 7.3 display the cluster means (or centroids) from each of the classes for each of the farms.

The spatial distribution of these classes across each of the farms under both management scenarios are demonstrated in Figure 7.27 and Figure 7.28 (“Merinda”) and in Figure 7.30 and Figure 7.31 (“BrookPark”).
Figure 7.23 Simple classifications for each of the properties under uniform and variable management across “Merinda”; (a) soil carbon accumulation for uniform and variable management; (b) crop yield for uniform and variable management and; (c) nitrogen leaching potential for uniform and variable management;
Figure 7.24 Simple integrated classification due to uniform management across “Merinda”

Figure 7.25 Simple integrated classification due to variable management across “Merinda”
Table 7.1 Simple classification counts on the “Merinda” farm grid

<table>
<thead>
<tr>
<th>Number of points on grid</th>
<th>Uniform integrated</th>
<th>Variable integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘0’</td>
<td>132</td>
<td>521</td>
</tr>
<tr>
<td>‘1’</td>
<td>2563</td>
<td>2782</td>
</tr>
<tr>
<td>‘2’</td>
<td>4828</td>
<td>3889</td>
</tr>
<tr>
<td>‘3’</td>
<td>17210</td>
<td>17541</td>
</tr>
</tbody>
</table>

Table 7.2 Class centroids (carbon, nitrogen and yield) for the fuzzy k-means classification across “Merinda”

<table>
<thead>
<tr>
<th>Class</th>
<th>C gain or loss</th>
<th>N leaching fraction</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>0.30</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>-10</td>
<td>0.32</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>0.19</td>
<td>5.3</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>0.32</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>0.23</td>
<td>4.2</td>
</tr>
<tr>
<td>6</td>
<td>-6</td>
<td>0.42</td>
<td>2.3</td>
</tr>
<tr>
<td>7</td>
<td>23</td>
<td>0.22</td>
<td>4.7</td>
</tr>
<tr>
<td>8</td>
<td>27</td>
<td>0.24</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Figure 7.26 Principle components and location of centroids across “Merinda” (red is uniform management and blue is variable management)
Figure 7.27 Fuzzy classification due to uniform management across “Merinda”

Figure 7.28 Fuzzy classification due to variable-rate management across “Merinda”
Table 7.3 Class centroids (carbon, nitrogen and yield) for the fuzzy k-means classification across "BrookPark"

<table>
<thead>
<tr>
<th>Class</th>
<th>Carbon gain or loss</th>
<th>N leaching fraction</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58</td>
<td>0.10</td>
<td>5.7</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>0.15</td>
<td>4.9</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.46</td>
<td>1.7</td>
</tr>
<tr>
<td>4</td>
<td>48</td>
<td>0.12</td>
<td>5.4</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>0.28</td>
<td>2.6</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>0.32</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>0.35</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Figure 7.29 Principle components and location of centroids across "BrookPark" (red is uniform management and blue is variable management)
Figure 7.30 Fuzzy k-means classification due to uniform management across "BrookPark"

Figure 7.31 Fuzzy k-means classification due to variable-rate management across "BrookPark"
### 7.3.5 Using potential performance classes

Figure 7.32 and Figure 7.33 display the annual rainfall that was calculated from the daily climate data generated using the SCL for both farms.

![Figure 7.32 Annual rainfall generated using the SCL for “Merinda”](image)

![Figure 7.33 Annual rainfall generated using the SCL for "BrookPark"](image)

**Across-farm rules for variable-rate fertilising**

Tables 7.4 and 7.5 outline the decision rules used for variable-rate management across “Merinda” and “BrookPark” respectively. With reference to crop yields simulated using uniform management, yield was either adjusted down 15%, not modified or adjusted up 15%. This impacted the degree of variable management within fields as some fields contained a greater number of classes than others.
Table 7.4 Variable-rate decisions based on the previous classification across “Merinda”

