Precision agriculture improves efficiency of nitrogen use and minimises its leaching at within-field to farm scales

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Abstract

We used precision agriculture techniques and the APSIM model for crop growth, water balance and nitrate leaching as a tool to monitor and improve the environmental and financial performance of farms at within-field resolution. We used yield maps, soil and climate data for two farms in Western Australia to determine spatial and temporal patterns of grain yield, drainage and nitrate leaching under a range of climatic, soil and management scenarios. On one farm, we up-scaled APSIM using soil type polygons and on another we used relationships between EM38 and soil water storage properties to map predicted yield and nitrate leaching and identify areas at greatest financial and environmental risks for management interventions.

Keywords: APSIM, drainage, nitrate leaching, EM38, plant available water.

Introduction

Precision agriculture aims to monitor and improve the financial performance of farms at within-field resolution by providing detailed information on site-specific yield, nutrient recovery and income. Recovery of nutrient can be used to evaluate and manage environmental risk for example, due to nitrate leaching (Ortega et al., 2003). Site-specific yield provides a means of matching fertiliser applications to crop requirements and reducing potential adverse environmental impacts of fertiliser use (Ebertseder et al., 2003, Wong et al., 2001). It can be used in conjunction with simulation model and real time weather data to take account of site-specific mineral nitrogen (N) in the soil profile (van Alphen, 2002). In combination with a simulation model, such as APSIM for crop growth, drainage and nitrate leaching (www.apsim.info), precision agriculture techniques can be used to monitor the environmental performance of a farm over time so that areas at risk can be identified and remediated (Pracilio et al., 2002). APSIM simulates carbon, water and N dynamics and their interactions within a crop/soil system that is driven by daily weather information (rainfall, maximum and minimum temperature and solar radiation). It calculates the potential yield, that is, the yield not limited by pests, diseases, P and K, but limited only by temperature, solar radiation, water and N supply. The model has been successfully tested against data from field experiments in Western Australia and elsewhere (e.g. Asseng et al. 1998a).

Temporal and spatial variation in yield, drainage and leaching losses is large because of variation in seasonal conditions and in soil properties critical for deep drainage and hence nitrate leaching (Wong and Asseng, 2004, Pracilio et al, 2002). Because of this, site specific management should improve farm gate nutrient balances which, although effective as a means of minimising the off-site effect of N use can be improved by
targeting specific areas within the farm. We suggest that this approach will allow precision agriculture techniques to be used to produce green products and production processes while at the same time improving profits for the farmer. In this paper, we develop a user-friendly method of combining the techniques with the APSIM simulation model to carry out this site-specific financial and environmental assessment and make management more precise.

Materials and Methods

Initial work was carried out at farm-scale on an intensive cropping farm at Wongan Hills in Western Australia (WA). The spatial resolution of the data and map outputs ranged from 5 m grid for yield maps to 1:10 000 for drainage and leaching based on soil type polygons. The main crops grown were wheat in rotation with lupin. The farm had several years of yield data that corroborated well with the farm record for the field-averaged yield measured at the grain bin. Grain N content was measured to represent a range of low to high yielding zones. It varied little across the farm compared with grain yield. For example, the mean N content of 56 samples of wheat was 2.2% and the standard error was 0.03. We calculated that spatially variable recovery of N in grain by multiplying the yield monitor grain yield with its average N content.

To estimate spatially variable N leaching, we need to estimate the volume of drainage and its N concentration. We initially used the APSIM model to derive linear relationships between rainfall and drainage volume for each of the major soil types on the farm. These soil types included pale sand, yellow sand, loamy sand, gravely loamy sand and duplex soils and represented the main textural contrasts for the farm. The model predictions of drainage were compared with published values in order to test their reliability. These linear relationships between rainfall and drainage volume allowed us to calculate spatially variable drainage volume each year based on soil type polygons. Average nitrate concentration in drainage water was calculated from the soil available N (fertiliser plus mineralised N). Mineralised N was derived from the decomposition rates of crop residues and of soil organic matter content of each soil type using the method of Bowden and Burgess (1993). This method of estimating N concentration in drainage was also evaluated with soil and water data published for Western Australia. We determined spatially variable N leaching annually for each soil polygon on the farm by multiplying the drainage volume with its N concentration.

In addition, we carried out a more spatially detailed work mapped at 5 m grid resolution on a 70 ha grower’s field at Three Springs in WA. The field had a lupin and wheat rotation that had been yield monitored since 1998. The yield maps were used to decide ten soil sampling locations to represent a range from low to high yielding areas. Soil samples were taken to a maximum depth of 2.5 m wherever possible at these ten locations to measure bulk density and soil water contents at crop lower limit and drained upper limit. The crop lower limit referred to the water content of the soil after harvest and is a measure of the ability of the crop to take up water from the soil and to dry it down prior to harvest. The drained upper limit is effectively the field capacity of the soil. The amount of water contained between the soil lower limit and the drained upper limit in the root zone is the plant available water (PAW) content. It was possible
to sample below 1.0 m at only eight locations due to large gravel content at two locations.

We measured bulk soil electrical conductivity in the field at 30 m line spacing using on-ground EM38 survey. We re-measured EC at the locations of PAW measurements so as to minimize positional and interpolation errors for correlating EC with PAW. The linear relationship obtained between EC (expressed in mS/m) and PAW (PAW = 22.6 EC – 25.0, $r^2 = 0.78$) was then used to transform the EM 38 map of the field into a PAW map. Measured and simulated wheat yields were linearly related to PAW as were drainage and nitrate leaching. These linear relationships were used to upscale APSIM and predict grain yield and nitrate leaching spatially and temporally for a range of seasonal and management scenarios for the field.

**Results**

**Farm scale work at soil polygon resolution**

Average grain N content was 2.2% N for wheat and 5.0% N for lupin. An example of the spatially variable removal of N in grains measured on the farm is shown in Figure 1. Variability in yield and N recovery were mostly driven by soil texture which in turn determined the soil’s ability to store water for crop use.

![Figure 1. An example of N recovery (kg/ha) in grains measured on the farm in 2000.](image)

APSIM predicted linear relationships between drainage values and rainfall for different soil types (Figure 2). The drainage values calculated in this simple manner were in accord with those reported in the literature (Figure 3).
Concentration of N in drainage water was estimated using total available N from soil mineralized N and fertilizers (Figure 4) and used to calculate nitrate leaching (Table 1). The gross margins achieved on each soil type are shown in Table 2.
Figure 4. Relationship between nitrate-N concentration in drainage water and total available N in the soil.

Table 1. Leaching of nitrate (kg N/ha) from different soil types encountered on-farm

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>3-yr Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loamy sand</td>
<td>20.0</td>
<td>0.0</td>
<td>0.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Duplex</td>
<td>14.9</td>
<td>1.9</td>
<td>2.8</td>
<td>19.6</td>
</tr>
<tr>
<td>White sand</td>
<td>19.6</td>
<td>7.3</td>
<td>17.0</td>
<td>43.8</td>
</tr>
<tr>
<td>Yellow sand</td>
<td>18.2</td>
<td>8.9</td>
<td>9.5</td>
<td>36.6</td>
</tr>
<tr>
<td>Gravelly loamy sand</td>
<td>25.5</td>
<td>5.7</td>
<td>7.2</td>
<td>38.5</td>
</tr>
</tbody>
</table>

Table 2. Gross margins ($/ha) achieved on soil type polygons occurring on-farm

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>3-yr Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loamy sand</td>
<td>149</td>
<td>103</td>
<td>403</td>
<td>218</td>
</tr>
<tr>
<td>Duplex</td>
<td>155</td>
<td>82</td>
<td>301</td>
<td>179</td>
</tr>
<tr>
<td>White sand</td>
<td>81</td>
<td>33</td>
<td>255</td>
<td>123</td>
</tr>
<tr>
<td>Yellow sand</td>
<td>168</td>
<td>94</td>
<td>251</td>
<td>171</td>
</tr>
<tr>
<td>Gravelly loamy sand</td>
<td>122</td>
<td>148</td>
<td>289</td>
<td>186</td>
</tr>
</tbody>
</table>

Filed scale work at 5 m grid resolution

The measured wheat yield on the 70 ha field (Figure 5) showed areas that performed well and those that did poorly during the years of observation. The patterns of lupin yields were similar but are not shown since we only simulated wheat yield.
Figure 5. Measured wheat yield for the 70 ha experimental field at Three Springs in 1998, 2000 and 2002.

The measured yield maps shown in Figure 5 are for dry (2000 and 2002) and medium rainfall years (1998). The simulated average yields for dry, average and wet years (Figure 6) had similar spatial patterns to the measured yields but allowed a broader assessment of site specific yield for a wider range of seasonal and management conditions. The lowest yielding areas were on coarse textured soils and this led to more nitrate leaching from them (Figure 6).

Discussion

The APSIM model has been extensively tested for the WA wheatbelt for more than ten years (Asseng et al, 1998a, Asseng et al, 1998b, Asseng et al 2001). We were therefore confident to use it based on past validations. Nitrate leaching varied spatially and temporally at both farm and field scales as a result of climate and soil variation and N use. The main soil property governing crop yield, drainage and leaching was plant available water (PAW). The APSIM program derived linear relationships between PAW
Figure 6. Simulated average wheat yield (left) and nitrate leaching (right, kgN/ha) for initially dry soil conditions given 60 kgN/ha for 0-33.3% percentile May to October rainfall (top), 33.3% - 66.6% percentile May to October rainfall (middle) and 66-100% percentile May to October rainfall years (bottom) for the 70 ha experimental field.

and yield, drainage and nitrate leaching for different seasonal conditions and rates of N applications. This allows the model to be used for tactical and strategic farm management. The one-off cost is that of a calibrated EM38 survey (~AU$ 10/ha for a farm) to determine spatially variable PAW. This approach is likely to be more effective than using soil type polygons which we initially used because of possible ambiguity between soil type and PAW and because of weakness in the assumption of uniformity within soil types. Areas within the field with large PAW performed well both financially and environmentally by consistently producing larger crops and by leaching less or no nitrate. Coarse textured areas had small PAW, low yield and much nitrate leaching. Further modelling showed that splitting N application decreased nitrate leaching on those areas but yield remained small due to water limitations.

Conclusions
Measurements of PAW extrapolated to the farm based on an EM38 survey together with simulation modelling form powerful tools to determine the grain production capacity of the farm and the areas at risk of nitrate leaching. Nitrogen management may be improved on these areas such as by split fertiliser application. Another option is to reassign these poor performing areas to perennial vegetation to increase water use and decrease the advance of salinity which is currently a major environmental issue in the WA wheatbelt. Our method of identifying areas for land use change is likely to be more palatable for growers currently reluctant to change land use since the poorest financially and environmentally performing areas are targeted. It is robust since it allows the effect of a broad range of soil, season and management scenarios to be assessed whereas the spatial modelling technique we used earlier for land use decisions could not anticipate the outcome of these scenarios and relied on yield maps available for average rainfall and dry years only and information on soil properties (Wong and Lyle 2003).

Acknowledgements

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References


