Precision variable rate nitrogen for dryland farming on waterlogging Riverine Plains of Southeast Australia?

Thomas L. Nordblom\textsuperscript{a,c,}\textsuperscript{*}, Timothy R. Hutchings\textsuperscript{b,b}, Sosheel S. Godfrey\textsuperscript{a,c}, Cassandra R. Schefer\textsuperscript{d,d,e}

\textsuperscript{a} Graham Centre for Agricultural Innovation (an alliance between Charles Sturt University & NSW Department of Primary Industries), Albert Pugsley Place, Wagga Wagga, NSW 2650, Australia
\textsuperscript{b} Meridian Agriculture, P.O. Box 8906, Wagga Wagga, NSW 2650, Australia
\textsuperscript{c} School of Agricultural & Wine Science, Charles Sturt University, Wagga Wagga, NSW 2678, Australia
\textsuperscript{d} Riverine Plains Inc., 4/97-103 Melbourne Street, Mulwala, NSW 2647, Australia
\textsuperscript{e} AgriSci Pty Ltd, 59 Sheridan Court, Rutherglen, VIC 3685, Australia

\textbf{ABSTRACT}

Precision agriculture, using satellite navigation, has grown in popularity around the world. Because of its practical uses for land preparation, sowing, nutrient applications, pest (weed, pathogen, invertebrate) management, stress sensing and harvest recording, many major equipment manufacturers include precision variable rate capability as standard fittings. GIS (Geographic Information System) maps may include georeferenced soil chemistry information and detailed historical harvest yield data. We integrate such data to examine Precision Variable Rate Nitrogen (PVRN) applications with whole-farm management information and rainfall records in a district where waterlogging frequently reduces crop yields.

Given wide variations in growing season rainfalls (GSR) and soils in the district, we test year-to-year stability of rainfed crop-yield rankings over time on 90x90m GIS grid-areas in large paddocks (over 100 ha). Variations in historical yield-quartile rankings of grid-areas across GSR levels over time are observed; some areas yield best at some GSR levels but not others, such that the best-yielding part of a paddock one year may be poorest in the next.

We answer the question: “Why would a farmer in this district choose to apply a uniform moderate rate of N to a paddock at sowing even though in possession of precision variable rate-capable (PVR) equipment, georeferenced electromagnetic conductance (EM38) data and crop-yield map data for that paddock in many past seasons?” We show that soil conditions in the study district challenge the economic value of PVRN versus uniform rates in farming systems prone to waterlogging.

If full-season GSR were reliably predictable early in the season, applications of N could be based on a rule calling for 40 kg/ha N/t of attainable yield at that GSR and grid-area EM38 level, minus sampled soil-N. Unfortunately, GSR is notoriously unpredictable. We simulate whole-farm financial risk profiles (CDFs of simulated decadal cash margins with varying prices and yields, minus all variable, fixed and capital costs) assuming moderate uniform N rates, as practiced in the study area, on two model farms; one with low and one with high-fixed-costs, given historical variations in GSR and prices. Assuming PVRN requires annual geo-referenced soil nutrient sampling of each hectare, these added costs could be covered by a 1% increase in yields across all wheat and canola crops or a 7% decrease in applied N. We cannot reject the null hypothesis that PVRN is no more profitable than uniform applications in this district. Near-real-time NDVI may lower the cost of PVRN for late applications.

\section{1. Introduction}

The aims of the present study relate to key challenges identified in the literature on precision variable rate N applications in rainfed farming systems. In particular, crop yield responses to N in dryland farming systems depend most notably on the quantity and timing of rainfalls, which are quite unpredictable. Other weather characteristics, soil chemistry and physical properties also affect crop yield responses. We describe these factors and their analyses in collaboration with farmers and staff of Riverine Plains Inc. (RPI) in north-central Victoria,

\url{https://doi.org/10.1016/j.agsy.2020.102962}

Received 10 September 2019; Received in revised form 22 September 2020; Accepted 30 September 2020
Available online 17 October 2020
0308-521X/ © 2020 Published by Elsevier Ltd.
In this paper we describe the agricultural systems setting of our question. The benefits of alternative options and their likely and worse case outcomes. Australia’s extremely variable rainfall arises from Australia’s extremely variable rainfall. (Swinton and Lowenberg-DeBoer, 1998). The complexity comes in describing by the simple rule of thumb taught to all budding agronomists: 40 kg/ha N per tonne of anticipated wheat yield. This fact is echoed by Hunt et al. (2019): “nitrogen management in grain crops is extremely simple — crop requirement is well related to yield as depends on weather and management after the nutrient is applied to a crop.”

Precision variable rate nitrogen PVRN on the two model farms mentioned above. Section 6 offers discussion drawing together meanings of the results. Section 7 concludes with ideas and questions for follow-up research.

2. Literature review

A number of salient aspects of precision variable rate nitrogen PVRN are addressed in the literature listed in Table 1. These are briefly mentioned here:

2.1. Uncertain rainfall (yields)

The importance of rainfall uncertainty for crop response to N was emphasised in the introduction. This aspect is covered in 32 of the 39 references listed in Table 1. The issue of seasonal conditions interacting with the performance and management of zones under PVRN interferes with the observability and trialability of PVRN. (Robertson et al., 2012).

2.2. Role of uncertain prices

This aspect of assessing the value of PVRN is covered in 19 of the 39 references. In Australia, international commodity prices are among the most volatile in the world (Keogh, 2013).

2.3. Flat yield responses given a particular GSR level

Jardine (1975a,b), Anderson (1975a) and Pannell (2006) are the seminal sources on why we cannot rely on super-accurate optimal N rates where response is likely to be flat. This problem is mentioned in 16 of the 39 references in Table 1.

2.4. Spatial variations within paddocks

The main reason for precision variable rates is to deal with spatial variations in paddocks; this is treated in 26 of the 39 references in Table 1. The most thoroughgoing review on this and the previous 3 points is that of Robertson, Ilewellyn, Mandel et al., (2012).

2.5. Controlled traffic

This has become an almost indispensable element of precision agriculture in minimising soil compaction and eliminating gaps and overlaps in applications. Chamen (2015) and Kingwell and Fuchsbiicher (2011) are key references among the eight dealing with this aspect.

2.6. Environmental harm of + + N

Thirteen of our references deal with this aspect, which can become a key concern if there are likely external effects of N use on rainfed farms on downstream or downwind communities. High-yielding, high rainfall areas with concentrated populations nearby, can face restrictions on N use due to public health concerns. Gandorfer et al. (2011) and Gourevitch et al. (2018) cover this aspect along with 11 other references among the 39.

Partial budgets for single crops are included in 21 of our 39 references. Whole-farm analysis is attempted in just 13 of the 39 references. Whole-farm financial risk is recognised as a key issue in eight of the 39 sources, including the conference paper (Nordblom et al., 2019) which is the basis of the present study.
Table 1
Literature on economics of precision variable N rates for rainfed cropping.

<table>
<thead>
<tr>
<th>Authorship</th>
<th>Country</th>
<th>Uncertain rainfall (yields)</th>
<th>Role of uncertain prices</th>
<th>Flat yield responses</th>
<th>GSR</th>
<th>Spatial variation within fields</th>
<th>Controlled traffic</th>
<th>Environmental harm of ++ N</th>
<th>Partial budget single crops</th>
<th>Whole-farm analysis</th>
<th>Whole-farm financial risk</th>
<th>Accumulating interest on debt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abadi and Farre (2015)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>GSR</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anderson (1975a)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biermacher et al. (2006)</td>
<td>USA</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>GSR</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cassman (1999)</td>
<td>Internat’l</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>GSR</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chamen (2015)</td>
<td>EU</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filippi et al. (2017)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gandorfer et al. (2011)</td>
<td>Germany</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gourevitch et al. (2018)</td>
<td>Canada</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRDC (2006)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huett et al. (2019)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jardine (1975a, 1975b)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kingwell and Fuchsbeichler (2011)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kingwell et al. (1993)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knight et al. (2009)</td>
<td>UK</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knight and Malcolm (2006)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liu et al. (2006)</td>
<td>USA</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowenberg-DeBoer and Boehlje (1996)</td>
<td>USA</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monnardino et al. (2015)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monnardino et al. (2013)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nordhjem et al. (2019)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nordhjem et al. (1985)</td>
<td>USA</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pannell et al. (2018)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pannell et al. (2006)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pannell et al. (2000)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rajasic and Weersink (2008)</td>
<td>Canada</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rajasic et al. (2009)</td>
<td>Canada</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robertson et al. (2012)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robertson et al. (2009)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robertson et al. (2008)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robertson et al. (2007a)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robertson et al. (2007b)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rogers et al. (2016)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schefe (Ed., 2018)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thirikovela et al. (1999)</td>
<td>USA</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al. (2003)</td>
<td>USA</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whelan and McBratney (2000)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whelan and Taylor (2013)</td>
<td>Australia</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Accumulating interest on debt is not yet widely recognised as an important aspect of whole farm financial risk. The afore-mentioned conference paper is the only reference among the 39 in Table 1 that includes this feature of risk analysis. Other references on whole-farm financial risk, which include accumulating interest on debt are: Hutchings and Nordblom (2011); Hutchings (2013); van Rees et al. (2015); van Rees and McClelland (2017); Nordblom et al. (2018a, 2018b); Godfrey et al. (2019a, 2019b).

In Table 1, the presence of any of the above aspects of precision N in a publication cited is indicated by a + sign. A publication with special strength in some aspect is indicated by a ++ sign at that point.

From our literature review we know there is wide use of PVRN elsewhere. We have cited Canadian (Gourevitch et al., 2018) and German (Gandorfer et al., 2011) examples of limiting intensive N use with PVRN to minimize environmental harm. There are places where such precise control is not deemed necessary and manual switching of N rates works well enough. One example will serve for illustration:

Eastern Oregon’s Columbia plateau farmland, on ancient rolling dunes of aeolian loess (silt) overlaying rocky volcanic terrain, presents a mix of very deep, well-drained soils, shallower soils and non-arable patches. A fourth-generation farmer, who has harvested rainfed grain crops on this land for 55 years, does soil sampling only on the deep soils. Knowing the previous season’s rainfall and harvest yield helps him quantify the need to replace nutrients for the next. In any case, the area’s low and variable rainfall means: “applying the ‘correct’ fertilizer amount is a ‘toss of the dice’, with top dressing usually not an economical option to add nutrients.”

Knowing where the deep and shallow soils lie in the land makes it an easy matter to manually switch to a pre-selected higher rate of fertilizer ‘on the run’ for the deep soil, and a pre-selected lower dose for the shallow. Of course, such manual switching of rates could have been automated with precision variable-rate equipment, GPS mapping, etc.; which no-doubt may be attractive to the next generation. (Weimar, 2020).

3. Methods for whole-farm crop yield simulation

This paper aims to take the two sources of risk above (temporal variations in weather and spatial variations in a paddock’s soils), as well as price variations, into account to allow our whole-farm, long-term financial analyses. The first source of risk (unknown final weather conditions affecting yield responses) is incorporated in the financial model, which uses long-run (56-year) local records of growing season rainfalls (GSR), drawn from the 1960–2015 period.

Decadal (10 year) financial risk profiles were separately developed for two model farms, a smaller one with low fixed costs and no debt and a larger one with high fixed costs and opening debts, based on actual costs for farms found in the region. Repeated simulation runs with random decades of historical growing season rainfalls, drawn from the districts over the 1960–2015 period combined with randomised weekly international commodity prices over the 2010–2014 period at the Port of Geelong, were carried out. Each farm started each 10-year iteration with a fixed opening cash balance: a significant level of debt in the case of the high fixed-cost farm and a significant positive cash balance in the case of the low fixed-cost farm.

3.1. Growing season rainfall and crop yield distributions in the study area

We aim to account probabilistically for temporal variations in weather and prices, while defining spatial variations in farm soils and considering all costs including the cumulative effects of interest over time. Examples of these factors and their analyses were developed in the present study in collaboration with farmers and staff of Riverine Plains Inc. (RPI) in north-central Victoria near Yarrawonga (36.03° S, 146.03° E) and Dookie Agricultural College (36.37° S, 145.70° E) in south-eastern Australia.

Here we define growing season rainfall (GSR) at a location as the weighted sum of monthly rainfalls recorded in a particular year, which varies widely from year to year. We converted Bureau of Meteorology, 2020a, 2020b monthly rainfall records sourced from each location into annual GSR values with Eq. (1).
\[ GSR_{mm} = \frac{((\text{Jan to Mar})/3) + (\text{Apr to Oct}) + (\text{Nov}/2))}{3} \] (1)

These GSR levels measured at both locations from 1880 through 2017 are charted as cumulative distribution functions in Fig. 1.

It may be of interest for some to note that our '1880-to-the-present' reference period is the same as used by climate modelers to study human-induced climate change (McIntyre and McKitric, 2003; Henson, 2019).

### 3.2. Whole farm crop yield variations

Raw, georeferenced harvester records of crop yields were provided by two co-operating farmers covering a number of seasons. In one case, records were from as early as 2000, and from 2010 in the other case, both for numerous paddocks in most years except in droughts (or floods) when there were no harvests. Georeferenced wheat yield (harvester records) from multiple paddocks in each of 19 crop years were provided between the two farms. Canola yield records for 13 years were also provided. There were no continuous wheat or canola records for single paddocks over time because of best-practice use of rotations of wheat and canola, sometimes also including barley and, rarely, faba bean, triticale and lentil. Gaps were found in any given paddock's sequence of season records due to drought periods (particularly in the decade from 2001), frosts or other reasons such as pasture phases in rotations.

Detailed analysis showed that the inclusion of half the November rainfall more accurately predicted crop yield in this area, probably due to the long growing season. Second-degree polynomial (quadratic) functions were fitted to show the relationship between GSR and mean yields from all wheat and canola paddocks on both farms in a year from the cooperating farms at Yarrawonga and Dookie. These response curves explained 76% of the variation in wheat yields over 19 years, with GSRs spanning 190 to 550 mm. Over a similar span of GSRs, 84% of canola yield variation was explained over 13 years. French and Schultz (1984) limit lines were plotted without contradicting the fitted curves, up to maximum yields at approximately 400 mm GSR. The presence of upper limits on yield due to water-logging at high GSR is indicated for both crops in these districts (Fig. 2). On well drained soils, water-limited crop yields can increase linearly with GSR, unless other constraints cause a “yield gap” (Yield Gap Australia, 2020).

### 3.3. Within-paddock variability

Finding a single paddock with sufficient years of canola or wheat records to complete a similar set of regressions for within-paddock yields as functions of GSR was challenging, even with the great number of records provided by the cooperating farmers. Two paddocks with enough years of detailed crop yield data were selected to illustrate within-paddock yield variations associated with GSR (Fig. 3).

We estimated grid-area canola yields as a function of GSR in Paddock 1 at Dookie by combining the detailed georeferenced records of four years of canola yields and two years of wheat, dividing the wheat yields by 1.9, which is the approximate ratio of the wheat yield curve to the canola yield curve across GSRs shown in Fig. 2.

Paddock 2, near Yarrawonga, offered detailed records of three years of wheat yields and two years of barley. We assumed barley grid-area yields could serve as proxies for wheat; French and Schultz (1984) had assumed similar WUE (water use efficiencies) for barley, 21 kg/mm and wheat at 20 kg/mm. With the help of CSU’s Spatial Data Analysis Network (SPAN), the georeferenced yield records for the two paddocks mentioned above were summarised in grid areas of 90 m × 90 m (0.81 ha) each of which was given a grid address (i.e., D6 for row D and column 6 in the Yarrawonga paddock, see Fig. 3). These grid areas were considered of sufficient size to act as the focus for PVRN applications. Smaller grid areas were considered but increased the complexity of PVRN applications because of the lag in the time taken to adjust the fertilizer rates during application. The GSR/crop-year specific yield data for each grid area provided the basis for our analysis of repeatability of annual yield rankings in quartile bands. The Dookie (canola) and Yarrawonga (wheat) paddocks each cover about 115 ha; thus, each could be mapped as 144 grid areas.

Quadratic regression analyses were conducted with the data behind Fig. 3 to relate each individual grid-area's yields over the crop years of record to the GSRs in those years (Eq. (2)), ignoring grid areas with missing data.

\[ y = ((a \times GSR^2) + (b \times GSR) + c) \] (2)

### 4. Results for three measures of calibrating PVRN

Commonly-used benchmarks for calibrating PVRN applications include electro-magnetic conductivity (EM38) measurements, long-term average yields and current NDVI measurements. The accuracy of each of these benchmarks was analysed separately:

#### 4.1. EM38 and yield

Data for Paddock 3 included detailed EM38 survey records as well as detailed crop yields for the previous four years. This presented an opportunity to examine correlations of estimated quadratic (simulated) yield curves (from Eq. (2)) with EM38 data across a rising sequence of GSRs (Fig. 4) on the same 90 m × 90 m grid areas as the maps of crop yield records. The scattered pattern of empty grid areas had estimated yield functions convex to the GSR axis (i.e., lower yields at mid-range GSRs than at the lowest and highest GSRs) and were ignored in the analysis.

Given observed EM38 data for the remaining grid areas in Paddock 3, we calculated correlations with the means of the estimated individual simulated yield curves. As a cross-check, within-paddock correlations of actual crop yield and EM38 level were calculated for each GSR level observed in 2011, 2012, 2014 and 2017. These matched well to the smoothed (simulated) average correlation curve over the range of GSRs (Fig. 5).

#### 4.2. Historical average yields: repeatability

Fixed zoning for PVRN is only feasible if the yield rankings of areas within the paddock are repeatable, such that some areas remain high yielding and others remain low yielding in most years. The poor repeatability of zoning over time is treated by Robertson et al. (2007b, p. 64) in Western Australian wheat crops, and by Liu et al. (2006) on corn crops in Michigan (USA).

In the Riverine Plains we could test this for three paddocks where four to five years of yield data were available for each 90 m × 90 m grid area. The yields of all grid areas in a paddock were ranked into quartiles each year, so that the number of years where the yields lay within a given quartile range could be calculated. In this case the number of years (out of five) that the yields lay within a given quartile were plotted (Fig. 6).

Our analysis shows very low frequencies of quartile rankings of any grid areas being repeated in all five years, and less than 5% repeated in four years out of five, which may be considered the minimum useful level of repeatability for fixed zoning. This result was consistent for all three paddocks.

#### 4.3. EM38 and yields

The data for Paddock 3 was our key source allowing correlation of grid area yields over several seasons with EM38 survey data. This one-paddock comparison showed low and variable correlation rates between yield and EM38 data as modulated by growing season rainfall (Figs. 5 and 6).
The results of a Riverine Plains Inc. N rate response trial in 2017 appear to support the point that EM38 and yield are not always positively correlated (Nordblom et al., 2018a, pp. 66–68). That trial was carried out in two large paddocks, each of which had a high EM38 zone and a low EM38 zone in which replicated N rate sequence plots were prepared and sown. Relatively flat responses to increasing N rates were observed in that season. Most pronounced were the reversals of response to EM38 between the two paddocks; in one paddock high EM38 plots had the highest yields; in the other the low EM38 plots had highest yields. Similar results were observed by Robertson et al. (2007b, p. 64).

It is doubtful that there were profitable responses to any rate of N fertilizer in either paddock due to the high levels of soil N present at all the sites prior to the trial. This result appears similar to those reported on vertosol soils in Spain where high rates of N had routinely been applied by farmers (Lopez-Bellido et al., 2005).

The above results suggest historical benchmarks alone (such as EM38 and average historical yields) have little reliability in determining PVRN rates from year to year. Furthermore, they raise doubt on the practice of dividing paddocks in this region into zones based on historical benchmarks to determine precision N rates in the absence of knowledge or certainty of remaining rainfall for a year.

4.4. Real-time NDVI as guide to PVRN versus EM38 and historical yields

The expected superiority of yields in high EM38 in one of the trial paddocks mentioned above was not seen in the other paddock, perhaps due to the confounding effect of relatively excess soil water or possible frosting and later sowing at that location.

Real-time NDVI control of N applications warrants further research here. It has been in common use in the EU for some time (Lowenberg-DeBoer, 2003; Vizzari et al., 2019). NDVI outperformed EM38 in selecting between 2 or 3 zones in a Western Australian wheat field (Robertson et al., 2007b, p. 64).

Fig. 2. Wheat (a) and canola (b) yield responses to growing season rainfalls, combining results from the Yarrawonga/Dookie area in the Riverine Plains of northeastern Victoria.
Fig. 3. Georeferenced harvester yield data (t/ha) summarised for 90 m × 90 m grid areas over six cropping seasons in two paddocks. For canola yield equivalents of wheat in paddock 1, wheat yields cell by cell were divided by 1.9. For wheat yields in paddock 2 we assumed barley yields, cell by cell, were equal to wheat yields. Regressions of yields by GSR were carried out cell by cell for each of the paddocks, solving for canola in Paddock 1 and wheat in Paddock 2. Notice two grid area positions are labelled in the ‘data’ maps of the two paddocks above; these correspond to the curves so labelled in the charts showing yields as functions of GSR. The heavy solid curves indicate paddock mean yields at each GSR level. These sub-paddock and paddock-level simulation results are similar in substance to those demonstrated for multiple paddocks at the district level in Fig. 2, but derived by detailed analyses of 90 m × 90 m grid-areas of two paddocks over years of low to high GSRs. Mid-range GSRs give highest yields, but high GSRs bring waterlogging losses.
5. Farm financial risk assessments

Farm financial risk can be expressed as the probability of a range of decadal cash margins measured over time (Hutchings, 2013). In this case, multiple simulated 10-year cash margins (ending cash balance minus opening cash balance) with simulated crop yields and prices (described below) with locally validated variable, fixed and capital costs on two model farms. These costs included equipment replacement costs, based on typical machinery inventories and farmer-estimated timing of replacements in these districts. This analysis assumes that all required machinery will be variable-rate-capable at the time of replacement; a situation which is already eventuating in Australia. The additional costs of PVRN are only those of annual soil N testing each hectare of the paddock to allow calculating variable rates to be applied. We speculate later on whether real-time NDVI greenness sensing could be used in place of soil sampling to determine rates for PVRN applications (Whelan et al., 2012).

Wheat and canola crop yields were simulated using the regression equations developed for the area (recall Fig. 2), with randomised 10-year historical sequences of GSR between 1960 and 2015. Across those 56 years, 46 decades of historical GSR sequences were defined, one of which was randomly drawn for each iteration for combination with randomised weekly international price records (from the Port of Geelong, Victoria, 2010–2014). This ensures an absence in our simulations of large correlations between local weather (crop yields) and international commodity prices. Australian crop revenues are the world’s most volatile (Keogh, 2013). Drawing from 46 decadal sequences of wheat and canola yields, and 260 weekly price sets (52 weeks × 5 years) provided a data pool of 11,960 combinations to draw from.

Annual gross income for each crop was calculated using the simulated yield sequences, priced using randomised price sequences, as outlined above. The calculated cash flow budgets included all variable, fixed and capital costs, plus interest on the compounding cash balance, which include living costs and income tax. This allowed calculation of
the simulated cash margin (closing cash balance minus opening cash balance) over each decade. The @Risk “Monte Carlo” software (Palisade, 2018) was used to calculate and record (simulate) the distribution of cash margins over 10,000 iterations, which allowed estimation of the probability of ranges of these values, for any scenario for a given farm. Results are presented as CDFs (cumulative distribution functions) representing a simulated farm’s decadal risk profile.

Risk profiles were simulated for each farm before and after including the cost of PVRN using current cash balances for the opening budget positions. For the high fixed cost farm the opening cash balance was assumed strongly negative; but for the low fixed cost farm, strongly positive.

5.1. Financial risk profiles

Our analysis deals with the effects of implementing variable rate N on whole-farm financial risk over time. This is a somewhat more complex matter than shown by a single year gross margin calculation or

Fig. 5. Correlations between measured grid area EM38 levels in Paddock 3, means of simulated fitted grid-area wheat yields and observed mean grid area wheat yields at the GSR levels observed in (a) 2011, (b) 2012, (c) 2014 and (d) 2017.

Fig. 6. Repeatability frequencies for a grid area’s yield quartiles indicate that recent yield records in three large paddocks are unreliable for predicting their relative yield responses to GSR in a new year. Note, each paddock’s columns sum to 100%.

Table 2
Data used for calculation of risk profiles.

1. Ten-year rainfall sequences selected randomly from the 1960–2015 historical records drive simulations of wheat and canola yields over time.
2. Yields for each year's growing season rainfall, calculated using wheat and canola yield response curves in Fig. 2.
3. Livestock GM from CSIRO GrassGro model for pasture productivity on the farm.
5. Total cash costs for farms selected to reflect high and low fixed costs.
6. Cost of soil sampling for N ($10/ha/yr) assumed for the planning of PVRN.
7. Machinery replacement costs calculated at assumed changeover year (at changeover, variable rate capability is expected to be the standard fitting).
8. 10 year cash margins after all operational costs, living costs and interest.
9. Output is change in cash (bank) balance over 10 years (decadal cash margin), simulated over 10,000 iterations of random prices and decades of local weather (GSR).

the net present value of a stream of annual gross margins. The sample farms shown are defined as models developed to illustrate the full range of likely results that may be encountered in the region. One of these farms is larger and has higher fixed costs than the other (where costs are judged as a percentage of gross income). A short list of the considerations we applied is given in Table 2, building upon the factors already described in this paper. (See Table 3).

The distributions of decadal cash margins, given price and weather variations, define the ‘Risk Profiles’ of these two model farms, with and without variable rate N technology (Fig. 7). This analysis compares the whole-farm effects on long term cumulative cash margins with and without variable rate technologies for N applications.

Marked differences in the risk profiles of the two farms are obvious in Fig. 7. The low fixed cost farm, with only positive cash margins, has zero probability of making a loss over any 10-year period, due to its high cash reserves. In contrast the high fixed cost farm, with high opening debt, shows a 10-year loss (negative cash margin) in 41% of decades, rising to 47% due to the additional costs of PVRN assuming no opening debt, shows a 10-year loss (negative cash margin) in 41% of 

6. Discussion

It must be stressed that the present analysis is limited because it is based largely on data from multiple paddocks over multiple years on two farms in the study area. However, the results are consistent with those of similar analyses cited in the literature and the method used can easily be scaled for larger analyses, as in the Farm 4 Prophet model (van Rees et al., 2015).

We used estimated responses of wheat and canola yields to GSR calculated with 56 years of local rainfall data from the Bureau of Meteorology for Yarrawonga and Dookie. These variations represent a key risk element in our model: combined with high-GSR-sensitivity in the form of yield variations from year to year. Simulated 10-year yield sequences were combined with randomised sets of international commodity prices from the Port of Geelong in southern Victoria for our 10,000-iteration decadal farm financial risk profiles.

The essential element of time and accumulation of debts through periods of droughts and good seasons is a distinguishing feature of the present analysis (Krause, 2014; Malcolm et al., 2005). This important feature of long-term (decadal) cash margins has been conspicuously absent from the literature on analyses of variable-rate N in dryland crop management.

Our analysis shows a low repeatability of historical yield rankings over time in our waterlogging-prone study area, such that EM38 zoning on its own has proven misleading and a poor predictor of yields. Combining grid-area yield data over several years with their GSR levels brings some measure of predictability in probabilistic terms, justifying follow-up research to consider alternate metrics on which PVRN could be more reliably based. Real-time NDVI greenness sensing is suggested as a clear possibility (Robertson et al., 2007b).

As suggested by Filippi et al. (2017), many seasons of georeferenced yield data have been accumulated by farmers in the study area; these could be combined with existing or new EM38 survey maps and appropriate public weather records. High-resolution, georeferenced satellite data NDVI levels can be accessed for past seasons for analysis in conjunction with high resolution yield records, soil and digital elevation maps to predict production capacities across a paddock over time. These data resources would allow testing our hypothesis of GSR-modulated rankings of high and low EM38 grid area crop yields over time. Measured or simulated present soil water availabilities and expected near future rainfalls might also be combined to guide follow-up site-specific N applications.

The value of permanent zoning for targeted PVRN is questionable in the study area due to unpredictable rainfall and its modulation of crop yields upwards and downwards on patchy soils. Low-cost farms may be able to exploit PVRN on a large scale without concern for financial losses, while high cost-farms may face slightly increased chances of financial loss. Real-time NDVI may allow new efficiencies for PVRN, i.e., applying extra N only to the pale-green areas of crop.

A rough indication of how much better PVRN must be to out-perform a moderate uniform N rate can be determined. For example, a 1% increase in crop yields or a 7% decrease in total N use, could just cover the cost one annual soil N sample and analysis per hectare to allow PVRN applications. Such a back-of-the-envelope calculation requires a number of guesses and can be altered to fit different price and yield assumptions (see Appendix A). Unfortunately, the field trial results on low and high EM38 soils in our study area provide no basis of assurance of sufficient yield increases or N-use decreases to cover the costs of annual soil sampling needed to justify the use of PVRN in place of uniform rates on those soils.

7. Conclusions

Paddock zoning based on EM38 or long-term yields (alone) appears unreliable for guiding precision variable rate nitrogen (PVRN) operations in our study area, due to the heterogeneity in soils prone to waterlogging and unpredictable rainfalls. Real-time NDVI top-up applications may offer an effective way to deal with variability in combination with PVRN and would not require permanent zoning. Trial results in 2017 showed mixed responses to increased N due to the high soil N levels present. Based on our initial results for the Yarrawonga and Dookie areas, PVRN needs to increase crop yields by about 1%, or reduce amounts of N applied by at least 7%, to break-even over time in just covering the costs of annual soil N sampling. However, we have no results to indicate such improved outcomes are likely. On the other hand, PVRN costs have a relatively small impact on whole-farm risk. The main impacts on financial risk arise from high fixed costs, or low
Other studies (including Whelan and Taylor, 2013 and GRDC, 2006), which depend on gross margin analyses over one or more years have indicated positive economic benefits of PVRN, though not in our study area. Clear benefits of PVRN are not evident from the present study, which considers price and weather risks over time with the effects of cumulative interest on debt, given the waterlogging challenge of the study area. The present study cannot reject the null hypothesis that PVRN is no more likely than modest uniform applications to improve profits on the low-fixed-cost farm. On the high-fixed-cost farm the extra costs of soil analysis for PVRN appears to slightly increase the likelihood of financial losses.

8. Further research topics

- Expand this form of analysis to more years, soil types and paddocks to test concepts.
- Test the accuracy of EM measurements for zoning applications.
quantifying possible negative effects of high EM on crop yield in high rainfall years.  
- Trialling real-time, tractor-mounted NDVI, and near-real-time satellite NDVI imagery, for tactical mid-season PVRN.

**Declaration of Competing Interest**

None.

**Acknowledgements**

This research was carried out in support of a project investigating ‘in-paddock variability' led by Riverine Plains Inc., funded by the Grains Research and Development Corporation (GRDC). An early version was presented at the Australasian Agricultural & Resource Economics Society Annual Conference at Melbourne in February 2019. This work was also supported by the Graham Centre, the Research Office and the Human Research Ethics Committee at Charles Sturt University (CSU). We acknowledge the academic and financial support provided by the Graham Centre for Agricultural Innovation.

First to be thanked are the cooperating farmers who generously allowed access to their extensive georeferenced crop harvester-yield data. We acknowledge the academic and financial support provided by the Agricultural and Food Research and Development Corporation (GRDC). An early version was presented at the 19th Australian Farm Business Management Conference, Wagga Wagga, NSW, 25–29 August 2019. Now, to calculate the amount of reduced N use needed to cover the cost of soil N sampling alone: it would be a reduction of ($10/ha) / ($157/ha) = 0.064 ≤ 7%.

Now, to calculate the amount of reduced N use needed to cover the cost of soil N sampling alone: it would be a reduction of ($10/ha) / ($157/ha) = 0.064 ≤ 7%.

That is, just a 7% reduction in N use, by lowering applications to areas not benefiting from it, could alone more than cover the cost of annual soil N sampling and analysis.

Of course, combinations of increased yields in parts of the paddock and decreased N use in other parts could also be sufficient to cover the costs of annual soil N sampling and analysis.

**References**

agronomy2015finalno00138.pdf.


https://doi.org/10.1007/BF00024984.


https://www.pnas.org/content/96/11/5952.


https://doi.org/10.1071/AR9840743.

https://doi.org/10.1016/j.agsy.2011.06.004.

https://ageconsearch.umn.edu/record/285063.


AFRM (Australian Farm Business Management) J. 8 (1), 19-42.  

Hutchings, T., Nordblom, T., Li, G., Conyers, M., 2010. Economics of managing acid soils in dryland cropping systems: Comparing analytical methods using gross margins with...