<table>
<thead>
<tr>
<th>Class (from Figure 7.28)</th>
<th>Class centroid yield ranking</th>
<th>Relative yield adjustments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>same</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>+15%</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-15%</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>-15%</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>same</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>-15%</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>+15%</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>+15%</td>
</tr>
</tbody>
</table>

Table 7.5 Variable-rate decisions based on the previous classification across "BrookPark"

<table>
<thead>
<tr>
<th>Class (from Figure 7.31)</th>
<th>Class centroid yield ranking</th>
<th>Relative yield adjustments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>+15%</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>+15%</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>-15%</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>+15%</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>same</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>same</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>-15%</td>
</tr>
</tbody>
</table>

Crop yield potential, nitrogen leaching potential and carbon sequestration potential

The variable-rate management scenario compared to the uniform management scenario resulted in greater within-field variability across the farm for each of the outcomes across “Merinda”. Figure 7.34 and Figure 7.35 demonstrate these results using crop yield as the example. For “BrookPark”, the variable-rate management scenarios compared to the uniform management scenario also resulted in greater within-field variability for each of the outcomes; however these differences are not as obvious. Figure 7.36 and Figure 7.37 demonstrate these results using crop yield as the example.
Figure 7.34 50 year mean yield due to uniform management across “Merinda” under the stochastic climate scenario

Figure 7.35 50 year mean yield due to variable management across “Merinda” under the stochastic climate scenario
Figure 7.36 50 year mean yield due to uniform management across “BrookPark” under the stochastic climate scenario

Figure 7.37 50 year mean yield due to variable management across “BrookPark” under the stochastic climate scenario
Potential performance classes

Eight and seven classes were optimal for the fuzzy k-means classification across “Merinda” and “BrookPark” respectively. Table 7.6 and Table 7.7 contain the centroids for the classes for each farm. The location of these classes within multivariate space is also demonstrated in the plots of principle components calculated from the farms outcomes from both the management scenarios (Figure 7.38 and Figure 7.39). This figure demonstrates some differences between the farm outcomes from both management scenarios.

Figure 7.40 and Figure 7.41 demonstrate the potential performance classes across “Merinda” for the uniform and the variable-rate management scenario respectively. The equivalent results across “BrookPark” are displayed in Figure 7.42 and Figure 7.43. For “Merinda” some differences between the management scenarios can be seen; again in the fields ‘Hol1-3’ and ‘Rosewood1-3’. For “BrookPark”, these two figures appear quite similar with a minor exception in the field ‘Griegs’.

Table 7.6 Class centroids (carbon, nitrogen and yield) for the fuzzy k-means classification across “Merinda” using results from the stochastic climate scenario

<table>
<thead>
<tr>
<th>Class</th>
<th>C gain or loss (t/ha)</th>
<th>N leaching fraction</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10</td>
<td>0.41</td>
<td>1.9</td>
</tr>
<tr>
<td>2</td>
<td>-41</td>
<td>0.37</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>0.34</td>
<td>2.4</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>0.21</td>
<td>4.7</td>
</tr>
<tr>
<td>5</td>
<td>-34</td>
<td>0.29</td>
<td>3.1</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0.25</td>
<td>4.9</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>0.20</td>
<td>5.1</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
<td>0.18</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Figure 7.38 Principle component analysis with location of centroids for “Merinda” under the stochastic climate scenarios (red is uniform management and blue is variable management)
Table 7.7 Class centroids (carbon, nitrogen and yield) for the fuzzy k-means classification across "BrookPark" using results from the stochastic climate scenario

<table>
<thead>
<tr>
<th>Class</th>
<th>C gain or loss (t/ha)</th>
<th>N-leaching fraction</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65</td>
<td>0.08</td>
<td>6.2</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>0.07</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>0.22</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>0.23</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>0.41</td>
<td>2.1</td>
</tr>
<tr>
<td>6</td>
<td>19</td>
<td>0.24</td>
<td>3.6</td>
</tr>
<tr>
<td>7</td>
<td>29</td>
<td>0.20</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Figure 7.39 Principle component analysis with location of the centroids for "BrookPark" under the stochastic climate scenarios (red is uniform management and blue is variable management)
Figure 7.40 Across farm classification due to uniform management across "Merinda" under the stochastic climate scenario

