Proximal Crop Reflectance Sensors

A guide to their capabilities and uses

Author: Brett Whelan, Precision Agriculture Laboratory, University of Sydney
One of the main goals of site-specific crop management (SSCM) is to improve decision-making about the use of inputs, such as fertilisers and agrichemicals, to better match spatial changes in soil/crop requirements and weed densities within a field. A better match should mean that inputs (including soil moisture) are used efficiently, profits are maximised and waste is minimised.

Ultimately, the assessment and treatment of variability in crop requirements would be undertaken in real time, and the scale of treatment is effectively restricted only by the functional abilities of the application equipment (that is, continuously variable real-time application). The only widely available commercial applications of this concept in Australia are the use of real-time crop reflectance/nitrogen application instruments and real-time weed-treatment technologies. They all rely on calibrating a treatment procedure (nitrogen or herbicide application) to the measured reflectance of light from plants.

The simplest use is in treating weed plants in a fallow field. The process identifies green plants on a ‘brown’ (soil or crop stubble) background and applies a target herbicide only in areas where living plants are identified. The use of reflectance measurements for nitrogen management relies on calibrations between reflected light and crop biomass and/or nitrogen content. In general, the management response is based on detecting how well the crop is growing and calculating a nitrogen application rate to match any inferred deficit.

This guide aims to provide information on the available systems and their standard operational methods to help potential users understand the different management techniques. It also provides examples of the agronomic relationships between crop reflectance and crop growth/nitrogen content that can be expected, and suggests alternative management uses. Users are reminded that these systems for nitrogen application also require the concurrent implementation of good all-round agronomic management of grain crops.

Through this report references are made to cereal growth stages. Zadoks is the most accurate and commonly used growth stage and is referred to in the text with the prefix GS or Z e.g. (GS30 or Z30).
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One of the important goals of site-specific crop management (SSCM) is to better match the application of fertilisers and herbicides to variations in crop production potential and weed loads across fields.

Many growers are now using historic yield and soil maps, along with in-field experimentation, to help guide where changes in fertiliser rates may be warranted. Having a number of seasons of yield maps and trial results for a paddock can help include seasonal influences in fertiliser application decisions, but ultimately it would be useful to include information on how the variability in soil, rainfall, temperature and sunlight hours are affecting the crop in the current season.

And given the vast majority of cropping fields have weeds covering less than 20% of their area, locating and treating only the weed patches rather than relying on uniform-rate, field-wide applications of herbicides would also be very useful.

Proximal crop reflectance sensor systems are helping to provide fertiliser rate information to tackle these issues. These systems use sensors mounted on ground-based vehicles or implements and they measure the intensity of light reflected from an area of leaves as they traverse a field. The data can be stored to make a map for later use or combined in real time with calibrations in the monitor console to provide a nitrogen application rate prescription that can drive a variable-rate application (VRA) controller.
The systems rely on the interaction of the crop leaves with certain wavelengths of light. In general a ‘healthy’, vigorous crop absorbs a lot of red and blue light in the cell chlorophyll and reflects a lot of the near-infrared wavelengths (NIR) due to good cell structure. Poorer crops absorb less (and therefore reflect more) red and blue light – that is, they look less green – and reflect less NIR. Bare soil or stubble reflects these wavelengths quite differently so plants can be easily distinguished from soil and stubble, making the technology also useful for detecting green weeds in soil or stubble backgrounds.

Given these physiological responses to light, the systems are designed to emit a light with a known intensity and to then detect the amount of light in the red and NIR regions of the light spectrum that is being reflected. The reflectance information from the two regions measured is converted into a ratio or index that is expected to correlate with nitrogen nutrition and the vigour of the crop. The main indices used by the commercially available crop reflectance sensor systems are listed in Table 1.

**Table 1** Explanation of the calculations for the standard reflectance indices used by the majority of crop reflectance sensor systems.

<table>
<thead>
<tr>
<th>Index</th>
<th>Bands used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation Index (VI) or Simple Ratio (SI)</td>
<td>IR, Red</td>
</tr>
<tr>
<td>Red Edge Index (REI)</td>
<td>IR, RedEdge</td>
</tr>
<tr>
<td>Normalised Difference Vegetation Index (NDVI)</td>
<td>IR – Red, IR + Red</td>
</tr>
<tr>
<td>Normalised Difference Red Edge (NDRE)</td>
<td>IR – RedEdge, IR + RedEdge</td>
</tr>
</tbody>
</table>

Note: The infrared part of the electromagnetic spectrum (wavelengths of 700nm to 1mm) is notionally divided into near-infrared (700 to 1400nm), mid infrared (3000 to 50,000nm) and far infrared (50,000nm to 1mm). ‘Red edge’ refers to the region of rapid change in reflectance of vegetation in the near-infrared part. Chlorophyll contained in vegetation absorbs most of the light in the visible part of the spectrum but becomes almost transparent at wavelengths greater than 700nm. There is a very rapid change in its reflectance between 680 and 730nm.