Figure 7.41 Across farm classification due to variable management across "Merinda" under the stochastic climate scenario
Figure 7.42 Across farm classification due to uniform management across "BrookPark" under the stochastic climate scenario

Figure 7.43 Across farm classification due to variable management across "BrookPark" under the stochastic climate scenario
7.4 Discussion

7.4.1 Data simulation

50 years of crop yield information
It is important to note that these crop yield simulations should be considered indicative of potential scenarios (see Chapter 6 results) rather than as an absolute representation of reality. Beyond improvements to the model that are relevant to the preceding two chapters, there is scope for discussion in this chapter about enhancing the validity of these simulations.

The major discussion point relating to these yield simulations is that management decisions are not incorporated into the simulations. These simulations assume 50 years of continuous wheat under exactly the same management conditions each year. It would be more realistic to include such things as fertiliser rates, crop cultivars and sowing dates. This limitation of the modelling is a particular issue for this chapter as one of the aims is to evaluate different management strategies. This leads to the need to acknowledge the major assumptions about yield and fertiliser response relationships across the farms. The simulated yields under the variable-rate fertiliser scenario are therefore considered to be particularly rough estimates of possible yield outcomes due to variable-rate fertiliser application.

This chapter serves to highlight a modelling priority for future work.

50 years of soil carbon information and nitrogen leaching fractions
Similar to the yield simulations, the soil carbon and the N-leaching modelling undertaken in this chapter should be treated as an indication of potential scenarios.

With respect to carbon, some quite arbitrary decisions about parameters for the carbon decomposition model were made, particularly $f$ and $k_{\text{optimum}}$. This contributes to uncertainty about the simulated soil carbon contents.

The model has proven quick and relatively simple to apply with the available data. Some conceptual simplifications have made this possible. These simplifications also contribute to uncertainty about the simulated values. One example is that only two pools of carbon are considered as opposed five in a more complex carbon model (Eg. Roth-C: Jenkinson and Rayner, 1977). Another example is that this model allows soil carbon to increase without limit while ignoring the possibility of a carbon saturation level (Six et al., 2002).

In terms of N-leaching, the Burns Leaching equation has also proven quick and relatively simple to apply with the available data. It is noteworthy that for some of the extremely high yield predictions, the N-leaching calculations became unreasonable. In terms of conceptual model simplification, it is worth mentioning the effect of intra-seasonal temporal variation of rainfall that is not included. The timing of rainfall within a season is likely to significantly impact the amount of nitrogen leaching down the soil profile due to the timing of nitrogen application and plant uptake.
7.4.2 Data integration
Comparing classification approaches
The simple classification approach relies on decisions about threshold values. The fact that these decisions significantly impact the results demonstrates the need for care when defining threshold values. There are many accepted/applied concepts regarding environmental management that in some way rest on the premise that limits/thresholds exist. For example, the ecological resilience concept describes the amount of disturbance (ie. a limit or threshold) that an ecosystem can withstand before it shifts to a new stable/equilibrium state (Scheffer et al., 2001). Other concepts that imply the existence of limits or thresholds are tradeoffs, classification and calculation of efficiencies. However, it is arguable that there can be more than one ultimate level of function or possibility. This is a convincing argument when considering that many different optimal management strategies exist at different levels of an indicator (Pannell, 2003). A ramification of this argument is that an adaptive approach to management upon acquisition of new information is important and setting of limits can be a fluid process. This discussion suggests that further research into the definition of threshold values that indicate such things as yield potential, carbon sequestration potential and nitrogen leaching potential would be valuable.

The fuzzy k-means classification provided a more objective approach to classifying spatial differences across the farms. An advantage of this approach over the simple classification approach is that this classification does not assume management decisions to be simply dichotomous. However, this approach can not be separated from discussion about defining thresholds/limits if these classes are to be used to make management decisions. The delineation of classes for potentially different management means that different levels of certain properties will necessarily be considered acceptable or not.

The fuzzy k-means classifications will form the basis of the remaining discussion.

7.4.3 Uniform management versus variable-rate management
Uniform management versus variable-rate management (first)
Comparisons between the fuzzy k-means classification maps for the first uniform and variable-rate management scenarios (Figure 7.27 and Figure 7.28 for “Merinda”; Figure 7.30 and Figure 7.31 for “BrookPark”) suggests that the long-term farm outcomes (considering yield, carbon and nitrogen) are dependent on the management approach for some fields, but not all. These results invoke some interesting discussion questions:

- First, is a long-term yield record such as 50 years useful for defining potential management classes and then undertaking variable-rate management (ie. the first approach in this chapter)?
- Secondly, is this approach useful for subsequent delineation of potential management classes (ie. use the resultant classes for variable-rate management – the second approach in this chapter)?
- Finally, in general, is variable-rate management a useful concept for long-term management?
With regards to the first question, it is apparent that differences in across-farm integrated outcomes are field specific. For “Merinda”, the potential performance of two fields did not change due to management scenarios. However, some notable differences due to variable-rate management are evident in ‘Hol1-3’ and ‘Rosewood1-3’. Variable management has led to greater variability within ‘Hol1-3’. Under uniform management this field is dominated by ‘Class 3’. Parts of the field are replaced with ‘Class 5’ under the variable-rate management. This change is an overall drop in potential performance. A similar drop in overall potential performance due to variable-rate management is evident in ‘Rosewood1-3’. For “BrookPark”, notable differences due to variable-rate management are only evident in one field (‘Griegs’). The potential performance within the northern section of this field becomes more variable due to variable-rate management. ‘Class 4’ becomes more dominant in amongst ‘Classes 1 and 2’. This appears to be a positive outcome overall.

There are also some notable differences within fields when considering each farm outcome alone. Consistent between farms, greater within-field variability for each of the management outcomes has occurred due to the variable-rate management scenario. The distributions of outcomes, at both the high and low ends have been exacerbated. These results imply that in the long-term, this approach to variable-rate management is not necessarily superior to uniform management across “Merinda” or “BrookPark”, particularly when evaluating multiple fields and farm outcomes simultaneously.

**Uniform management versus variable-rate management (secondly)**

With regards to the second discussion question, similar differences between the second uniform and variable-rate management scenarios are evidenced in the fuzzy k-means classification (Figure 7.40 and Figure 7.41 for “Merinda”; Figure 7.42 and Figure 7.43 for “BrookPark”). The same fields on each of the farms are responsive to management approaches.

In ‘Hol1-3’ greater variability due to variable-rate management is apparent. Again, the classification results suggest an overall drop in potential performance due to variable-rate management. However, in ‘Rosewood1-3’, the classification results suggest an overall improvement in potential performance as ‘Class 7’ is replaced with ‘Class 8’ due to variable-rate management. In ‘Griegs’, areas classified as ‘Classes 1 or 6’ under uniform management are diminished and coverage under ‘Class 2’ is increased. This result is a clear increase in potential performance.

It is demonstrated that the changes due to the second approach to variable-rate management are more substantial than those due to the first approach. This result is particularly significant across “Merinda”. Across “BrookPark”, differences between uniform and variable-rate management due to both approaches are minor. This suggests that the prior classification might be a useful approach for delineation of potential management classes across “Merinda” while this is not the case for “BrookPark”. These scenarios clearly demonstrate that certain fields appear to be more suitable for SSCM.
than other fields. It is apparent that using a classification procedure that accounts for a number of farm outcomes based on a 50-year management scenario for variable-rate management is more effective than the initial approach that used yield, elevation and ECₐ to delineate classes.