The technical specifications for the commercially available sensors and the recommended set-up configurations are provided below for comparison. Three of the systems are based on individual sensors that can be mounted at a range of heights on a range of platforms. Two systems are designed to be mounted and operated from the roof of a tractor or vehicle.

**Crop Circle®**

**Company** Holland Scientific  
**Height of operation** 0.25m to 2.5m  
**Field of view** Height x 0.6 (up to 8 sensors on CANbus)  
**View angle** Nadir  
**Active light source** Model ACS430 – Red (670nm) or Red edge (730nm) & NIR (780nm)  
**Data output** Model ACS-430 – band information and NDVI or NDRE  
**Calibrations** Crop biomass and nitrogen uptake

**Crop Spec®**

**Company** TOPCON Precision Agriculture  
**Height of operation** Tractor cab height  
**Field of view** 3m-wide strip on each side of the tractor  
**View angle** Oblique  
**Active light source** 730–740nm and 800–810nm  
**Data output** Biomass index and N recommendation  
**Calibrations** Winter wheat, winter barley, spring wheat, spring barley, potatoes, protein in winter wheat
**GreenSeeker®**

- **Company**: Trimble Navigation Ltd
- **Field of view**: 0.6m (multiple sensor capable)
- **Height of operation**: 0.6 to 1.6 m above target
- **View angle**: Nadir
- **Active light source**: Red (656nm) & NIR (774nm)
- **Data output**: NDVI or four alternatives and nitrogen recommendation
- **Calibrations**: Yield potential and nitrogen responsiveness – winter wheat, spring wheat, canola, corn, sorghum, cotton

**OptRX™**

- **Company**: Ag Leader
- **Height of operation**: 0.25m to 2.5m
- **Field of view**: Height x 0.6 (up to 8 sensors on CANbus)
- **View angle**: Nadir
- **Active light source**: Red (670nm) or red edge (730nm) & NIR (780nm)
- **Data output**: Vegetation index (NDRE or NDVI) and nitrogen recommendations
- **Calibrations**: Corn, wheat and user defined for other agrochemicals

**N-Sensor® (ALS)**

- **Company**: Yara International ASA
- **Height of operation**: Tractor cab height
- **Field of view**: 3m-wide strip on each side of the tractor
- **View angle**: Oblique
- **Active light source**: Red edge (730nm) and NIR (760nm)
- **Data output**: Biomass index and nitrogen recommendation
- **Calibrations**: Winter wheat, winter barley, spring wheat, spring barley, canola, winter rye, corn, triticale, oats, potatoes, protein in winter wheat
OPERATIONAL DESCRIPTIONS

These sensor systems are each marketed with specific operating instructions that the manufacturers have developed with the goal of achieving particular aims. They are summarised here to help potential users understand the various operational techniques that are being commercially recommended and make informed decisions on their potential usefulness.

**Crop Circle®**

**Aim**

To determine changing nitrogen application requirements in-season and provide VRA prescriptions.

**Technique**

The system incorporates three optical measurement channels that can be adjusted in-field to select optical measurement bands of interest, thereby allowing the instrument to be spectrally customised to a particular sensing application. Spectral configuration is performed via the use of standard 12.5-millimetre interference filters.

The sensor is calibrated to determine a vegetation index (VI) related to the mass of green crop. This index is then compared to the expected index based on the crop variety and stage of development. Crops with a low VI for the development stage are identified as requiring more nitrogen and those with a higher-than-expected VI receive reduced nitrogen. Those areas with the required VI receive the planned nitrogen application. The planned nitrogen application is set by the user.

It is also possible to operate the system using a 'virtual reference strip’. The sensors measure the average VI across a transect of the field and the planned nitrogen application is set to this value. Nitrogen is then varied up or down across the field depending on changes in the observed VI. Again, the user has total control over the planned amount of nitrogen applied (whether more nitrogen is applied with lower VI or the reverse) and the cut-off VI.

**CropSpec™**

**Aim**

To determine changing nitrogen application requirements in-season and provide VRA prescriptions.

**Technique**

The CropSpec™ was developed in conjunction with Yara International ASA, the developers of the N-Sensor®. The sensors mount in a similar fashion but the CropSpec™ system uses pulsing laser diodes as a light source and measures reflectance in slightly different spectral bands. The system calculates a biomass index, which is used to infer nitrogen uptake by a crop. This system can be used to determine changes in required nitrogen application rates in two ways:

- a simple two-point calibration is built by using the sensors to measure the lowest and highest performing areas in a field as determined by the user. The user then sets the application rate to apply the field average and the sensors will vary application rates around this level based on observed variability in the index; or
- subscription to optional software from Yara International ASA provides crop-specific calibrations to determine actual nitrogen requirements from the observed variation in the biomass index.

The CropSpec™ can be used to record and map the observed reflectance for further analysis or provide real-time prescription data to drive on-the-go VRA of nitrogen.

**GreenSeeker®**

**Aim**

To determine changing nitrogen application requirements in-season and provide VRA prescriptions.

**Technique**

The system uses a process of comparing the reflectance (calculated as normalised difference vegetation index, NDVI) of unfertilised plants to those in a non-limiting nitrogen strip to gain a response index (RI). The whole procedure involves the use of a series of generic functions in an algorithm that is made region or site-specific by the inclusion of calibration coefficients obtained from local observations.

Essentially, the process involves:

- the prediction of potential yield without fertiliser (YP 0) from the NDVI and information on the growing degree days (GDD) or time since sowing;
- calculation of RI, which then is used to predict yield with added fertiliser (YP N); and
- from the difference between YP 0 and YP N the nitrogen fertiliser deficit can be calculated and a nitrogen rate determined.

**N-Sensor® (ALS)**

**Aim**

Primarily used to determine changing nitrogen application requirements in-season and provide VRA prescriptions, but also calibrated for the VRA of growth regulators.

**Technique**

The N-Sensor® (ALS) is a progression from the original N-sensor®, which used ambient light as the source for reflectance measurements. The system calculates a biomass index using reflectance measured at the ‘red edge’ of the spectrum, which is used to infer nitrogen uptake by a crop. Generally, the system can be used to determine changes in required nitrogen application rates in two ways:

- comparison of real-time reflectance to that from a previously measured nitrogen-rich strip or optimal treatment section with a known nitrogen level; or
- comparison of real-time reflectance to that from a number of initial field transects to variably apply a predetermined field average application.

The system has calibrations for a wide range of crops, but essentially it is designed to apply more nitrogen fertiliser...
These systems are set with a minimum of two sensors but often up to six (or more if desired) are used in many boom/implement-mounted systems. They measure the reflectance response in each wavelength at greater than 1 Hertz (more than once per second) at each sensor, but save an average measurement for a one-second observation window. The measurements across all the available sensors are then averaged to produce a single measurement of the reflectance response in each designated wavelength, which is then used to calculate the predetermined reflectance index. Some systems will record the information from the individual wavelengths for the user along with reflectance index, and some will only record the index. Some systems now provide an option for recording the index calculated at each sensor.

The recorded reflectance index information (calculated as NDVI) from a 27-metre, boom-mounted system operated in a barley crop is shown in Figure 1(b) and the data obtained at the same time from an aerial-based monitoring system is shown in Figure 1(a). Figure 1 shows that the data from a ground-based sensor system can be expected to be comparable to that obtained from the traditional aerial (or satellite) platforms. This is important because it means that users can be confident that the long history of research into relationships between crop reflectance and crop physiology that has been developed using the aerial/satellite platforms can be applied to the crop sensor data.

**OptRx™**

**Aim**

To determine changing nitrogen application requirements in-season and provide VRA prescriptions.

**Technique**

The system incorporates three optical measurement channels that can be used to construct two different vegetation indices (NDVI and NDRE). OptRx™ uses the virtual reference strip concept. The healthiest area of the field is identified by the user and that area is scanned in real time. The VI calculated from this portion of crop represents plants with sufficient nitrogen available and is called the VI reference value. This process locally calibrates the OptRx™ crop sensors to vary nitrogen application for the given growth stage.

Ag Leader suggests that the OptRx™ is used for side-dressing corn at growth stages V5 to V12 and wheat anytime between tillering and stem elongation. In this operational mode the user can define minimum and maximum nitrogen rates to keep the system working within an input budget.

The system can also be used to vary nitrogen application to match a user-defined optimal nitrogen uptake amount for the crop growth cycle. The desired optimal nitrogen uptake is set, along with any known values for residual soil nitrogen and previously applied nitrogen fertiliser. By deducting the known soil and applied nitrogen amounts from the desired uptake, the potential nitrogen requirement can be calculated and compared with the calibrated VI measurements of the changing crop condition in the field. Nitrogen is then applied at rates to fulfil this mass-balance approach.

![Figure 1](image.png) (a) a comparison of NDVI calculated from an aerial image with a 2m spatial resolution and (b) reflectance data obtained using proximal crop reflectance sensors on a 27m swath.
OPERATIONAL ISSUES

Using the chosen sensor system in the manufacturer’s recommended operational mode is the obvious approach to consider when purchasing/using these systems. Users are directed to the detailed operational manuals provided by the manufacturers. However, there are a number of operational issues that should be kept in mind when deploying these systems.

Sensor location
All boom-mounted or implement-mounted sensors should be mounted level to maximise the total amount of reflectance received back at the sensor. They should also be placed directly over crop rows to maximise the amount of crop that is contributing to the total reflectance. Placement relative to crop row is especially important for monitoring reflectance in early crop growth stages, which is when most Australian broadacre grain producers would be using the systems to predict crop health and nitrogen requirement.

A minimum of one sensor per harvest width is also recommended. For example, a 27-metre boom used over a nine-metre harvest system would require at least three sensors. This ensures a number of things:
- that enough variability in reflectance across the width of the boom is incorporated in any decisions on N recommendations made from an average reflectance index; and
- that enough variability in reflectance across the width of the boom is incorporated in the average reflectance index to match the variability in crop yield that would be recorded by a harvester-mounted crop yield monitoring system.

The last point is important for assessing the production outcome of any variable-rate treatments based on the crop reflectance information. It is also important for building new site-specific relationships and calibrations between average crop reflectance indices and crop yield. For systems where the individual sensor information is provided for the user, being able to directly match reflectance information with crop yield would be even more valuable.

An example of the variability that can be found across a crop reflectance sensor system is shown in Figure 2. The correlation between the individual sensors in Figures 2(a) to 2(d) ranges from 0.73 to 0.96. It highlights the importance of including reflectance information from across the width of the boom/application implement to ensure the average reflectance. Figure 2(e) is representative of field conditions.

Leaf surface moisture
Moisture on the leaf surface affects the reflectance of light differently to the moisture within the leaf. Surface moisture decreases reflectance in total but using NIR will show a further decrease. This can significantly dampen the reflectance index as shown in Figure 3 above. Here, the same transect of crop was measured during the day and then during the night with surface dew on the crop. This means that:
- reflectance surveys for a whole field should be carried out in similar leaf-surface-moisture conditions; and
- combining reflectance information from dry and wet leaf surface conditions in building nitrogen and yield calibrations is not advisable.

In-season repeatability
In a normal growing season, a strong positive correlation between reflectance surveys undertaken between GS30 and GS60 should be expected. Figure 4 (page 13) shows an example of survey maps produced over an eight-week period. Table 2 records the positive correlations between the individual surveys and the final crop yield. The correlation decreases as time between surveys increases, and in general the relationship with yield strengthens with later NDVI surveys.
FIGURE 2. Maps of reflectance index data from four different sensors mounted along a single boom (a) to (d) and the average reflectance index map (e).

(a) Sensor 1

(b) Sensor 2

(c) Sensor 3

(d) Sensor 4

(e) Average map

Legend:

- NDVI
- 0.31-0.36
- 0.37-0.42
- 0.43-0.47
- 0.48-0.53
- 0.54-0.59
- 0.60-0.64
- 0.65-0.70
- 0.71-0.75
- 0.76-0.81
- 0.82-0.86

- NDVI
- 0.34-0.39
- 0.40-0.44
- 0.45-0.49
- 0.50-0.55
- 0.56-0.60
- 0.61-0.65
- 0.65-0.70
- 0.71-0.75
- 0.76-0.80
- 0.81-0.85

- NDVI
- 0.26-0.32
- 0.33-0.37
- 0.38-0.43
- 0.44-0.48
- 0.49-0.54
- 0.55-0.59
- 0.60-0.65
- 0.66-0.71
- 0.72-0.76
- 0.77-0.82

- NDVI
- 0.33-0.38
- 0.39-0.43
- 0.44-0.48
- 0.49-0.53
- 0.54-0.58
- 0.59-0.63
- 0.64-0.68
- 0.69-0.73
- 0.74-0.78
- 0.79-0.83

Scale: 0 140 280 420 560 meters
However, the whole-field correlation value may mask the fact that the relationship between properties may change across the field. Figure 5 shows a map of local correlation made by calculating relationships within 50m areas within the field. It shows that while the whole-field correlation between NDVI 3 and crop yield is +0.76, there are coherent areas where the relationship is actually negative. Areas of significantly negative correlation, where yield declines as reflectance rises, may be indicative of areas with significant weed pressure. Areas of negative correlation where yield rises as reflectance declines may have experienced temporary waterlogging around reflectance survey time. Identifying these areas for investigation at the end of the season will help improve the understanding of spatial variability in crop yield potential within a field.

### Using standard N recommendation operations

#### Initial N applications

Within-field variable-rate experiments with N conducted for the GRDC across numerous seasons and regions have shown that in a majority of instances the benefits would be derived from savings in fertiliser application. So growers should expect that the benefits of using crop reflectance sensors in standard N management mode would be achieved by locating and assessing areas where less N fertiliser is required. To achieve the maximum benefit, the initial application of N fertiliser pre-sowing or at sowing should be the lowest possible to establish and promote early crop growth.

A low-risk option would be to apply no more than 50% of the expected seasonal fertiliser requirement up-front and then use the sensor systems to guide the application of any additional fertiliser following reflectance surveys as per each manufacturer’s instructions to ensure any potential savings are not negated. It is also necessary to keep in mind that a split application approach relies on future applications being matched with potential rainfall after the application, although less so if liquid N is being considered. However, in low rainfall environments or where in-season rainfall is traditionally low, the split application method may create greater risk than up-front applications of total N requirements.

#### High N reference strips

A number of the systems suggest the use of ‘high N reference strips’ to establish the reflectance benchmark for the crop under non-limiting N conditions. Important points to consider if using these strips include:

- use at least one strip per field;
- ensure establishment in an area that is considered to be subject to the average field conditions (soil type and depth, aspect, slope) or establish a separate strip for each identified management class within a field;
- use small sized strips instead of large strips – a small strip or patch that is as wide as the measurement width of the system and 50m long is sufficient;
- rotate strip locations between years to avoid N build-up – using small patches allows a number of alternate locations to be identified in close proximity to each other to maintain conditions representative of the field/class average; and
- re-scan the strip approximately every two hours during sensor operation to maintain a representative benchmark as leaf orientation and climatic conditions change during the reflectance survey.

### Calibrations of crop reflectance and N requirement

The use of reflectance measurements for estimating nitrogen requirement relies on calibrations between reflected light and crop biomass and/or nitrogen content. In general the management response is based on detecting variability in how well the crop is growing and calculating suitable nitrogen application rates. The critical points that need to be considered with this approach are:

- whether any variability in growth is mainly due to variability in nitrogen availability and not some other factor (for example moisture stress); and
- whether the calibrations are accurate.

It is important when employing these systems in standard operational mode that users understand that they are only a tool to aid already good management. Their application requires growers to keep their agronomic limitations in mind. As there may be other factors other than low available nitrogen affecting a crop’s growth the crop should be closely monitored. Other factors that may interfere with the correct N management response from the sensor systems include:

- damaged or restricted growth of roots due to waterlogging;
- other nutrient deficiencies (for example, phosphorus, zinc, magnesium, potassium, iron or sulfur) that may cause yellowing or reduced growth;
- diseases;
- weeds; and
- poor crop germination/establishment.

The occurrence of these conditions in a field will reduce the usefulness of the standard calibrations. Growers should be wary of employing the sensor systems for N management in areas where they suspect these conditions may be present.

All of the systems for N management require user input of data in some form or user decisions on base application rates of N from which the systems will calculate variable application rates. Most of the systems
will allow users to build their own calibrations between reflectance measurements and N requirement, and it is advisable to use this feature of the proprietary software to test the applicability of the standard calibrations and to customise responses to local conditions. However, field experimentation with different N application rates (refer to the GRDC guide Advanced field-scale experimentation for grain farmers, available to download at www.grdc.com.au/AdvancedFieldScaleExperimentation) to measure reflectance response changes, followed by physical crop and soil sampling to ground-truth the data, allows users to identify the local agronomic information these sensing systems can best provide.
LOCAL CALIBRATION AND ALTERNATIVE OPERATIONAL METHODOLOGIES

Independent local calibration

Independent local calibrations can be built using all brands of sensor systems. The process requires:
- a crop reflectance survey;
- sampling of crop and soil parameters based on the range of reflectance values; and
- analysis of relationships and construction of local calibration formula.

A single field where wheat was grown in two consecutive seasons is used here as an example to explain the process. Figure 6 below shows the elevation and apparent soil electrical conductivity (ECa) maps that describe the landscape of the field.

Reflectance and sampling design

The initial reflectance survey (NDVI) is shown in Figure 7(a), with an overlay of the survey path and physical sampling site locations. The NDVI has been mapped onto a continuous surface to allow comparison with data from other sensors or NDVI surveys from later times. The sampling sites were allocated by dividing the range of the reflectance values into 10 classes (Figure 7(b)) and randomly choosing sites from each class. The number of classes may be reduced, especially if the range of reflectance values is small. The number of replications within each class can be chosen based on the sampling budget, but at least one replicate per class will help build calibrations across the full range of observed reflectance.

Sample site measurements

At the sampling sites, measurements were taken of:
- crop N (%);
- dry matter (DM) measured in tonnes per hectare (t/ha);
- tillers per square metre (tillers/m²); and
- deep soil N (DSN) measured in milligrams per kilogram (mg/kg).

Total N in the crop (kg N/ha) was calculated by Equation 1:

\[
\text{Total } N = \frac{N\% \times (\text{DM} \times 1000)}{100} \quad \text{(kg N/ha)}
\]

Further measurements

A second reflectance survey was undertaken three weeks after the first survey and is mapped in Figure 8(a). A NDVI change map was calculated by subtracting the first survey value from the second and is mapped in Figure 8(b). Crop yield was collected by a harvester-mounted yield monitor (Figure 9).

| Correlation coefficient interpretation: 1 = perfect positive correlation – as the value of one attribute rises, so does the other by the same relative amount; -1 = perfect negative correlation – as the value of one attribute rises, the other falls by the same relative amount. Values greater than +/- 0.36 significant at p = 0.05 (n=30). |

TABLE 3 Correlation coefficients (r) for crop and soil sample data with NDVI.

<table>
<thead>
<tr>
<th>NDVI 1</th>
<th>NDVI 2</th>
<th>NDVI diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI 1</td>
<td>1</td>
<td>0.97</td>
</tr>
<tr>
<td>NDVI 2</td>
<td>0.97</td>
<td>1</td>
</tr>
<tr>
<td>NDVI diff (survey 2 – survey 1)</td>
<td>-0.29</td>
<td>-0.05</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.25</td>
<td>0.38</td>
</tr>
<tr>
<td>Dry matter (kg/ha)</td>
<td>0.74</td>
<td>0.66</td>
</tr>
<tr>
<td>Tillers/m²</td>
<td>0.77</td>
<td>0.78</td>
</tr>
<tr>
<td>Total N (kg N/ha)</td>
<td>0.78</td>
<td>0.73</td>
</tr>
<tr>
<td>DSN (kg/ha)</td>
<td>0.68</td>
<td>0.65</td>
</tr>
<tr>
<td>Soil ECa (mS/m)</td>
<td>-0.02</td>
<td>-0.04</td>
</tr>
<tr>
<td>Elevation (m)</td>
<td>-0.30</td>
<td>-0.41</td>
</tr>
<tr>
<td>Yield (t/ha)</td>
<td>0.66</td>
<td>0.65</td>
</tr>
</tbody>
</table>

FIGURE 6 Example field (a) elevation and (b) apparent soil electrical conductivity (ECa).
Relationships with reflectance indices

A correlation analysis is used to explore the relationships between crop reflectance and the measured crop and soil properties at the sample sites (Table 3). NDVI shows a strong positive relationship with tillers/m² and dry matter (DM). It demonstrates a poorer relationship with nitrogen percentage (N%). A strong positive relationship with total N can be seen due to the incorporation of the DM figure in the calculation. Repeated use on numerous fields has shown that the relative strengths of these relationships can be expected in most circumstances.

The deep soil N and final crop yield show a strong positive relationship with NDVI. These relationships are encouraging for the use of reflectance information generally because they confirm a site-specific link between soil N supply and production and that the reflectance information may be directly related to final grain output and not just biomass production. However, research experience shows that these relationships cannot be expected to be identified across all fields/crop seasons. The deep soil N relationship depends on soil type and fertiliser application history while the seasonal conditions between the reflectance survey and harvest control the reflectance/yield relationship.

The difference in NDVI between the two surveys shows an improved positive relationship with N% in the paddock, but a negative relationship with DM, tillers/m² and crop yield. The inference here is that the degree of change in NDVI over the three-week period is being driven by the N in the plant and not the biomass. So while the general relationship of more tillers/m² → more biomass → more yield is evident...
across the field, changes in NDVI over short periods within the season may be useful in identifying areas of suboptimal development early in the season. It also has implications for the decision on N fertiliser applications at this time. More N in these areas of highest change may be detrimental or a financial waste.

Predicting N requirements

Given the sensor systems aim to help in N application decisions, the ability to predict total crop N from reflectance data is very important. Figure 10(a) shows a comparison of the predicted N using a calibration based on the reflectance data with the measured crop N at the sample sites. The $R^2$ value of 0.60 is reasonable, but local research has shown that by including some landscape (e.g. elevation, soil ECa) or historical yield information in the calibration process, along with the reflectance data, the predictive ability will usually be improved. In this field, previous wheat yield was not available and soil ECa had no significant relationship with reflectance ($r = -0.02$), but the inclusion of elevation ($r = -0.30$) did significantly improve the predictive ability from an $R^2$ value of 0.60 to 0.65 (Figure 10(b)). A basic stepwise regression process can be used to test the validity of including any ancillary information recorded for the sample points.

The best calibration can be used to estimate the total N in the crop. Comparing the estimated total N in the crop with the N requirement to achieve a desired yield/quality goal then allows any N deficit to be determined. The N requirement for a specific yield/protein goal in a wheat crop can be calculated using Equation 2:

$$\text{N requirement} = \text{Yield goal} \times \text{Protein goal} \times 1.75$$

With rainfall for the beginning of the year well below average (Table 4), then a return to approximately average rainfall for the two months prior to the reflectance survey, a slightly conservative yield goal of 4.0t/ha was set. Applying Equation 2, a 4.0t/ha yield, 12 per cent protein content wheat crop requires at least 84kg N/ha to be taken up by the crop over the season. The deficit in N requirements can then be determined in real time using this process and N application rates calculated based on the desired N product and an assumed uptake efficiency.

**FIGURE 10** Prediction of total N in the crop by (a) NDVI alone and (b) by including elevation with NDVI.

**FIGURE 11** Prediction of total N uptake at GS30 using (a) NDVI and elevation and (b) N requirement based on a crop requirement of 84kg N/ha and predicted total N uptake.
produced at or above 75 per cent of the yield goal, with the tops of the sand ridges being the main areas falling below this level. This result indicates that the N supply determined in August using the calibrated reflectance data was sufficient to achieve production goals for the majority of the field.

### TABLE 4 Rainfall statistics for the location (mm).

<table>
<thead>
<tr>
<th></th>
<th>Jan-May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td>107</td>
<td>65</td>
<td>35</td>
<td>27</td>
<td>39</td>
<td>21</td>
<td>58</td>
<td>10</td>
<td>362</td>
</tr>
<tr>
<td>Year 2</td>
<td>318</td>
<td>43</td>
<td>45</td>
<td>87</td>
<td>60</td>
<td>115</td>
<td>54</td>
<td>112</td>
<td>834</td>
</tr>
<tr>
<td>130-year average</td>
<td>204</td>
<td>58</td>
<td>55</td>
<td>57</td>
<td>50</td>
<td>53</td>
<td>39</td>
<td>36</td>
<td>552</td>
</tr>
</tbody>
</table>

Seasonal repeatability

Figure 13(b) shows the pattern of NDVI obtained for a wheat crop in the following season. The correlation with data from the initial reflectance survey in the previous season is high ($r = 0.83$). The repeatability of the patterns is matched by the repeatability of relationships between NDVI and crop and soil sample data (Table 5). While this may not be found in every field/crop season, numerous research trials have shown similar results which is encouraging for building robust local calibrations to vegetative indices.

### TABLE 5 Correlation coefficients ($r$) for crop and soil sample data with NDVI in year 2.

<table>
<thead>
<tr>
<th></th>
<th>NDVI 1</th>
<th>Nitrogen %</th>
<th>Dry matter (kg/ha)</th>
<th>Tillers/m²</th>
<th>Total N (kg N/ha)</th>
<th>DSN (kg/ha)</th>
<th>Soil ECa (mS/m)</th>
<th>Elevation (m)</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.22</td>
<td>0.91</td>
<td>0.74</td>
<td>0.85</td>
<td>0.68</td>
<td>-0.39</td>
<td>-0.39</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Correlation coefficient interpretation: $1 =$ perfect positive correlation – as the value of one attribute rises, so does the other by the same relative amount; $-1 =$ perfect negative correlation – as the value of one attribute rises, the other falls by the same relative amount. Values greater than $\pm 0.36$ significant at $p = 0.05$ (n=30).

Validating the process

To test the validity of this process, the calibration based on the samples was applied to the initial reflectance survey data for the whole field. A map of the total N in the crop across the field is shown in Figure 11(a). The predicted total N ranged from 30kg N/ha to 190kg N/ha. Figure 11(b) shows the calculated N requirement (using Equation 2), indicating that most of the field had taken up enough N to achieve the production goal. The two larger areas showing a requirement for N were areas on top of sandy ridges with low NDVI and DM. Given the pre-season rainfall, moisture was determined to be the limiting factor and applying more N to the small areas would not be effective.

As can be seen from Table 4, the amount of rainfall for the August to October growing period was low, reaching just 55 per cent of the long-term average. This was expected to significantly reduce the forecast crop yield. The map in Figure 12 partitions the actual yield into areas that achieved above the yield goal, above 75 per cent of yield goal (3.0t/ha) and those that fell below 3.0t/ha. The majority of the field
Nitrogen use efficiency

Calibrating the reflectance sensors to Total N and mapping the information provides the ability to assess nitrogen use efficiency (NUE) post-harvest. In conjunction with yield data from a harvester-mounted yield monitor, the NUE can be calculated using Equation 3:

\[
\text{NUE} = \frac{\text{grain yield (kg/ha)}}{\text{total N (kg/ha)}}
\]

Equation 3

Figure 14(a) shows that the conversion rate of crop N into crop yield (NUE) for the first season decreases as the total amount of N taken up by the crop increases. Figure 14b shows that the NUE plateaus at 550 to 600 tillers/m² and 14kg grain for every kilogram of N in the crop. Hitting 550 tillers/m² should optimise the yield/N ratio and confirms much of the recent canopy management advice being distributed in the grains industry. Figure 15 maps the NUE across the field and shows substantial spatial variability.

Including NUE data from the following wheat season provides a more complete picture of NUE of the site. Figure 16 shows that the conversion rate of crop N into crop yield continues to decrease as the total amount of N in the crop increases. So the more N that is taken up by the crop, the less efficient the plant is at using N to photosynthesise and produce grain.

In season 1, where there was a lower amount of moisture available for crop growth, the total N in the crop when sampled was less than the second season, and the yield was less. The combination of the data from the two seasons provides a useful guide to the production output and efficiency limits that can be expected with regard to N over a reasonably broad range. This information and the map in Figure 15 provides an opportunity for farmers to explore in further detail the areas of the field where NUE and yield are low and diagnose any management issues.

Response index approach to locally optimising seasonal N requirements

This simple operation can be used to test the responsiveness of a field to increased N application to help guide any further decisions on in-season application of N. Small strips or patches of different N fertiliser rates are applied within the field or management class. These
applications are above a uniform base rate of N fertiliser applied across the remainder of the field. The whole-field crop reflectance is then measured at a growth stage where further fertiliser application could be warranted (e.g. GS30 in wheat).

Figure 17(a) shows the reflectance map of a field where such a trial was conducted. The average reflectance response for each increased N strip was calculated and is recorded in Table 6. The maximum reflectance (0.763) was recorded for the application of 31 kg N/ha in this instance. This value was then used as a benchmark to compare with the reflectance measured at all other locations across the field using Equation 4:

\[
\text{Response index} = \left( \frac{\text{Benchmark NDVI}}{\text{Observed NDVI}} - 1 \right) \times 100
\]

The response index calculated across the field is mapped in Figure 17(b). In Figure 17(c) the values are allocated into categories that increase by five per cent to make it easier to see any cohesive potential management classes.

With the assumption of a simple linear relationship between the response index and crop yield, it is possible to identify the response index classification above which additional fertiliser application may be financially worthwhile. This can be done by using seasonal input and grain prices in conjunction with Equation 5:

\[
\text{Response index} \geq \left( \frac{\text{Cost of additional N to achieve benchmark ($)}}{\text{Grain price per tonne ($)}} \right) \times 100
\]

In this example, the cost of 31 kg of extra N (at $1.30/kg) was $40. The seasonal price for wheat was $270/tonne. This equates to a minimum response index of 15 per cent being required to at least achieve the financial break-even point. Using this assessment, an N prescription map can be constructed for consideration in in-season fertiliser management decisions by farmers and their advisers (Figure 17(d)).
The current reflectance sensing systems can reliably assess the vegetative production (dry matter and tillers/m²) and ‘health’ of the crop, which can be very useful in helping diagnose establishment and early growth issues. Operating with high nitrogen reference strips offers a method for comparing relative production but the estimation of local N requirements directly from general calibrations and reflectance data alone should only be considered if users can be very sure that other nutrition and cultural issues are not impacting on crop growth.

The systems generally allow a user to set a base application rate for a field or management class that reduces the risk associated with sensor-driven VRA but may not deliver the optimisation of N that could be achieved. Research has shown that with ground-truthing, local calibrations can be constructed to predict the amount of N-uptake by the crop. Comparison of the predicted uptake with yield goal N requirements provides a method for assessing N uptake sufficiency. This method has been shown to successfully identify where N has been adequately supplied. Where a deficiency is identified there remains a question in assuming that increased N application is required. Supply of more crop N by soil reserves may be possible. However, constructing VRA maps based on areas identified as insufficiently supplied with N can be practiced to remove the risk of N-deficiency. The application quantity of N should aim to match the deficiency calculated, with the inclusion of a local uptake-efficiency coefficient.

Using the sensor systems in a response index approach appears to be a simple and useful method for including seasonal influences in N fertiliser decisions. The initial quantity of N applied is controlled by the user, then the sensors are used to compare responses from a number of different extra applications. Risk is totally under the control of the user and current prices can be included in the assessment of any management actions.

Using a crop reflectance sensor system with local information should allow improved economic and environmental N management when compared with a uniform field-wide application of N based on traditional soil analysis. However, some directed soil sampling to keep a check on the soil N status during a crop rotation series is advisable. The maps provided by the systems in conjunction with yield monitor data would provide the information to direct where soil sampling is required.

### TABLE 6 Mean reflectance index response to different rates of applied nitrogen in a within-field experiment.

<table>
<thead>
<tr>
<th>Nitrogen applied (kg N/ha)</th>
<th>Mean NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.721</td>
</tr>
<tr>
<td>21</td>
<td>0.738</td>
</tr>
<tr>
<td>31</td>
<td>0.763</td>
</tr>
<tr>
<td>42</td>
<td>0.754</td>
</tr>
<tr>
<td>53</td>
<td>0.736</td>
</tr>
</tbody>
</table>
NOTES