With regards to the third question, the potential value of variable-rate management in the long-term has been demonstrated to be specific to the approach used for management decisions and field-specific. Within a field, variable-rate management enhances the performance of some areas and reduces the performance of other areas. The balance between these outcomes determines the overall value of the management strategy and some extent of this balance is determined by inherent soil and landscape properties. These scenarios have demonstrated that the potential value of variable-rate management in the long-term is limited to certain fields; these scenarios have also served to identify parts of the farm that might be inherently unsuitable for SSCM. A confirmation of these results would be an interesting departure point for further work. This does not mean that variable-rate management is not a useful concept for long-term management. Rather, this suggests that there is potential for a combination of PA strategies to enhance management across a farm. As well, there are significant opportunities for further research into approaches for management zone delineation using 50 years of yield data.

7.4.4 Whole-farm planning

An additional use for the PA information gained in this chapter is to make land-use decisions at the farm scale. The perspective gained from these scenario analyses and the across-farm classifications could be used to consider alternative land-use options across parts of the farm.

It could be assumed that parts of the farm showing minimal performance potential under variable-rate management are those parts of the farm that are inherently unsuitable for SSCM. For example (considering the second climate scenarios across “Merinda”), both ‘Kilhouse’ and ‘Kilrosewood’ are non-responsive to variable-rate management over the long term. According to the classification, the potential performance of these fields is also quite low. For example, the centroids for each of the four classes located within these two fields display net soil carbon losses, the nitrogen leaching fractions are relatively high and the crop yields are relatively low. Similarly for “BrookPark”, the field ‘Quarry’ is dominated by ‘Class 5’ which has the highest leaching potential, the lowest yield potential and the lowest carbon sequestration potential across the farm. It is possible then to presume that an alternative land-use on these fields could enhance management outcomes both financially and environmentally.

Generally this information can be used to locate the least financially (indicated with yield potential) and environmentally viable (indicated with carbon sequestration and nitrogen leaching potential) parts of the farm. This valuable spatial information based on long-term management scenarios could be incorporated into a framework that considers changing land-use across a farm.
7.5 Conclusions
This chapter has generated 50 years of crop yield, soil carbon and nitrogen leaching information under four different management scenarios. Integration of this information using two different classification approaches has enabled some discussion and conclusions that are aimed towards management decisions using a whole farm planning perspective.

In terms of developing a framework that enables integrated analysis of crop yield, soil carbon and nitrogen leaching potentials across farms:

- The simulation of 50 years of crop yield, soil carbon accumulation and nitrogen leaching information is extremely useful given the temporal extent and the spatial resolution.
- There is scope to improve modelling crop yield with inclusion of management decisions, particularly to include fertiliser inputs.
- The fuzzy k-means approach to classification is more suitable than simple classification rules as greater detail about spatial variation is preserved.
- There is scope to improve understanding about limits or thresholds for each of the farm outcomes under question to enable management decisions based on the classification schemes.

In terms of delineating potential management classes for variable-rate management:

- 50 years of spatially-dense financial and environmental management outcomes are useful for delineation of potential management classes across a farm.
- Potential performance classes that account for yield potential, carbon sequestration potential and nitrogen leaching potential proved most effective for delineation of potential management classes for variable-rate management.

In terms of investigating the value of variable-rate management for integrated management of crop yield, soil carbon and nitrogen leaching:

- Suitability for variable-rate management is field specific; over the long-term, variable-rate management is a potentially valuable management strategy within certain fields.
- However, across farms over the long-term, a combination of variable-rate management and other PA management strategies could improve overall management outcomes.

In terms of locating suitable parts of a farm for making land use changes:
This analysis proved useful for identifying areas on a farm that are the least financially and environmentally viable. From a whole-farm planning perspective this is useful information when considering alternative land use options.
References:


