FINAL REPORT 2015/070

Spatially explicit estimation of Achievable Yield Potential – An improved basis for fertilizer management

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ABSTRACT

Current practice in implementing the SIX EASY STEPS (6ES) is to use the 'district yield potential' (DYP) to guide development of nitrogen (N) fertilizer recommendations. However, because both land (soil, topography) and weather/climate may be strongly spatially variable at district scale, yield may also vary rendering use of DYP as sub-optimal. This project explored finer-scale alternatives to DYP as input to 6ES using spatial analysis of mill data and also data collected using yield monitors. The project was focussed in the Herbert River district.

Analysis of mill records over 7 seasons shows that there is a marked spatial variability in yield in the Herbert River district, with the patterns of this variation stable across seasons and crop class. Accordingly, we conclude that DYP is not appropriate as an input to 6ES. Rather, a block yield potential derived from a map of the maximum yield of first ratoon achieved over these 7 seasons is suggested as a better alternative; this map, which is derived from interpolated maps of first ratoon yield for each year for which data are available, can be readily updated as more data become available.

Growers with access to yield mapping could readily adopt a similar means of estimating yield potential at the within-farm or within-field scale. However, it is unlikely that sufficient data are yet available to support this given that data from several seasons are needed for yield zone delineation.

Whether at the within-region or within-farm or field scales, further location-specific refinement of the application of 6ES is possible with access to data on soil carbon (C) content, whether derived from regional soil survey or local soil testing.

Similar analyses to those reported here could be readily conducted in other sugarcane growing regions. Likewise, examination of spatial variation in the other factors underpinning 6ES may also be valuable as the industry seeks to optimise its N use efficiency.

EXECUTIVE SUMMARY

Potential yield is one of the criteria used as an input to nitrogen (N) fertiliser management decisions made using SIX EASY STEPS (6ES). Whilst 6ES allows the estimate of potential yield to be made at whatever scale is deemed appropriate (block, farm, region, etc), the fact is that 6ES is generally implemented using a district yield potential (DYP). However, the gradual adoption of Precision Agriculture (PA) technologies, such as remote sensing and yield monitors, along with mill records of yield at the block and farm scale, suggests that yield varies markedly within regions. This raises questions as to the merits of using DYP as an input to 6ES. It also suggests that an alternative, more location-specific approach, might deliver benefits in terms of improved N use efficiency (NUE). Increasing NUE in the sugar industry is an important step in protecting the economic and ecological benefits provided by the Great Barrier Reef. Importantly, an increase in NUE also offers opportunities to improve profitability, providing an incentive for practice change.

In partnership with Herbert Cane Productivity Services Ltd (HCPSL), and using data made available by Wilmar Sugar, this project used spatial analysis of yield variation in the Herbert River district over 7 seasons using mill records. The results of this analysis suggest that there is marked spatial variability in yield in the Herbert River district, and that the patterns of this variation are stable across seasons and crop class. They therefore provide a basis for moving away from the use of DYP as an input to 6ES and, for those Herbert growers who have not yet adopted PA for the fine-tuning of fertiliser management at the within-block or -farm scales, a basis for a more location-specific application of 6ES. It is suggested that a map of the maximum yield of first ratoon achieved over the study period provides an appropriate basis for estimating block yield potential (BYP). Combining BYP with discounts to the N applied based on soil mineralisation potential, derived from either a regional scale soil survey or contemporary soil testing, enables location-specific implementation of 6ES. Comparison of maps showing recommended N rates in the Herbert region when 6ES is used with either DYP or BYP and data obtained during a 1:5,000 soil survey conducted in the late 1980s and early-mid 1990 suggests that, on average, savings in N use of approximately 26 kg N/ha, equivalent to $23/ha saved in input costs of production, might be readily achieved. When the same analysis is done with contemporary soil testing as the source of the N mineralisation discount – which enables the analysis to be extended to the entire current Herbert cane growing area – the projected savings in use are the same; that is, 26 kg N/ha on average. This equates to a total annual reduction in applied N in the Herbert district of 1,980 t, saving Herbert canegrowers $1.8M p.a. Note that in estimating these savings, no changes were made to the rationale which underpins 6ES or the calculations it uses to generate recommendations; rather, all that was done was to apply these in a location-specific way.

The project sought to undertake similar analyses to those detailed above at the within-farm and within-block scales, using data that adopters of precision agriculture (PA) can be expected to have ready access to through yield monitoring and mapping. However, whilst the benefits of this approach are intuitive, we conclude that there is insufficient reliable yield monitor data available at present to enable such an approach to be robustly implemented. This situation is expected to change as yield monitors become more readily commercially available.

An important feature of this work is that, for the analysis of DYP and BYP, it relied on data that is routinely collected every year at all mills. Thus, a similar analysis could be readily conducted in other sugarcane growing regions. We also suggest that examination of spatial variation in the factors other than yield potential, which underpin 6ES may also be valuable.

In this study, we used soil carbon (C) data obtained from soil survey and soil testing to assess the soil N mineralisation potential. In most cane growing regions, soil survey data is only available at much

lower resolutions than in the Herbert district. However, the coordination of soil testing at regional scale is clearly feasible, as demonstrated by HCPSL-led activities in the Herbert. In addition to such an approach, and examination of yield variation, examination of spatial variability in crop N uptake, crop N requirement and N loss through run-off, leaching and volatilization would also assist in promoting improvements to NUE.

Finally, we re-state here the most important message to emerge from this work: the notion of a district yield potential (DYP) is an inappropriate basis for the delivery of fertilizer advice, since potential yield is markedly spatially variable at the within-district scale with the patterns of yield variation being remarkably stable from year to year. Accordingly, location-specific estimates of yield potential (YP), such as the block yield potential (BYP) should be used in preference to DYP, a practice which could lead to significant savings in average N input costs and a reduced risk of N loss offsite.

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

1. BACKGROUND

Recent research has shown that the amount of nitrogen (N) fertilizer applied in excess of crop uptake is an important determinant of N discharge from catchments in tropical Queensland, in which sugarcane production is a major land use (Thorburn and Wilkinson, 2013). Thus, increasing the efficiency of N use in cropping systems such as sugarcane is an important step in protecting the economic and ecological benefits provided by the Great Barrier Reef (Bell, 2015). Importantly, an increase in N use efficiency (NUE) also offers opportunities to improve profitability, providing an incentive for practice change.

The key input criteria used in deriving N fertilizer management recommendations for sugarcane using the SIX EASY STEPS (6ES) system (Schroeder et al., 2005, 2010; Schroeder, 2009) are the yield potential (YP) of sugarcane and the N mineralization potential of the soil; the latter is estimated as a function of the soil organic matter content in the top 20 cm. Given the varied scale and availability of yield and soil information, 6ES is sensibly not prescriptive about the scale at which such information is brought to bear on the delivery of fertilizer recommendations. However, common practice is for 6ES to be implemented using a district yield potential (DYP) which is defined as the estimated highest average annual district yield (based on mill statistics collected since 1990; Schroeder, 2009).

The gradual adoption of Precision Agriculture (PA) technologies, such as yield monitors, has provided compelling evidence of significant variation in sugarcane yield at the within-field scale (Bramley and Quabba, 2002; Johnson and Richard, 2005; Bramley and Jensen, 2013; Rodrigues et al., 2013; Bramley et al., 2017). Likewise, the use of remote sensing as a yield prediction tool (Robson et al., 2012, 2016), suggests that yield may vary markedly within a given region. This variation raises questions as to the merits of using DYP as an input to 6ES from the perspective of NUE and the possible on- and off-site impacts of excessive N use (Bell, 2015 and references therein).

This project sought to use spatial analysis of yield variation in the Herbert River district at a range of scales, using mill records and yield monitor data, with the aim of evaluating the merits of a move towards a more location-specific application of 6ES than is currently typically employed when based on DYP.

2. PROJECT OBJECTIVES

As stated in the project contract, the original project objectives were to:

- In partnership with HCPSL, select data from a small number of harvester groups in the HCPSL database which
    - used the TechAgro/Solinftec yield monitor during the yield monitoring project,
    - represent contrasting Herbert soils,
    - represent differing annual rainfall, and
    - have good mill records of harvest events.
- Re-analyse these data to enable robust yield maps to be produced at the block, farm and group scale along with estimates of the yield variation measured by the data at these scales.
- Identify management zones, as appropriate, at the within block scale and the magnitude of yield differences between these.
- Use the results to generate estimates of YP at these different scales, the associated recommended N rates (based on 6ES) and use these to quantify the error associated with

  regional estimates of YP for all years for which data are available and the consequences of
  this error for N management.
- Produce a protocol for scale-appropriate YP estimation based on the methods used here, for
  implementation in other districts, including documentation of data input requirements.

As will be apparent below, and with better understanding of the available data, its utility and
shortcomings, the main focus in the project was on within-district yield variation. We attempted a
substantial analysis of variation at the within-farm and -block scales, but data availability and
inconsistency conspired against this; the present wide geographic spread of farms allocated to
harvester groups as a means of maximising the efficiency of use of harvesting resources rendered
analysis at the harvester group level inappropriate. However, given the potential impact of the
results obtained at the within-district scale, the revised focus is considered appropriate – see section
6 (below).

3. OUTPUTS, OUTCOMES AND IMPLICATIONS

3.1. Outputs

Noting that this project was a 'proof-of-concept' activity focussed on the Herbert River district, but
with transferability of methodology, if appropriate, to other districts, the contracted outputs
included delivery of:

- Robust yield maps for selected harvester groups within the Herbert district.
- Multi-year quantification of the difference in maximum yield achieved in zones, blocks,
  farms and harvester groups when determined at these scales using yield monitor and mill
  data and measures of the difference between these estimates and district yield potential.
- A protocol for determination of such estimates for use in other districts for which such data
  are available or will become available.
- A measure of how N management would be different if fertilizer application was based at
  either the district, farm, block or management zone level.
- Enhanced industry awareness of the opportunities presented by using location-specific
  estimation of YP through industry publications, PEC videos and presentations at industry
  fora.
- Journal publications describing the work.

A critical enabling element of the work was the provision of mill and other data, under licence, by
Wilmar Sugar. Implementation of the methodologies employed in this work in other districts and
therefore realisation of similar outputs elsewhere, will be similarly critically dependent on access to
relevant mill and other data in those districts.

3.2. Outcomes and Implications

Work conducted in SRA Project CSE022 (Bramley et al., 2014) demonstrated that variable rate
application (VRA) of nutrients and/or soil amendments could be highly profitable. A grower survey
conducted during that project also demonstrated a high level of industry 'buy-in' to the prospect of
PA delivering financial benefits to farm businesses. Intuitively, VRA (putting the right amount in the
right place) should also lead to enhanced NUE and a consequently reduced risk of off-site nutrient
export. Accordingly, it was foreshadowed that successful completion of this project will enable:

- greater understanding of YP and its variation at a range of scales
- more efficient use of N (and other) fertilizers, resulting in
- cost savings/improved profits for growers
- more accurate data for harvest planning
- reduced risk of offsite export of N.

In one of the analyses undertaken as a part of the project (see below), we have estimated that implementation of N fertilizer recommendations using 6ES based on a block yield potential rather than district yield potential would lead to an average reduction in N applied to Herbert cane fields annually of approximately 21 kg N/ha. Assuming that N (as urea) costs $0.90/kg, this equates to a saving in input costs of approximately $19/ha or around $1.5M in the Herbert district as a whole. It is therefore expected that the work described here will deliver a small boost to grower profitability.

Whilst we did not attempt to measure or model potential N losses offsite in this work, we infer that a reduction in N inputs will lead to a reduction in the risk of N loss off-site which, in turn, implies reduced detrimental environmental impact, both on- and off-site, including in the Great Barrier Reef marine lagoon. Webster et al. (2016) provide strong evidence in support of this.

Follow-on social benefits, including the 'feel good' derived from responsible fertilizer use / demonstration of best practice / improved environmental stewardship, may also accrue. In turn, Queensland's attractiveness as an environmentally sound tourist destination may be enhanced.

In addition to these outcomes, it is also anticipated that this work will inform future N trial work, which will underpin grower adoption of new practices.

4. INDUSTRY COMMUNICATION AND ENGAGEMENT

4.1. Industry engagement during course of project

This project was conducted as a partnership between CSIRO and Herbert Cane Productivity Services Ltd (HCPSL), arguably the primary grower extension, liaison, and provider of advice to Herbert River growers. Accordingly, the project has enjoyed direct industry engagement during its conduct. A 'hand-over' meeting of project outputs between CSIRO and HCPSL is planned for early August 2017 at which a presentation of project results to the HCPSL Board will be made.

The project team have also been in close communication with Wilmar Sugar who control all milling operations in the Herbert. In addition, the project has been presented on two occasions to workshop meetings convened by the Queensland Department of Environment and Heritage Protection, both of which were attended by the Canegrowers organisation.

Finally, the project was described to a broader sugar industry audience through a paper presented to the 2017 (Cairns) conference of the Australian Society of Sugar Cane Technologists (ASSCT – see Appendix 2); this paper was awarded the ASSCT President's Medal – Research.

4.2. Industry communication messages

This work has led to two key messages. First, the work makes clear that the notion of a district yield potential (DYP) is an inappropriate basis for the delivery of fertilizer advice, since potential yield is markedly spatially variable at the within-district scale with the patterns of yield variation being remarkably stable from year to year. Accordingly, location-specific estimates of yield potential (YP),

such as the block yield potential (BYP) should be used in preference to DYP, a practice which, on average, could lead to significant savings in N input costs and a reduced risk of N loss offsite. This project provides a protocol for determining BYP based on mill statistics and it is suggested that there would be strong industry value in implementing work similar to that reported here in all other Australian sugarcane growing districts.

Second, the philosophy which underpinned the work was based on that which underpins the adoption and implementation of Precision Agriculture (PA) practices at the block- and within-block scales, such as were demonstrated in SRA Project CSE022. Accordingly, as growers who have adopted, or are adopting PA on their farms, access yield monitors and accumulate yield maps, the approaches used in this project for estimating YP may be used. However, at present we would caution against the use of yield monitor data for this purpose where this data derives from those types of yield monitors identified as sub-optimal in CSE022. In this work, we drew on data that has been collected in the Herbert River district over many years, but with a focus on data that appeared reliable, notwithstanding that it derived from these same sub-optimal technologies. Yet the yield maps derived from these data contain numerous artefacts/spatial discontinuities which render them of concern for determination of YP, given its status as a critical input to fertilizer decision making. However, apparently robust yield monitors are now becoming commercially available and we would expect their use over several seasons to promote more targeted N fertilizer management at the block and within-block scale when used as a basis for determining YP as described in this project.

5. METHODOLOGY

The basic approach taken in this work was to analyse yield and other data, irrespective of the scale of analysis, using the approach taken when PA is implemented with a view to targeting management at the within block scale (Fig. 1). Bramley et al. (2017) provide an illustration of this approach with the same sugarcane case study from the Burdekin as shown in Fig. 1. It involves generating map layers from available data – yield maps for several years, soil maps, etc..., with each map interpolated onto a common grid derived from the field boundary - and integrating these using cluster analysis to identify so-called 'management zones'.

5.1. Yield variation at the within-district scale

Mill records in the form of the 'cane block layer' for the 2009-2015 harvest seasons in the Herbert River district were used in this work; data were supplied as a single GIS feature layer (one per year) for the Victoria and Macknade mill areas combined. This timeframe was chosen as it was believed to match that for which yield monitor data were also available.

For each of these seven harvest seasons, the GIS feature layer contained data on a sub-block basis covering yield of sugarcane (t/ha), variety and crop class, amongst numerous other details not relevant to the analysis reported here. Importantly, all of these data were geo-referenced to the sub-block boundaries pertinent to each record/year.

Since 6ES makes no distinction between varieties, we assumed for this analysis that the yield potential for all varieties in any given year was the same.

For each year, coordinates were generated for each data record based on the centroid of each sub-block. The data were then filtered on the basis of crop class and data retained for plant crops and for first, second, third and fourth ratoon crops. Thus, data for ratoon crops older than fourth ratoon
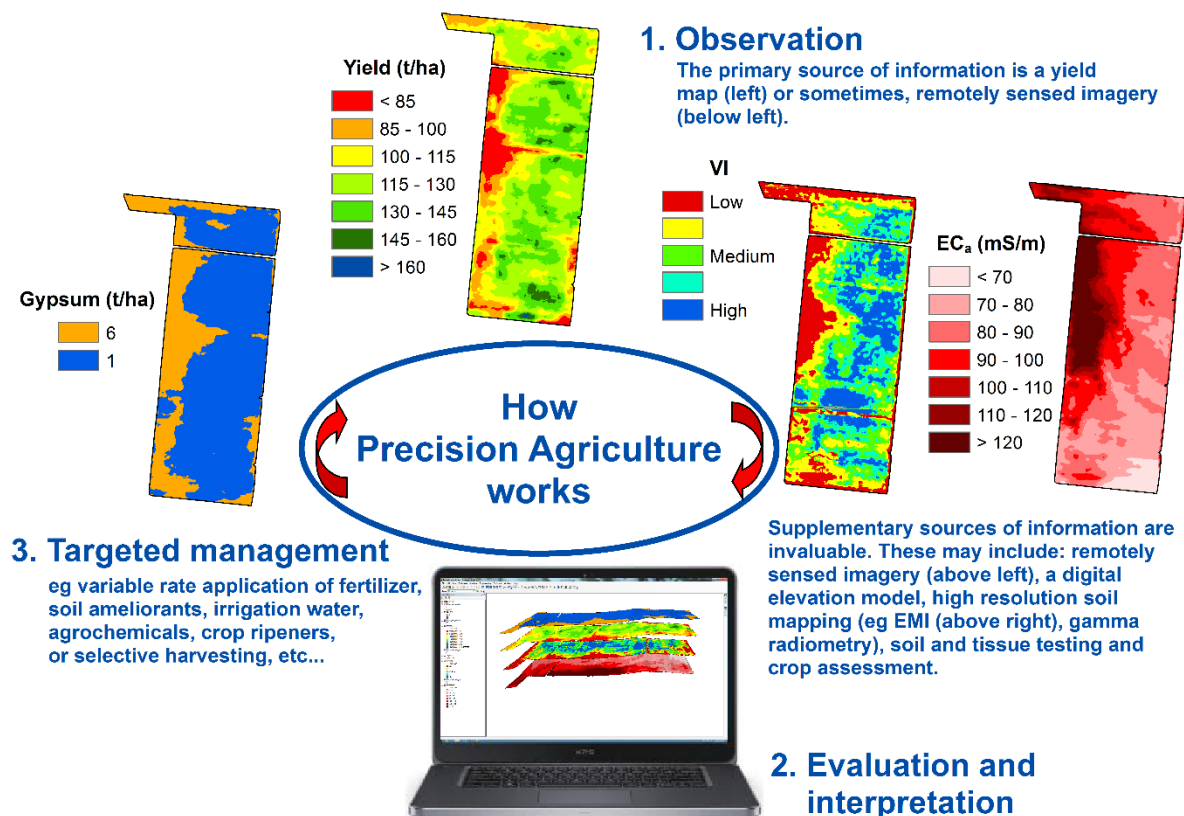
Figure 1.   Schematic representation of Precision Agriculture as applied to a 27 ha cane field from the Burdekin region. In the present study, our focus was confined to available yield and soil data, but we nevertheless followed the same basic process based on observation (mapping), evaluation and interpretation of the maps and then integration of the data to identify zones of characteristic performance for which appropriate fertilizer recommendations might be made (targeted management), irrespective of the scale of focus – district, farm, block, etc.

were discarded, as were data for standover cane. Plant and re-plant crops were assumed to have the same potential yield and so were treated as the same.

For each crop class in each year, the yield data were normalised to a mean of zero and standard deviation of one and any records that were not within +/- 3 standard deviations of the mean were discarded. Note that, for a normally distributed dataset, 99% of the data values lie within three standard deviations of the mean. Discarding those data records that lie outside this range is therefore a useful way of removing outliers and otherwise aberrant values.

The 'cane block layer' shapefiles for each year were merged in ArcGIS (version 10.4; ESRI, Redlands, CA, USA) to enable generation of a single boundary for the cane-producing area of the Herbert River district over the 2009-2015 period, and from this, a raster grid was generated comprising pixels of 100 m x 100 m (i.e. 1 ha).

For each crop class by year combination, maps of normalised yield were then interpolated onto the 100 m raster using local block kriging (Webster and Oliver, 2007) in VESPER (Minasny et al., 2005), with a data cloud of 100 points (i.e. 100 sub-block records), exponential variograms and blocks of 500 m. In effect, this is an 'upscaling' of the sugarcane yield mapping protocol of Bramley and Jensen (2013; see also section 5.2 below). In addition, for each year, the normalised crop class-based

datasets were merged and a further map layer was interpolated summarising annual yield variation for the district as a whole independent of crop class. Note that this is considered legitimate on the basis that the effect of data normalisation on a crop class basis is to remove the effect of crop class.

Typically, the crop class-based maps have a support of approximately 2,500 sub-block records, whilst those interpolated independently of crop class were derived from approximately 13,000 records.

5.2. Yield variation at the farm and block scale

For maps at the within-farm, -block and -sub-block scales, yield monitor data were used. These derived from the ongoing yield monitoring and harvester-tracking project being run in the Herbert River district by HCPSL and were available for the period 2011-15. Somewhat disappointingly, data for 2009-10 were not accessible as foreshadowed prior to project commencement.

The mapping of yield monitor data followed the protocol of Bramley and Jensen (2013), albeit using data that had been normalized (mean of zero, standard deviation of one) on a per harvest event basis, to remove artefacts due to crop age (time since harvest), crop class, varietal differences, mill consignment errors and yield monitor calibration. Following kriging, the maps were back-transformed to a t/ha basis using the mean yield calculated from mill records of sub-block tonnages and knowing the area harvested. The map data were then further adjusted to a first ratoon equivalent basis using a relationship describing ratoon yield decline (see section 6.1 - below).

Note that we did not attempt to generate yield maps for all blocks in the HCPSL yield monitor dataset. Rather, for each of the district-scale yield clusters identified in the district-scale work (see section 6.1 - below), 8 farms were identified in each of the low, medium and high yielding clusters on the basis of them:

- being of large farm area;
- having a consistent farm area/boundary over the 2009-15 period for which we had mill data;
- covering contiguous, as opposed to fragmented areas; and
- falling within a single district-scale yield cluster.

Yield maps were then generated for each year for available blocks within each farm. Based on the consistency of yield map coverage over the period for which yield data were available, yield maps for blocks and sub-blocks were selected within each farm for analysis at these finer scales.

5.3. Yield variation at scales intermediate between within-district and farm.

Aside from yield variation at the district and farm (farm, block and sub-block) scales, our original intent was to also look at yield variation at the level of the sub-district and harvester group. In the latter case, this was based on the misunderstanding that harvester groups were geographically constrained – as used to be the case prior to the mid-late 1990s. In fact, as a means of increasing the efficiency of investment in expensive harvesting equipment, harvester groups now comprise farms that are widely spread throughout the district rather than being contiguous. Thus, whilst some harvesting groups are recognised by HCPSL as doing a more careful job of both consignment and managing the other aspects of harvesting which impact yield monitoring (speed, harvester settings appropriate to presentation of the cane), analysing yield variation on a harvester group basis was quickly deemed inappropriate to the overall objectives of the project due to the dispersed nature of individual groups.

In respect of sub-district variation, our initial approach was to select groups of farms which were members of the preferred harvester contractors (see above), and which were perceived to be in

contrasting sub-districts in terms of soils and rainfall, based on the local expertise of HCPSL who have operated for several years on the basis of the Herbert River district having a number of identifiable 'productivity zones' (Fig. 2). However, as discussed below, these analyses were abandoned in light of results obtained from the work described in sections 5.1, 5.2 and 5.4.
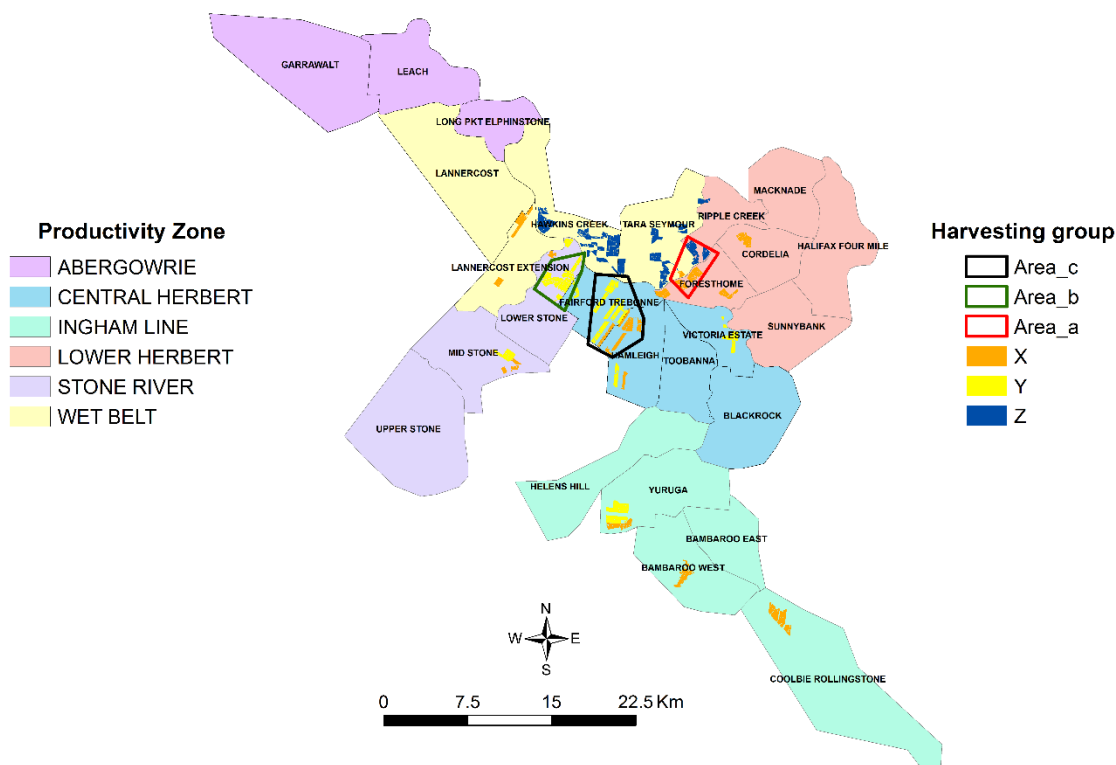
Figure 2.   Map of the Herbert River district highlighting HCPSL 'productivity zones', preferred harvesting groups (those perceived to do yield monitoring well), and preliminary study areas identified based on these factors and local perceptions of yield, soil and climatic variation.

5.4. Analysing temporal stability in patterns of yield variation.

Similarities in patterns of spatial variation in the mapped data between years (c.f. identification of management zones in Fig. 1) were examined using *k*-means clustering in JMP (v.11.0.0, SAS Institute, Cary, NC, USA). This is a standard approach used in PA research and implementation (Taylor et al., 2007; Bramley et al., 2017). As an alternative, the method of Diker et al. (2003) was also explored; this examines yield variation in the context of probability surfaces. In this method, over the period for which yield maps are available (2009-15 in this study, that is, 7 years) the number of years for which, at any given location, yield was either above or below the district mean is counted. By mapping these counts (possible values ranging from 0-7 in this study) a yield probability surface is generated. Here, the modification to this method of Bramley and Hamilton (2004) was used. Thus, maps were produced showing the number of years in which a particular 'yield target' was achieved along with the number of years in which yield was below a level of minimum performance.

5.5. Soil mapping and determination of the discount to recommended N rates due to mineralisation.

5.5.1. The 'Andrew Wood' data set.

During the 1980s and '90s, Dr Andrew Wood, then Chief Technical Field Officer with what was CSR Sugar (now Wilmar Sugar), led the conduct of a survey of Herbert River soils at a scale of 1:5,000. This survey was subsequently digitised and made available in GIS shapefile format (Fig. 3). Subsequently, Wood et al. (2003) provided soil interpretation guidelines which included indicative mean values for the soil organic carbon (C) content (%) and a consequent classification of Herbert soils in terms of the discounts to applied N rates used in 6ES based on the soil's N mineralisation potential (Fig. 4). Wood et al. (2003) used these various data to provide recommended N rates for sugarcane production on Herbert soils assuming a DYP of 120 t/ha. Using the data presented in Wood et al. (2003), a regression relationship was developed to re-express the N mineralisation discounts as a percentage of the 'base rate' (see section 5.6.1) based on DYP (Fig. 5). This enabled construction of a raster-based map based on the same 100 m pixel grid as was used for yield mapping (section 5.1) describing the discount to be applied to 'base' N rates (Fig. 6).

Note that the extent of the 'Andrew Wood soil survey' is somewhat less than the extent of the entire Herbert River cane-producing area, with much of the southern part of the district remaining unmapped (e.g. compare Figs. 2 and 3) which is why the N mineralisation discount does not cover the entire cane-producing area (Fig. 6).
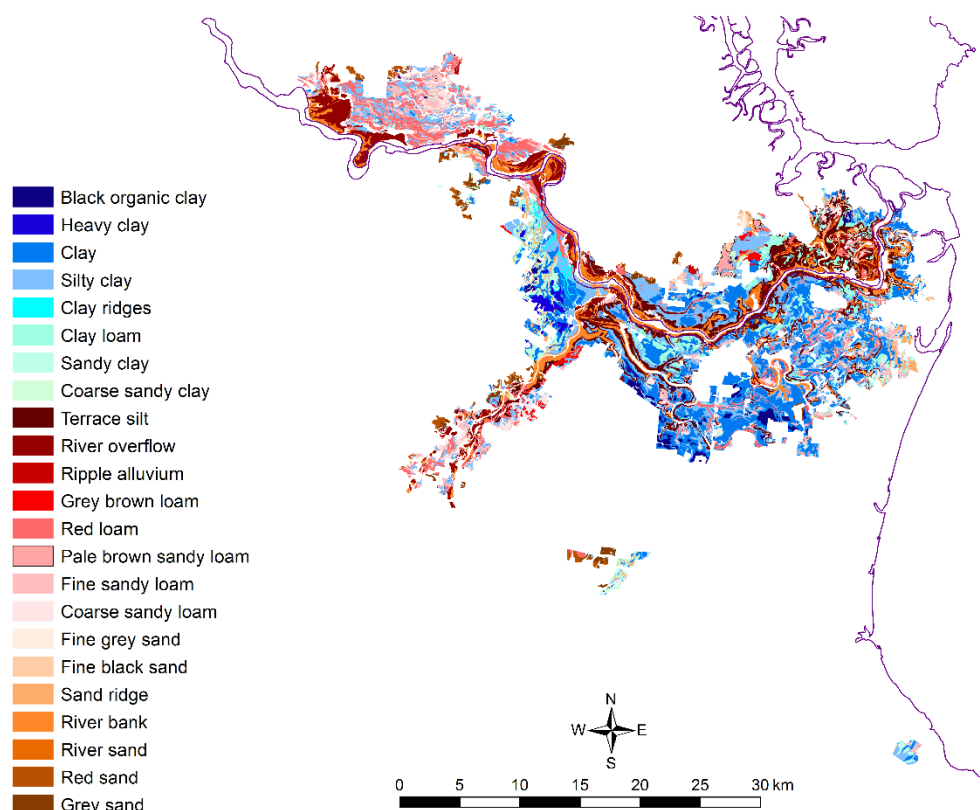
Figure 3.   The 'Andrew Wood' 1:5,000 Herbert River soil survey. This map is the same as that of Wood et al. (2003) except for a re-ordering of the soils and use of a revised colour legend based on soil texture to assist with geomorphic understanding of soil variation; clay soils in shades of blue, sandy soils in browns and silts and loams in reds.
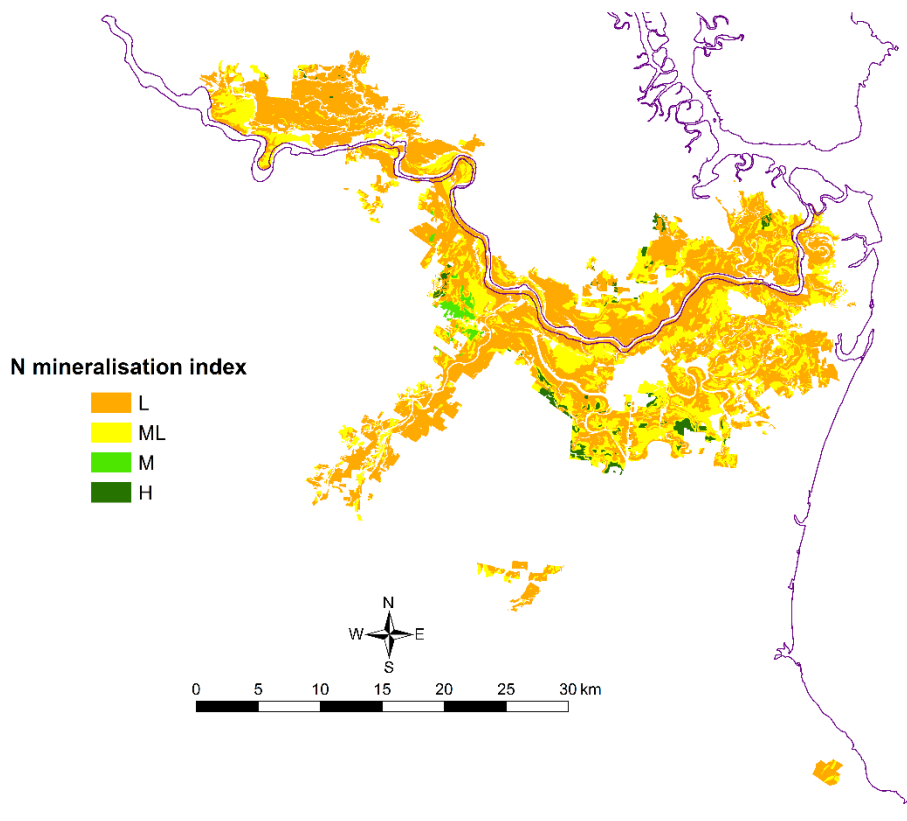
Figure 4.   Variation in the N mineralisation potential of Herbert River soils (data of Wood et al., 2003).
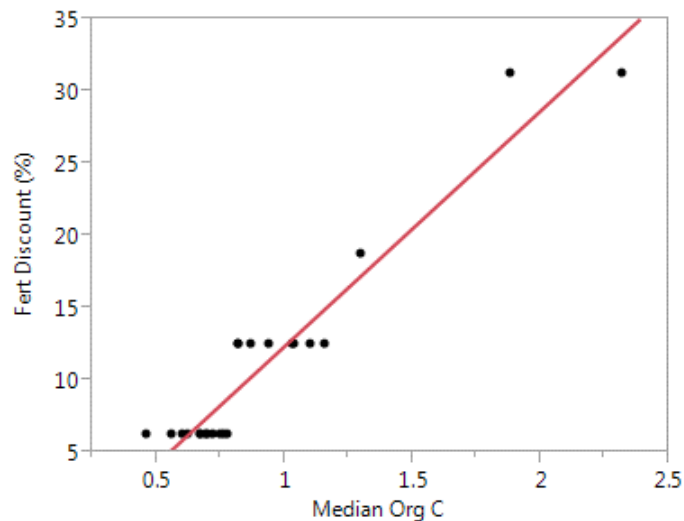
Figure 5.   Relationship between median soil organic C (%) in Herbert River soils and the discount applied to 'base' fertilizer rates (%), based on the data in Wood et al. (2003). The equation to the fitted line is: Discount = -3.94 + 16.31 C; R^2 = 0.92 (*P*<0.001).
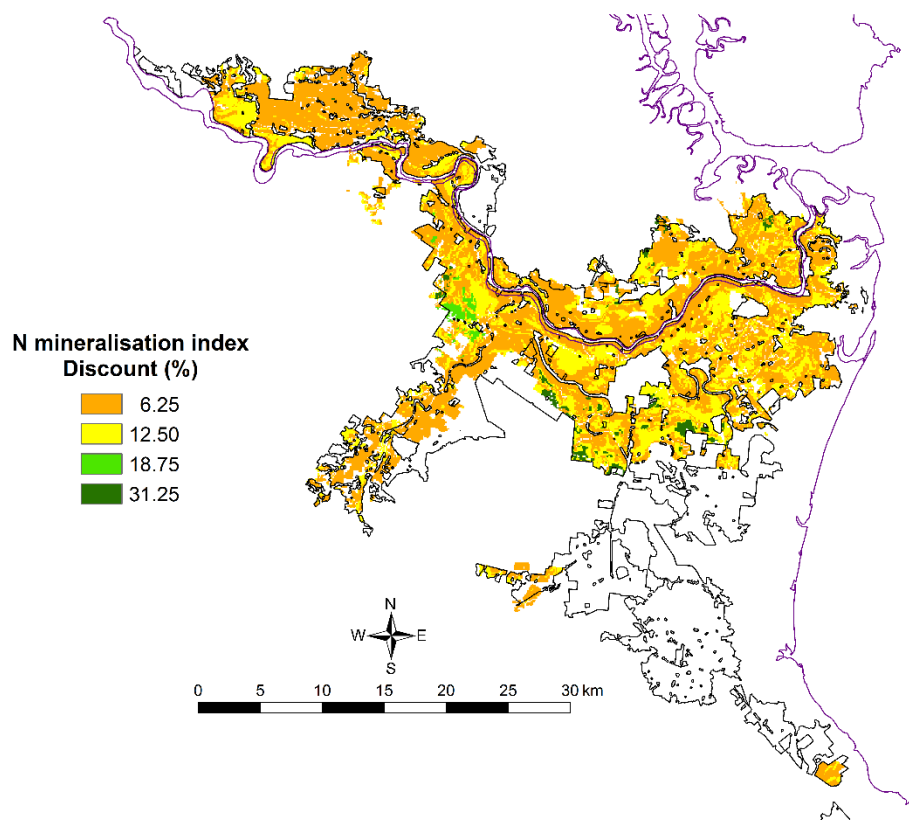
Figure 6.   Discount to 'base' fertilizer rates (%) due to soil N mineralisation potential derived from
the 'Andrew Wood' soil survey (Figs. 3 and 4) and the regression relationship shown in
Fig. 5.

5.5.2. Mapping soil variation based on soil test data

In recent years, HCPSL have coordinated a soil testing program throughout the Herbert River district.
This has been based on so-called 'representative soil samples' collected from sub-blocks, with
approximately 300 samples collected annually since 2009. Knowing the sub-block numbers for the
sub-blocks sampled, along with the coordinates of the centroids of the sampled sub-blocks (see
section 5.6.1), it was possible to generate maps showing soil sampling locations (Fig. 7); this was
done using the same kriging procedure as for regional scale yield map generation. As can be seen,
these samples give a good coverage of the entire Herbert River district, especially when grouped
across years.

For the purposes of this study, a very conservative view was taken of soil organic matter
accumulation over time; it was assumed that over a three year period, no measurable change in soil
organic C content would occur. Thus, using the soil test data for 2014-16 only, a map of soil C
content was interpolated onto the same 100 m pixel grid used for yield mapping (section 5.1). The
raster calculator available in ArcGIS (v10.4; ESRI, Redlands, CA, USA) was then used, along with the
regression relationship shown in Fig. 5, to generate a map of the discount to be applied to 'base'
fertilizer rates based on contemporary soil analysis (Fig 8).

a.
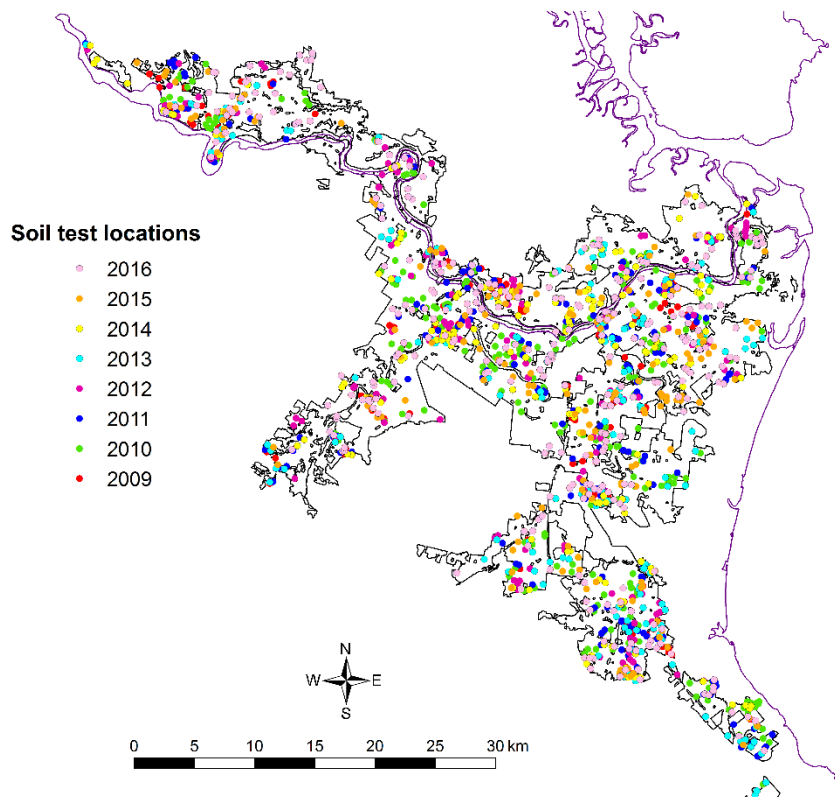
b.
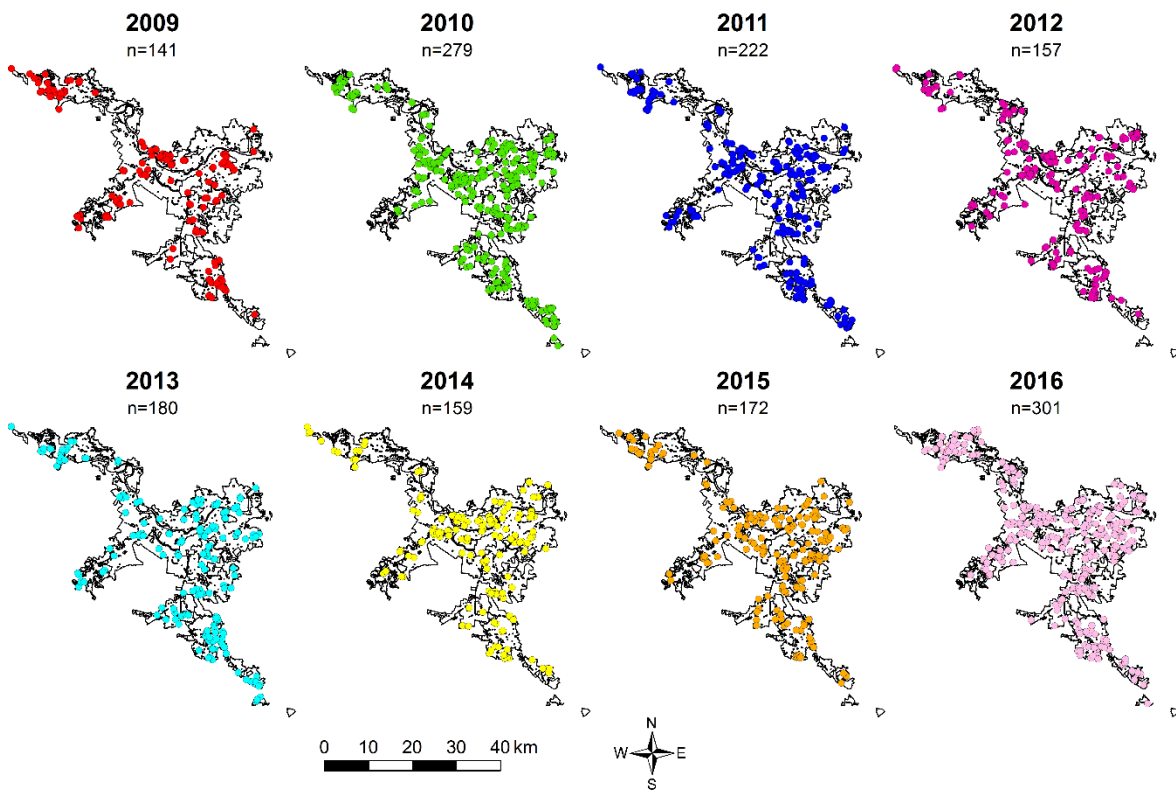
Figure 7.   Locations of soil samples collected for soil testing by HCPSL in the 2009-2015 period. (a) all years, and (b) by year.
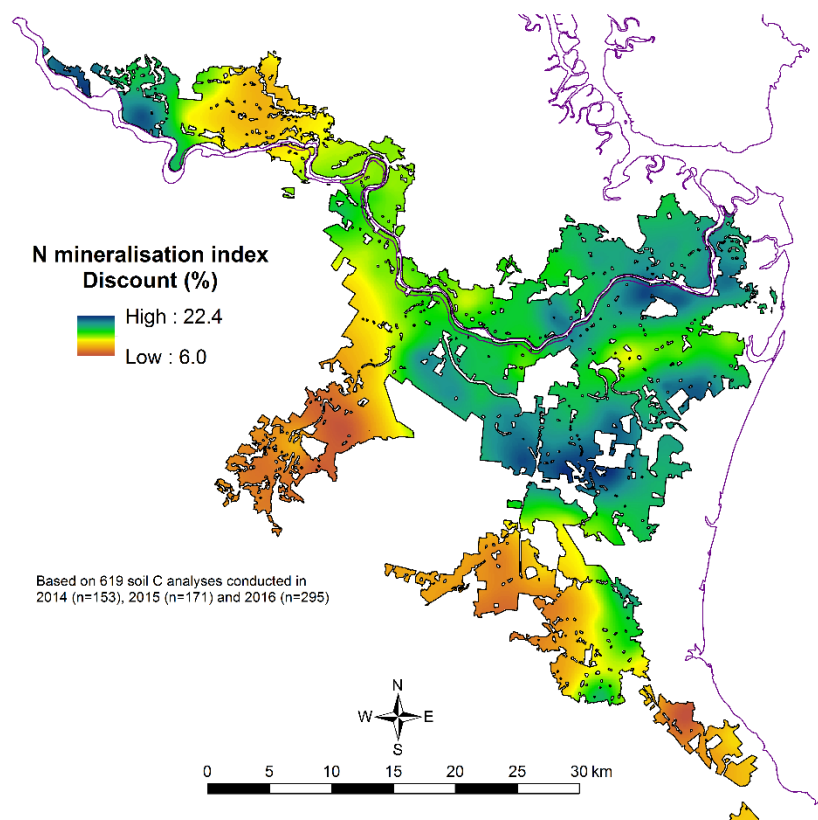
Figure 8. Discount to 'base' fertilizer rates (%) due to soil N mineralisation potential derived from soil testing undertaken by HCPSL in the period 2014-2016.

5.6. Estimating N fertilizer recommendations using SIX EASY STEPS, yield maps and soil maps.

As noted, common practice is for 6ES to be implemented using DYP which is defined as the estimated highest average annual district yield (based on mill statistics collected since 1990; Schroeder, 2009). In the Herbert River district, DYP is assumed to be 120 kg/ha. This is the same value as used by Wood et al. (2003) and is still in use today (Lawrence Di Bella, HCPSL – pers. comm.) in the local delivery of fertilizer advice to growers.

The DYP is multiplied by a factor to determine nitrogen required (1.4 kg N/t cane for the first 100 tonnes of cane and 1.0 kg N/t for additional tonnage above 100); here, we refer to this as the 'base' amount of N to be applied. The discount due to soil N mineralisation (section 5.5) is then applied based on soil organic C content. In this study, we followed an identical process, albeit using data appropriate to the scale of interest. It is thus important to note that, in this work, we made no modification at all to the principles underpinning 6ES; we have simply sought to apply them in a spatially astute way.

5.6.1. Within-district scale

As explained in section 6.1, and so as to be consistent with the 6ES approach to defining YP on the basis of the maximum average district yield achieved, we used a map of the highest location-specific yields achieved as the basis for defining YP. The raster calculator available in ArcGIS (v10.4; ESRI, Redlands, CA, USA) was then used to calculate the 'base' N rate using the rules indicated above. The

discount due to soil N mineralisation potential was then applied using the maps in Figs. 6 and 8 to produce an N fertilizer recommendation map based on a block yield potential (BYP) and a mineralization discount based on either soil survey (Fig. 6) or recent soil testing (Fig. 8).

5.6.2. Within-farm and -block scale

Farm and block scale maps generated over several seasons as described in section 5.2 were clustered together using *k*-means (section 5.4). Following a similar philosophy to that described for implementation of 6ES generally, and the district scale mapping (5.6.1 above), the highest value of each cluster mean was taken to represent the cluster or 'management zone' YP. These were used as the basis for calculating 'base' N rates.

Estimation of the N mineralisation discount at these finer, within-farm, scales is problematic given the availability and scale of soil mapping or soil test data. Clearly, soils may be highly variable at the within farm scale (e.g. Fig. 1) with the consequence that N mineralization potential is likewise expected to be highly variable; Bramley and White (1991) demonstrated variation in soil nitrification potential to be very short range (of the order of 12 m in a pasture soil), whilst Webster et al. (2016) have likewise shown that N loss can be expected to be variable and related to soil variation. However, in spite of the very high quality and high resolution reconnaissance soil survey data available in the Herbert (Fig. 3), along with the HCPSL soil testing program (Fig. 7), it is not possible to robustly estimate soil N mineralisation potential at finer scales than the 1 ha pixel grid used for district scale mapping. Accordingly, for this analysis, the dominant soil type occurring in a field or farm was used for determination of the N mineralisation discount to be applied to the within-farm scale 'base' N rate. Note that with access to soil test data for the blocks of interest, a more robust discounting would be possible.

Note also that, consistent with the 'proof-of-concept' nature of this project, this procedure was implemented to demonstrate the approach; as it turned out, insufficient yield data were available to support a robust PA-based implementation of 6ES at the within farm or block scales.

5.7. Spatial/statistical analysis and map display.

All map interpolation was done using VESPER (Minasny et al., 2005). *k*-means clustering and other statistical analysis was done in JMP (v.11.0.0, SAS Institute, Cary, NC, USA). All map display and map algebra was done using the ArcGIS software suite (v10.4; ESRI, Redlands, CA, USA).

6. RESULTS AND DISCUSSION

6.1. Yield variation at within-district scale

Irrespective of crop class, the patterns of variation in yield in any given year show marked spatial structure and follow a characteristic pattern when examined at district scale (Fig. 9). Thus, for example in 2009, those parts of the Herbert River district that were relatively low yielding for first ratoon sugarcane, were also low yielding for fourth ratoon sugarcane (Fig. 9). Similarly, areas that were relatively high yielding in plant crops were also high yielding for second ratoon. This result is to be expected, since it is consistent with the idea that yield variation is driven by variation in the land underlying the crop. Thus, when the normalised yield data for each crop class are pooled and a crop class-independent map generated (bottom right map in Fig. 9), it has the same characteristic pattern of spatial variation in yield as is seen in maps interpolated on a crop class basis. This is in spite of the decline in mean yield from plant cane to fourth ratoon (Fig. 10).
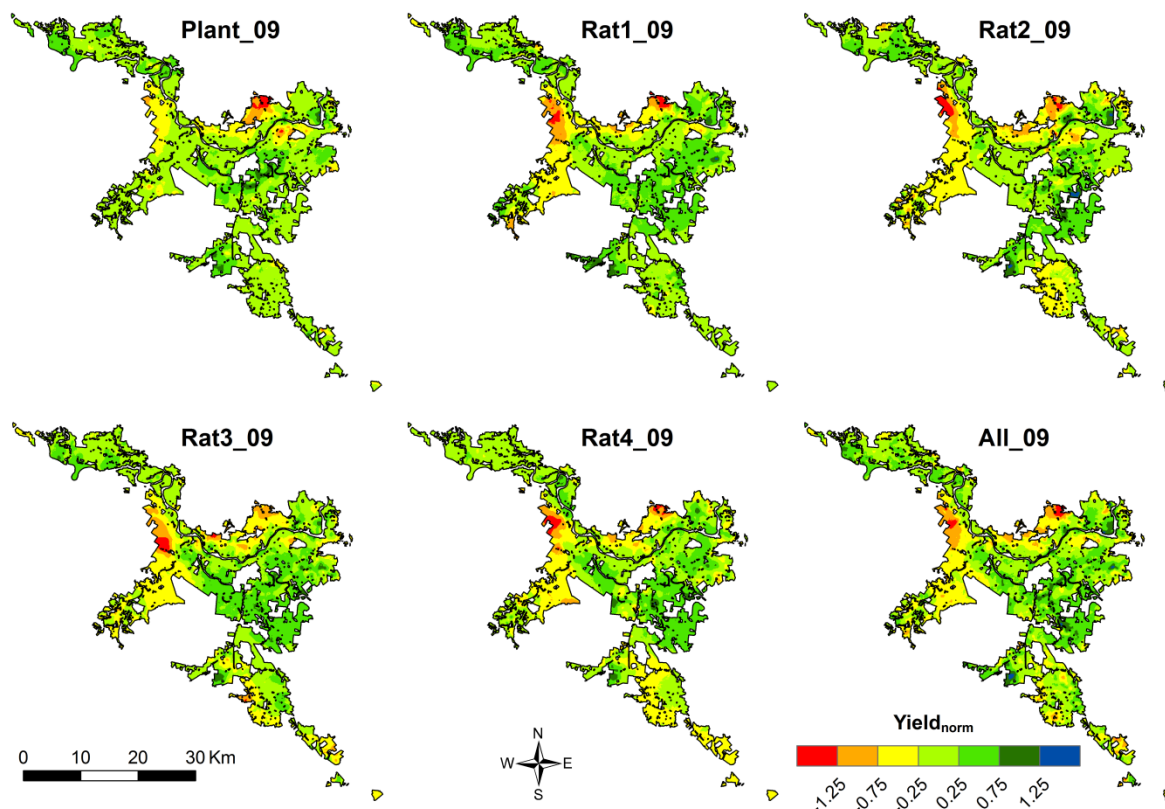
Figure 9. Variation in the yield of sugarcane in the Herbert River district in 2009 for plant and first to fourth ratoon (Rat1-Rat 4) crops. Also shown (bottom right) is a map summarising the variation across each of these crop classes. Note that the same legend applies to all maps and that the units of $Yield_{norm}$ are standard deviations; in 2009, the standard deviation in yield of first ratoon, for example, was 26.0 t/ha.
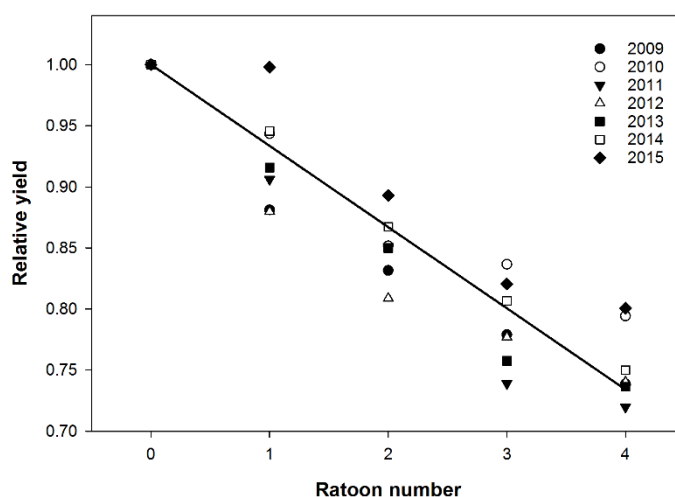
Figure 10. Decline in the relative mean district yield of sugarcane as a function of crop class (i.e. ratoon number) in the Herbert River district over the 2009-2015 period. Here, for each year, plant cane has been assigned a relative yield of 1, with ratoon crop mean yields expressed relative to the mean plant crop yield in the same year. The equation to the fitted line is: RY = 1 - 0.066 RN, R^2-adj = 0.89 (P<0.001), where RY and RN denote relative yield and ratoon number, respectively.
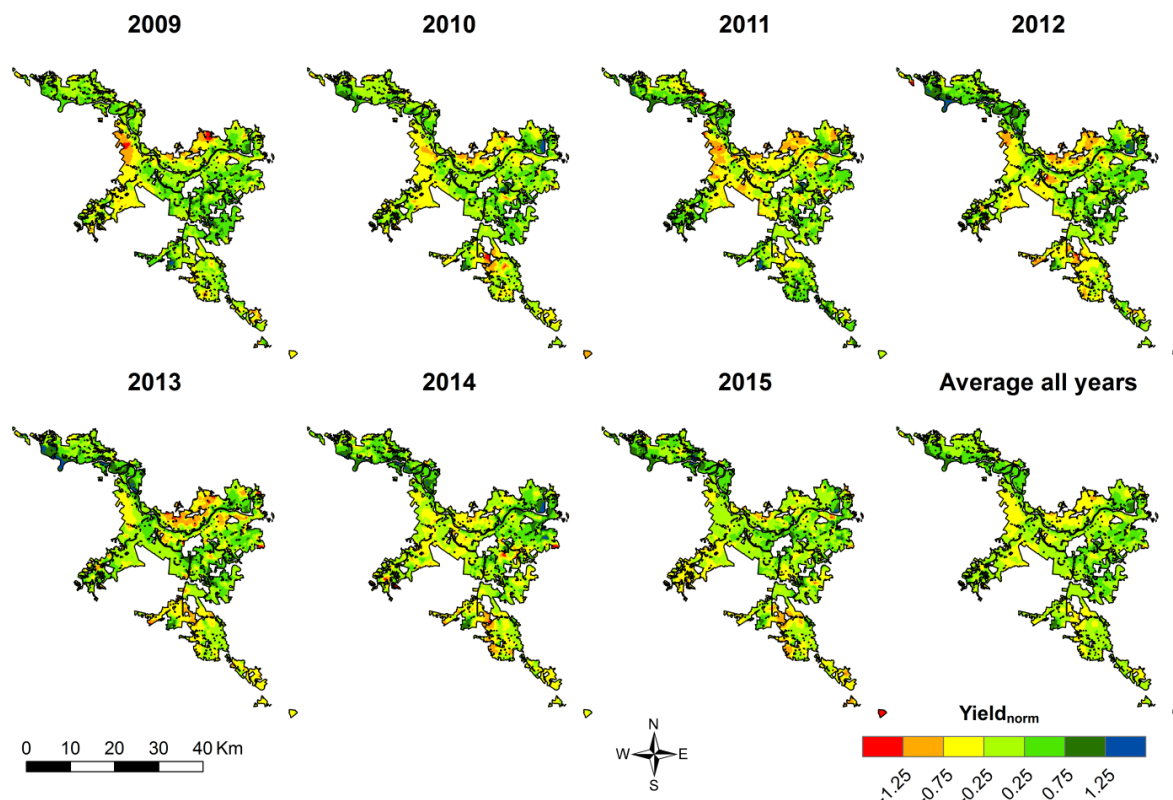
Figure 11.   Variation in sugarcane yield (plant cane to fourth ratoon) in the Herbert River district (2009-2015).

An almost identical result to that shown in Fig. 9 was obtained for each of the years 2009-2015 (not shown) such that when the crop class-independent maps (cf bottom right map in Fig. 9) are compared across years, these also show the same characteristic pattern of within-district yield variation (Fig. 11). Thus, when the crop class independent maps (Fig. 11) are clustered using *k*-means, zones of characteristic performance may be identified (Fig. 12). In the three cluster solution shown in Fig. 12, the low yielding cluster has a mean yield that is characteristically around 0.45 standard deviations below the district mean yield, the medium cluster has yields close to the district mean, whilst the high yielding cluster has mean yields that are characteristically 0.48 standard deviations above the district mean. Since, for a first ratoon crop, the mean standard deviation in yield across the seven years of the study was 24 t/ha, based on mill statistics, the results shown in Fig. 12 infer a difference of approximately 22 t/ha between the mean yields of the lower and higher yielding zones. Clearly, the yield potential of these clusters cannot be considered to be the same.

As indicated, 6ES defines DYP on the basis of the estimated highest average annual district yield. It is therefore of interest to examine variation in the maximum yield obtained at any location in addition to the mean. Accordingly, the crop class-independent maps (Fig. 11) were back-transformed to a first ratoon equivalent basis knowing the district mean yield and standard deviation of first ratoon crops in each year of the study. The resulting interpolated maps of first ratoon yield were then used to generate further maps of the mean, median and maximum yield of first ratoon crops over the 2009-2015 period (Fig. 13).

For all practical purposes, maps of mean and median yield are the same (Fig. 13) – as would be expected for normally distributed data. However, of particular interest is that the pattern of variation in maximum yield is essentially the same as the patterns of variation in mean or median yield; that is, characteristically low yielding areas also have the lowest maximum yield, as might be

	2009	2010	2011	2012	2013	2014	2015
🟧	-0.42	-0.48	-0.45	-0.55	-0.49	-0.39	-0.34
🟩	0.06	-0.01	-0.03	0.01	0.02	-0.04	-0.01
🟩	0.41	0.43	0.44	0.61	0.60	0.51	0.38
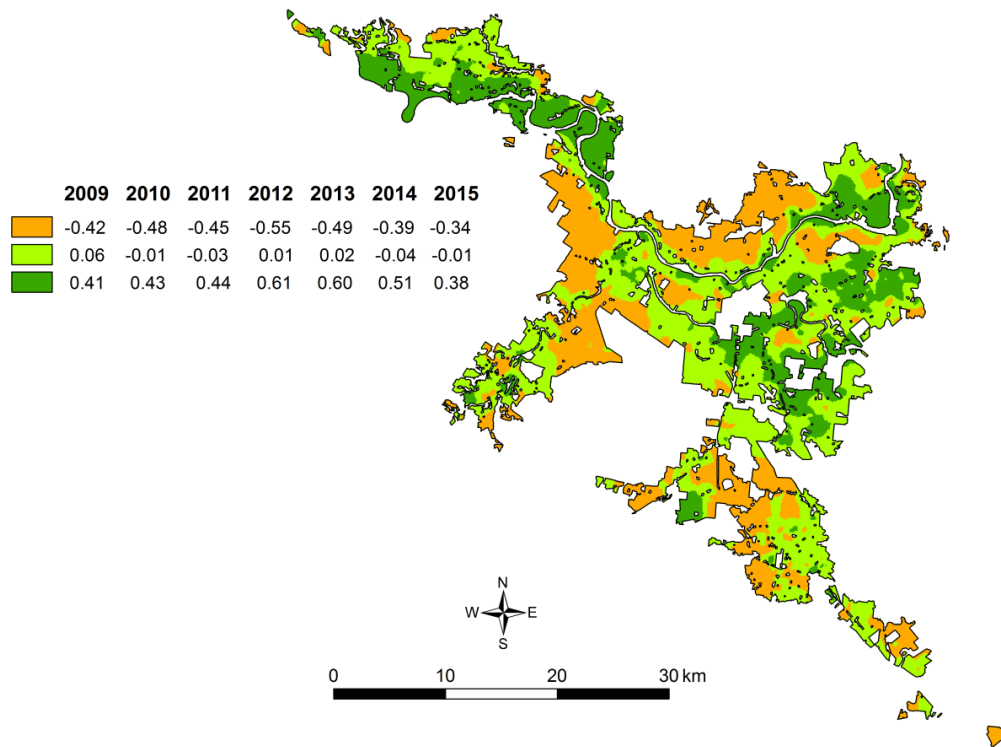
Figure 12. Results of clustering the season specific maps shown in Figure 11 using *k*-means (3 cluster solution). The values in the legend are the cluster means.
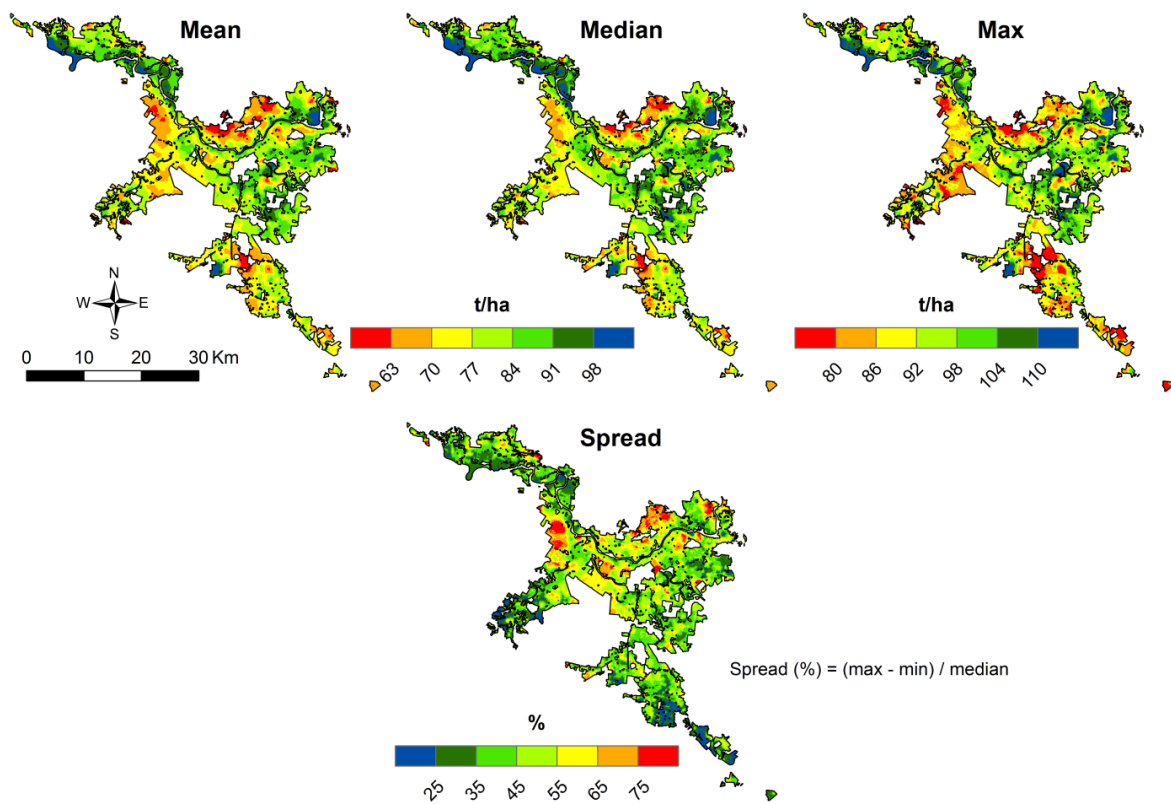
Figure 13. Variation in the estimated mean, median and maximum yield of first ratoon sugarcane in the Herbert River district (2009-2015) and the magnitude of this variation as denoted by the 'spread' statistic.

expected. In other words, Figs. 9 and 11 provide a robust basis for consideration of spatial variation in yield potential (as opposed to actual yield) at the within-district scale, with Fig. 12 offering one possible delineation of sub-regions for which different values of DYP might be assigned for the purposes of implementing 6ES. Also of interest is the contrast between Figs. 12 and 13 and the district 'Productivity Zones' used by HCPSL (Fig. 2) for the purposes of local extension and delivery of agronomic advice. HCPSL are currently re-considering these zones as a consequence of the results shown here.

Also shown in Fig. 13 is the 'spread', a statistic developed by Bramley (2005) for characterising within-vineyard variation in attributes of grape quality. 'Spread' is defined as the range in variation (i.e. maximum-minimum) expressed as a percentage of the median value of the attribute of interest. Fig. 13 shows that, whereas the consistently low yielding area at the southernmost part of the Herbert River district (near Bambaroo and Rollingstone) has a low 'spread' value (i.e. consistently low yield with little variation about the mean), other low yielding areas, such as in the north-central area (near the Seymour River) show greater variation about their otherwise low mean. Since climate is the major driver of seasonal variation in sugarcane yield (Muchow et al., 1997; Everingham et al., 2003), one possible interpretation of these observations is that low yielding areas with low values of 'spread' are constrained by non-climate factors (e.g. a soil constraint such as salinity, sodicity or low plant available soil water), whereas low yielding areas with a high 'spread' are more constrained by climate-related factors. Such an explanation makes sense here, since Bambaroo and Rollingstone are both dry and characterised by sodic soils, hence low yielding, whereas the Seymour River area is characteristically wet and its heavier, more clayey soils are subject to 'wet season' waterlogging and flooding – which only occurs in wetter years.

An alternative to the cluster analysis (Fig. 12), is to consider the temporal stability of patterns of yield variation in the context of yield probability surfaces (Diker et al., 2003; Bramley and Hamilton, 2004). Thus, in Fig. 14 the likelihood of either achieving a yield that was 5% greater than the district
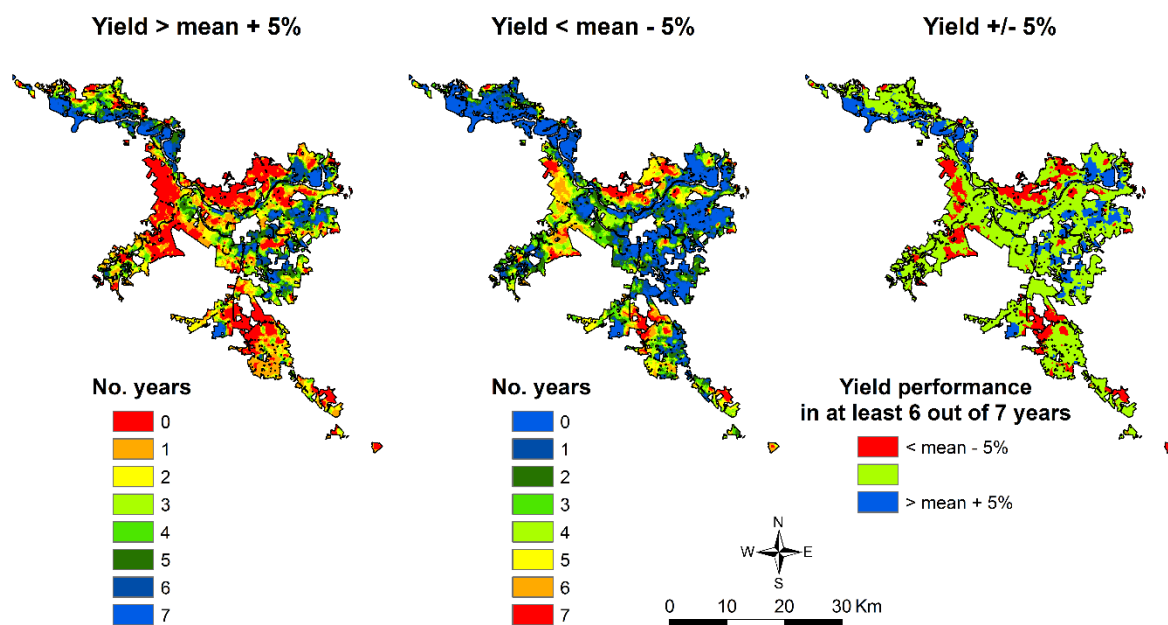
Figure 14. Probability surfaces for 'target' yields of either 5% greater or less than the district mean yield of first ratoon based on the number of years in the period 2009-2015 in which the target was achieved. Also shown in the right hand map are those areas which consistently yielded either 5% above or below the mean in at least 6 out of the 7 study years.

mean, or of obtaining a yield lower than 5% below the district mean is examined. Those parts of the Herbert River district that rarely attain a yield greater than 5% above the district mean, are also those that generally fail to yield more than 5% below the district mean. These are also the parts of the district identified as being in the low yielding 'zone' in Fig. 12. Conversely, those parts of the district that are the highest yielding in most years, are never the lowest yielding and correspond to the higher yielding zone in Fig. 12. Areas that are seen as somewhat inconsistent performers (Fig. 14) are those that yield close to the district mean (Fig. 12).

Over all study years, the district mean yield of first ratoon, based on mill statistics, was 79.3 t/ha, so Fig. 14 can be viewed as showing the likelihood of yielding either greater than approximately 83 t/ha or less than 75 t/ha in first ratoon. Obviously, this 8 t/ha difference is not large, something which is doubtless a consequence of the smoothing that is implicit in the kriging process, and of the use of normalised data based on all crop classes and a back-transform to a first ratoon equivalent. As a means of exploring this further, the mean actual annual yields (as opposed to interpolated/back-transformed) of first ratoon cane for each of the zones shown in Fig. 12 were calculated using the mill statistics for all sub-blocks whose centroids fell within the areas of the identified clusters. The significance of differences between these means was tested using the Tukey-Kramer test (Table 1).

For every year of the study, the mean yields of the low, medium and high yielding clusters were significantly different ($P<0.05$) when calculated from actual, rather than estimated, first ratoon sub-block yields, even though the standard deviations were high (Table 1) – equivalent to approximately 30-35% when expressed as coefficients of variation. This large degree of variability is no doubt due to differences in management between farms/farmers, which may be attributable to a range of factors including farmer skill (Stringer et al., 2016). Nonetheless, in spite of this within-cluster variation, the spatial structure exhibited in Figs. 9 and 11-14 is still readily identified and so may be regarded as robust. Thus, the data in Table 1 reflect that, on average over the period of the study, the difference in yield between 'high' and 'low' cluster blocks was 27.7 t/ha, that between 'high' and 'medium' clusters was 13.4 t/ha and the 'medium' and 'low' yield difference was 14.2 t/ha. Thus, the important point which emerges from this analysis and the maps presented in this section, is the consistency in the spatial structure/patterns of variation and the conclusion that some parts of the Herbert River district are inherently divergent from the mean. This fact calls into question the merit of a single DYP.

Table 1.   Mean cluster yields of first ratoon cane (t/ha) calculated from mill data (c.f. interpolated maps) for the clusters shown in Fig. 12. For any year, values not connected by the same letter are significantly different ($P<0.05$).

Year	Low cluster		Medium cluster		High cluster	
	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
2009	69.2c	24.15	85.9b	23.23	98.1a	23.66
2010	73.9c	23.02	90.6b	23.64	104.0a	22.35
2011	45.0c	20.88	57.2b	21.45	71.5a	21.74
2012	58.5c	20.07	76.8b	21.90	94.6a	21.51
2013	63.7c	21.55	80.6b	20.75	96.6a	20.42
2014	71.3c	20.36	82.1b	20.14	94.0a	20.19
2015	80.6c	20.71	88.8b	20.72	97.1a	21.11

6.2. Implications of variation in yield at the within-district scale for implementation of 6ES

The results presented in section 6.1 show that there is a marked spatial variation in yield in the Herbert River district, and that the patterns of this variation are stable across seasons and crop class. Importantly, the patterns of variation seen in all of the maps in Figs. 9 and 11-14, aside from the 'spread' map (Fig. 13), are similar, a result that lends weight to the idea that there is no such thing as a single potential yield that applies equally to all parts of the district. The results therefore provide a basis for improving on the use of DYP as input to 6ES and, for those Herbert growers who have not yet adopted PA for the fine-tuning of fertiliser management at the within-block or -farm scales (See section 6.3), a basis for a more location-specific application of 6ES. Since DYP, as used in 6ES, is based on the estimated highest average annual district yield, the map of variation in maximum yield obtained (Fig. 13) might provide a useful basis for location-specific estimates of potential yield; this is reproduced as Fig 15.

Figure 16 shows a map of 'base' N rate derived from Fig. 15 and the 6ES assumptions of N requirement. This base N rate (Fig. 16) was then discounted using the N mineralization potential derived from either soil survey (Fig. 6) or soil testing (Fig 8). The results are the suggested rates of N application shown in Fig. 17; note that in Fig. 17a, the reduced coverage reflects the extent of the 'Andrew Wood ' soil survey. As can be seen, Figs. 17a and 17b appear to produce similar results, with the most obvious difference being a reduction (~10 kg N/ha on average) in the recommended N rate, when the soil test data (Figs. 7 and 8) are used for discounting due to N mineralisation potential in lieu of the soil data of Wood et al. (2003). This reduction is greatest in the central part of the district around Trebonne. It is beyond the scope of the present work to investigate the possible cause of this difference in the context of changes in soil organic matter levels. Suffice to say that the 'Andrew Wood' soil survey commenced at around the time that green cane trash blanketing begun
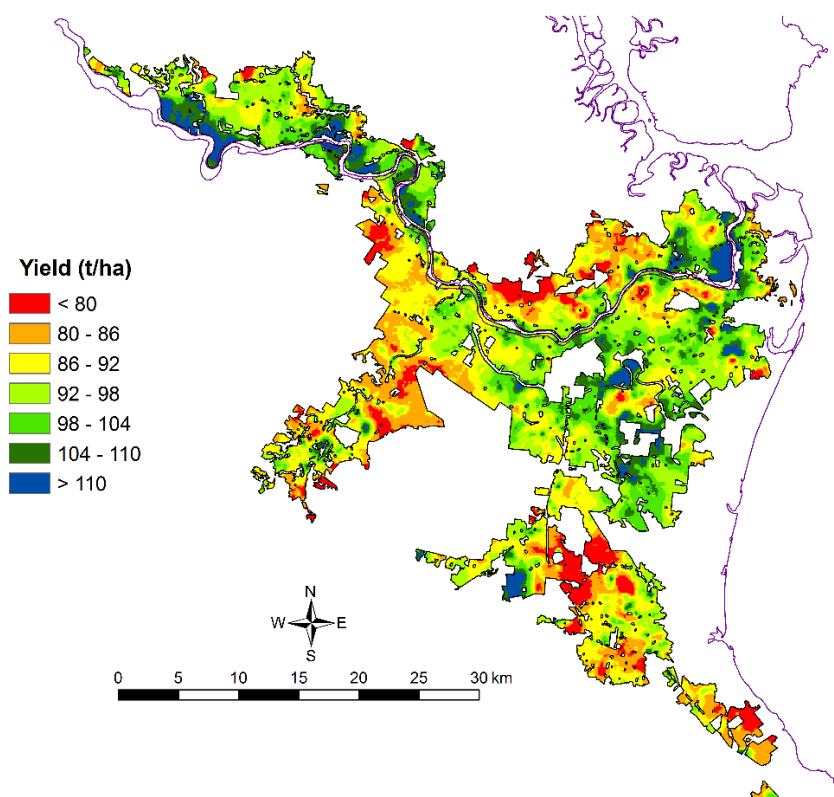
Figure 15.   Variation in the estimated maximum yield of first ratoon sugarcane in the Herbert River district (2009-2015) as an indicator of variation in yield potential.
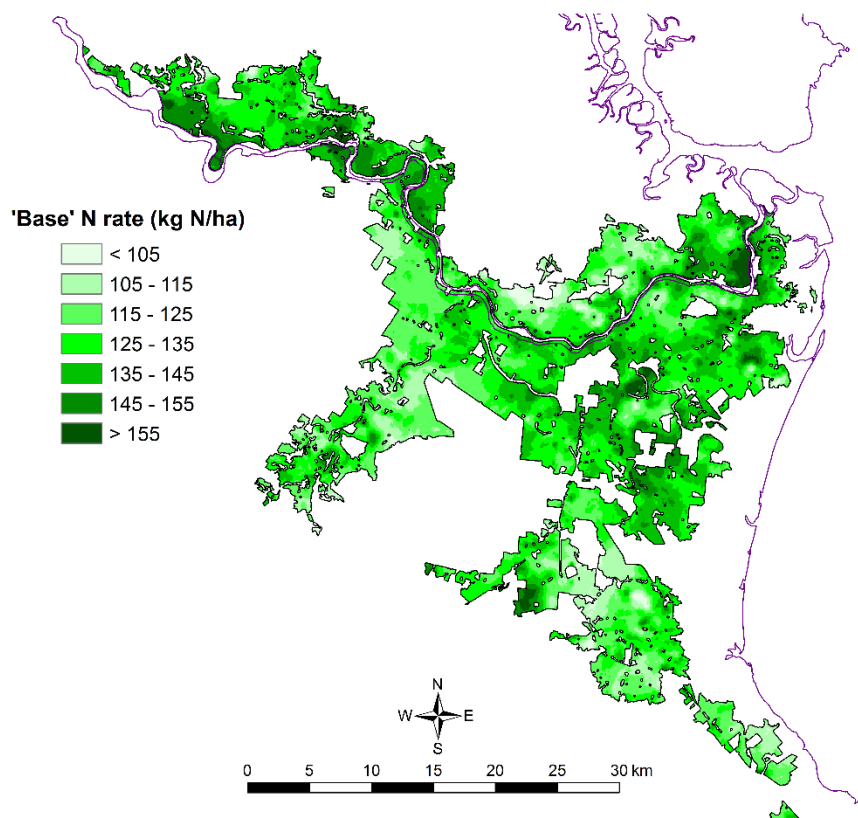
Figure 16.   'Base' rate of N application derived from Fig. 15 using SIX EASY STEPS.

to be used. There are good arguments in favour of preferring either Fig. 17a or b; Fig 17a reflects a robust and very careful soil survey which, in particular, considered soil texture and landscape position, and a large number (~1000) of soil analyses, albeit constrained by mapped soil boundaries; nonetheless it considers the soil *in toto*. Fig. 17b relates simply to 619 soil analyses that are unrelated to the soil mapping shown in (Fig. 3), but has the advantage of being more contemporary. Whether 619 soil tests can be considered sufficient for the purposes illustrated here is worthy of further investigation; clearly, this number of soil tests reflects a much lower *support* (Webster and Oliver, 2007) for Fig. 8 and maps derived from it, than the yield maps shown in Fig. 9 and especially in Fig. 11.

When 6ES is implemented under typical current practice based on a DYP of 120 t/ha, the base rate of N to be applied is 160 kg/ha. Discounting this using either Figs. 6 or 8 leads to the recommended N rates shown in Fig. 18. By subtracting Fig. 17a from Fig. 18a and Fig. 17b from 18b, the potential saving in N application can be calculated (Fig. 19) when BYP (Fig. 15) is used as input to 6ES rather than a uniform DYP of 120 t/ha.

It is important to note from Fig. 19, that some parts of the Herbert River district are likely under-fertilized under current practice, that is, when fertilizer recommendations are made using 6ES and the assumption of a DYP of 120 t/ha. However, examination of the values which underpin Fig. 19a suggests that on average, Herbert growers could potentially reduce their N fertilizer application by 26 kg N/ha/y. Over the area covered by Fig. 19a, this reduction represents an annual total of 1,230 t N/y or 1,968 t N/y if extrapolated to the entire cane growing area. If it is assumed that N as urea costs $0.90/kg, this equates to a potential saving to growers on N input costs of $23 ha/y. Application of an identical analysis to Fig. 19b suggests the same average reduction in N inputs of approximately 26 kg N/ha/y could be achieved. For the entire Herbert cane growing area, this

a.

b.
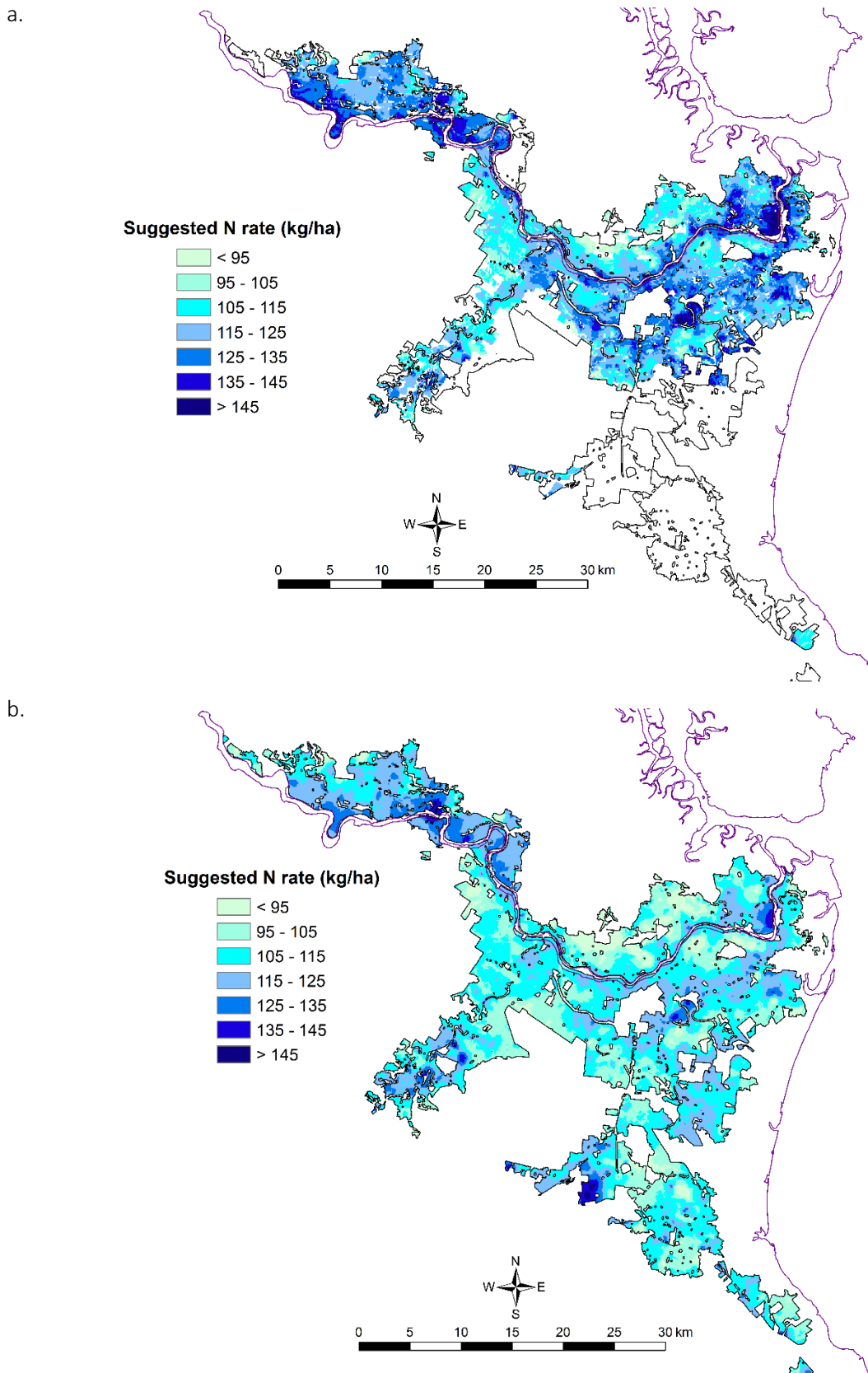
Figure 17.   Suggested rate of N application when a block yield potential (Fig. 15) is used as input to SIX EASY STEPS discounted for N mineralization potential when estimated from either (a) the 1:5,000 soil survey (Fig. 3) or (b) 619 soil tests conducted in 2014-16 (Figs. 7-8).

a.

b.
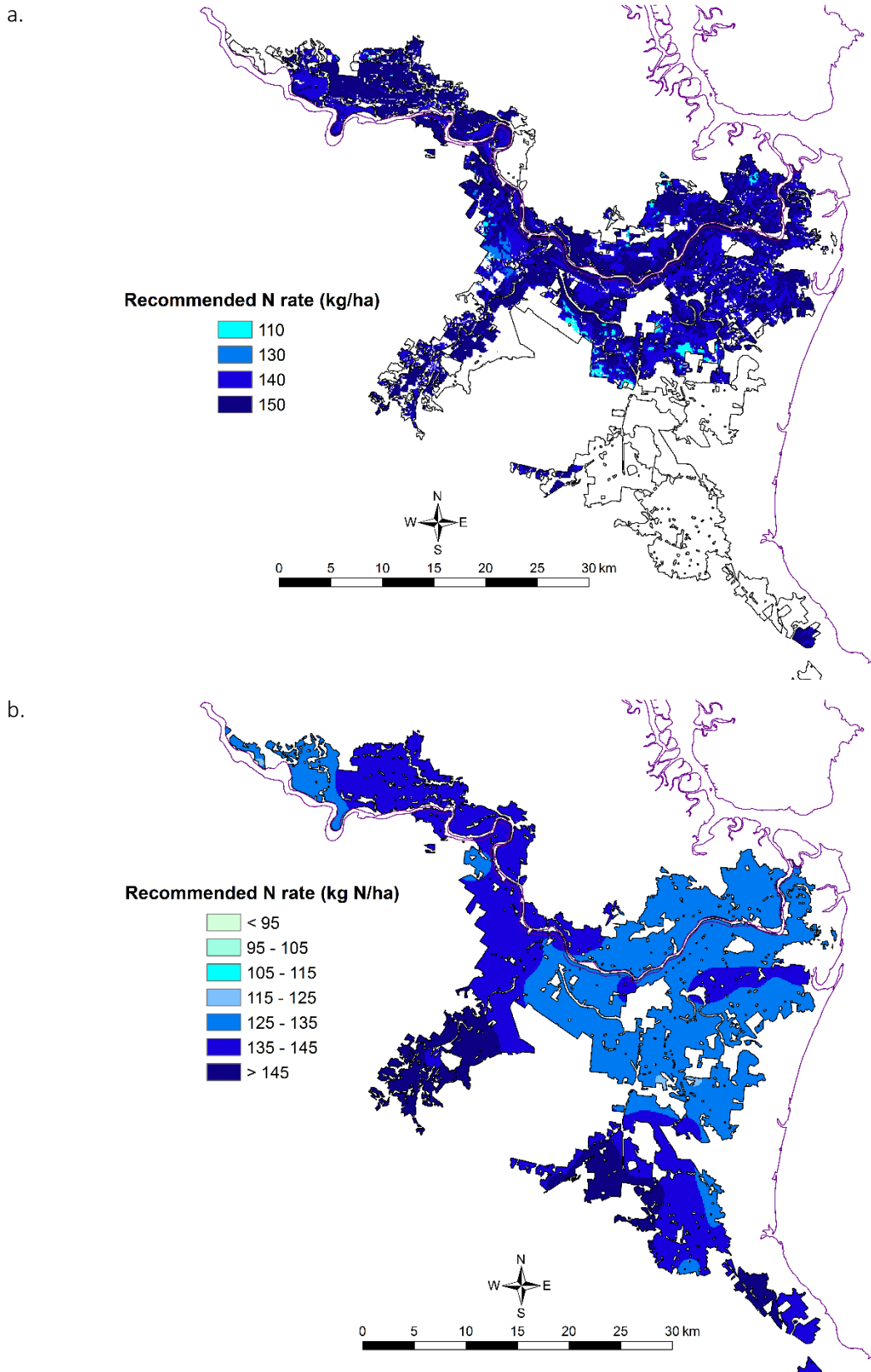
Figure 18.   Recommended rate of N application derived from SIX EASY STEPS when a district yield potential (120 t/ha) is used with discounting for N mineralization potential derived from either (a) the 1:5,000 soil survey (Fig. 3) or (b) 619 soil tests conducted in 2014-16 (Figs. 7-8).

a.

b.
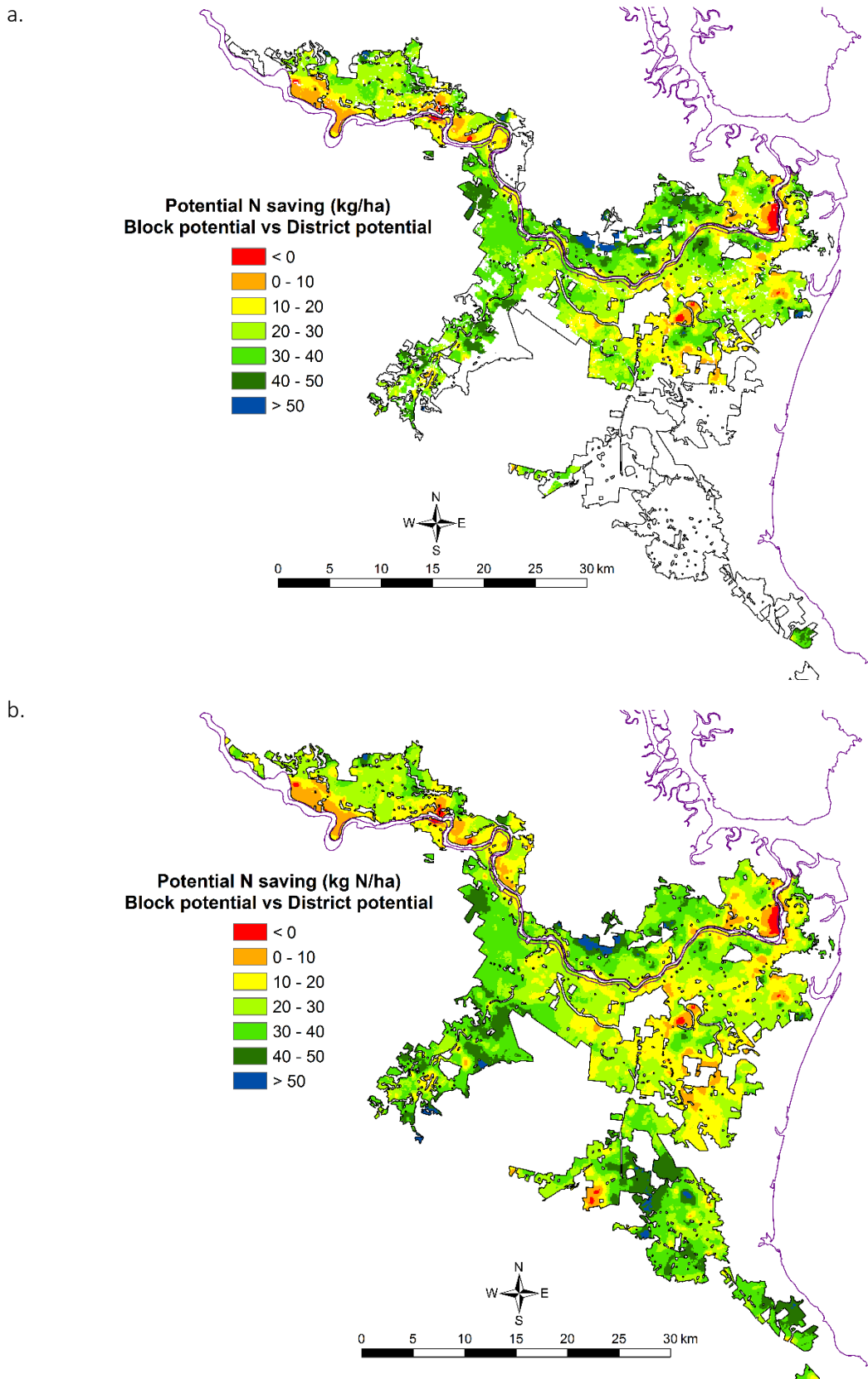
Figure 19.   Potential savings in applied N when application rates are determined using SIX EASY STEPS and block yield potential (Fig. 15) rather than district yield potential (120 t/ha) and discounting for soil N mineralization potential derived from either (a) the 1:5,000 soil survey (Fig. 3) or (b) 619 soil tests conducted in 2014-16 (Figs. 7-8).

equates to a total annual reduction in applied N of 1,980 t N representing potential savings in annual input costs of approximately $1.8M in the district as a whole.

Because this project is a desk-study, we can only make inferences about N use efficiency; ideally this should be measured in field trials across a range of soils and rainfall regimes. In this connection, we note that, in addition to the spatial variation in yield potential and N mineralization which has been factored into this analysis, spatial variation in N loss (leaching, volatilization), crop N uptake and even crop N demand is possible and likely in both space and time (Thorburn et al., 2017). With the important caveat that these things have not been assessed, we can nevertheless infer the likely implications of our analysis for NUE, noting that Figure 17 derived from an analysis of potential yield, and therefore that, the suggested reduced N rates ought to lead to no net reduction in yield assuming that the SIX EASY STEPS algorithms are robust.

Fig. 19 assumes that all growers currently follow SIX EASY STEPS recommendations using DYP which we know is unlikely to be the case; anecdotal evidence suggests that many growers fertilize at higher rates. Nevertheless, we can infer from a simple analysis at district scale that there is potential to improve NUE when 6ES is followed using BYP rather than DYP as follows. The average recommended rate of N application in Fig. 18a is 146 kg/ha. If the yields shown in Fig. 15 were to be achieved, the average yield would be 93 t/ha. Thus, assuming no loss of N from the system, district N use efficiency may be estimated at approximately 0.64 t cane/kg N applied. The average suggested N application rate in Fig. 17a is 120 kg N/ha. Again, assuming an average yield of 93 t/ha and no loss of N from the system, NUE may be estimated at approximately 0.78 t cane/kg N applied. This represents an improvement of around 22% in NUE. However, since this simple analysis ignores N loss pathways, it is considered more appropriate to evaluate the merits of the revised fertilizer recommendations simply in terms of the reduced input cost incurred by growers. Over the area covered by the analysis shown in Fig. 19b, the potential N savings amount to an opportunity for Herbert River cane growers to collectively save $1.8M annually on N fertilizer input costs. Of course, a better understanding of N loss pathways and their possible impact (including with respect to spatial variability) on application of SIX EASY STEPS would be valuable for optimizing N use efficiency.

Recently, Webster et al. (2016) used knowledge of yield variation at the within-block scale, obtained through yield mapping, coupled with measurement and modelling of the N budget, to demonstrate that under conventional uniform fertiliser management, areas of cane blocks that are low yielding are those that pose the greatest risk of N loss offsite. This is because they are the areas of lowest NUE. It is therefore inferred that, when fertiliser recommendations are made on the basis of DYP, characteristically low yielding areas within a cane growing region will be those where NUE is low and therefore where the risk of loss of N offsite is greatest. A move to using BYP rather than DYP in implementing 6ES could therefore be beneficial in reducing the risk of N loss to the Great Barrier Reef.

6.3. Within-farm scale yield mapping and implementation of 6ES

Analysis of yield maps at the farm and block scales followed an identical logic to that described in the preceding sections and is illustrated by Fig. 20. In this example, a precision agriculture-based derivation of potential 'management zones' (c.f. Fig. 1) has been followed. In the case of the block scale analysis (Figure 20a), two zones are identified in which, over the period for which yield maps are available, maximum yields (c.f. Fig. 15) of 110.3 and 129.5 t/ha were attained in the low and high yielding zones. When the yield variation is mapped at farm scale, and a two zone solution is again used, the maximum attained yields are assessed somewhat differently at 89.3 and 103.0 t/ha in the low and high yielding zones.
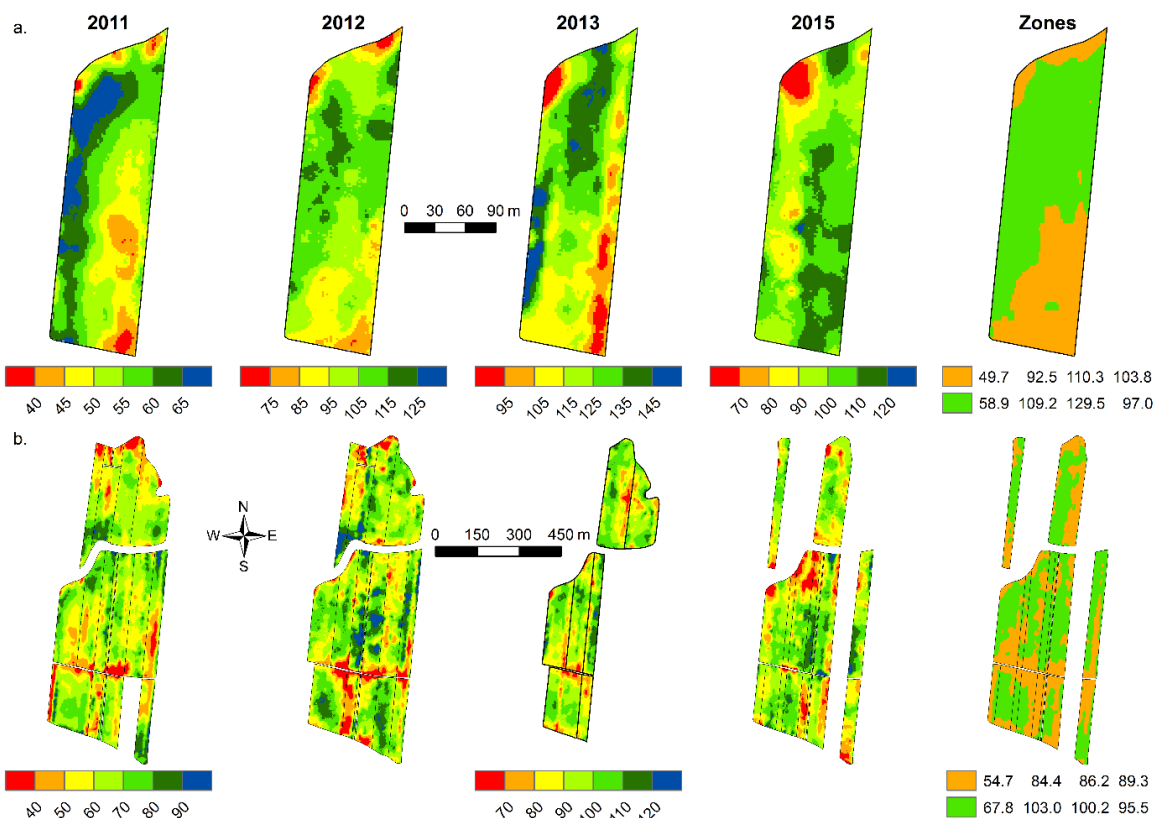
Figure 20.   Yield map analysis for a farm in the Herbert River on (a) a block, and (b) a farm basis.

The soils on this farm are varied; in the block shown in Figure 20a, they comprise the 'Terrace Silts' and 'Silty Clays' of Wood et al. (2003), both of which are in the 'low' category for N mineralization potential (discount to N application of 6.25%). However, the farm more broadly is also underlain by sections of 'Fine Red Sandy Loam', 'River Bank' (both also in the 'low' category for N mineralization potential) and a small area to the south east which is underlain by 'Clay'; this latter soil is in the 'medium-low' N mineralization potential category leading to a discount to the N application rate of 12.5%. Because of the mismatch in scale between the yield monitor-derived data shown in Fig. 20, which is mapped onto pixels of 2 m x 2 m, and either the 1:5,000 soil survey data (Fig. 3) or the interpolated map of soil C derived from soil testing (Fig. 8 – mapped onto pixels of 100 m x 100m) along with likely error in the position of soil type boundaries in the soil survey given its 1:5,000 scale, and also in the interests of simplicity, it is assumed here that the 6.25% N mineralization discount applies to the entire farm. With these assumptions in place, Fig. 20a infers suggested N application rates to the low and high zones respectively of 141 and 159 kg/ha; at the farm scale, these rates reduce to 117 and 134 kg/ha. The low and high zones in the block shown in Fig. 20a comprise 1.08 and 1.42 ha, leading to a net application of N to the block of 378 kg N, which is equivalent to 151 kg/ha overall. Ironically, this is slightly more N than would be applied based on the status quo using district yield potential (150 kg/ha). In terms of the farm scale zonation, the low and high zones comprise 10.27 and 13.78 ha, leading to a net N application to the farm of 3,052 kg, equivalent to 127 kg/ha overall.

Fig. 20 highlights a number of potential difficulties with the farm and block scale approach. First, this is a small farm of only 24.1 ha; the block shown in Fig. 20a is also small at only 2.5 ha. Experience in the wine sector (vineyards have similar dimensions to cane blocks and the yield mapping protocols for winegrapes and sugar are based on very similar principles) strongly suggests that 2.5 ha is right at the low end of block size for which implementation of PA (i.e. targeted management) would be justified. In practice therefore, the farm scale zonation is a more realistic proposition for the farm

shown in Fig. 20. Second, Fig. 20 derives from only 4 years of data (i.e. less than a typical crop cycle), and the data that are available do not provide a complete coverage in each year, presumably due to yield monitor malfunction and or use of fallow. Third, in contrast to the stability in patterns of yield variation mapped at regional scale using block data (e.g. Figs. 9, 11), Fig. 20 shows the data to be much less stable at both block and farm scale in this example; this also contrasts with what was seen in the Burdekin case study developed as part of CSE022 (Bramley et al., 2014, 2017). Whilst the analysis derived from Fig. 20 is consistent with that derived from Fig. 15 in that it highlights both the possibility of small areas needing similar N rates to those recommended using DYP, as well as significant reductions over wider areas, we treat it with circumspection given concerns relating to the amount and quality of yield monitor data and our expectation that patterns of yield variation show greater stability between seasons.

It was in order to examine the extent to which Fig. 20 reflects a general difficulty with analysis at the within-farm scale that we conducted the work described in section 5.2 using a sub-sample of farms from the yield clusters identified in Fig. 12. Fig. 21 shows the location of the farms used in this part of the work, whilst Figs. 22-24 illustrate analyses similar to that shown in Fig. 20 for exemplar farms from each of the low, medium and high yielding clusters identified in Fig. 12. A significant constraint to these analyses, notwithstanding the considerable effort of HCPSL in coordinating yield monitoring over many years, is the lack of data continuity for the same block or farm areas. As Table 2 notes, the yield mapped area is generally considerably less than the whole farm area, due to (a) not all sub-blocks being harvested in any one year, (b) yield monitor data missing, too sparse or with a yield sensor coefficient of variation (CV) so low that it indicates likely sensor failure, (c) mill data (tonnes or area) missing, or (d) blocks with either a ratoon number > 4 or standover cane which was excluded from processing. These kinds of problems are undoubtedly exacerbated by the common
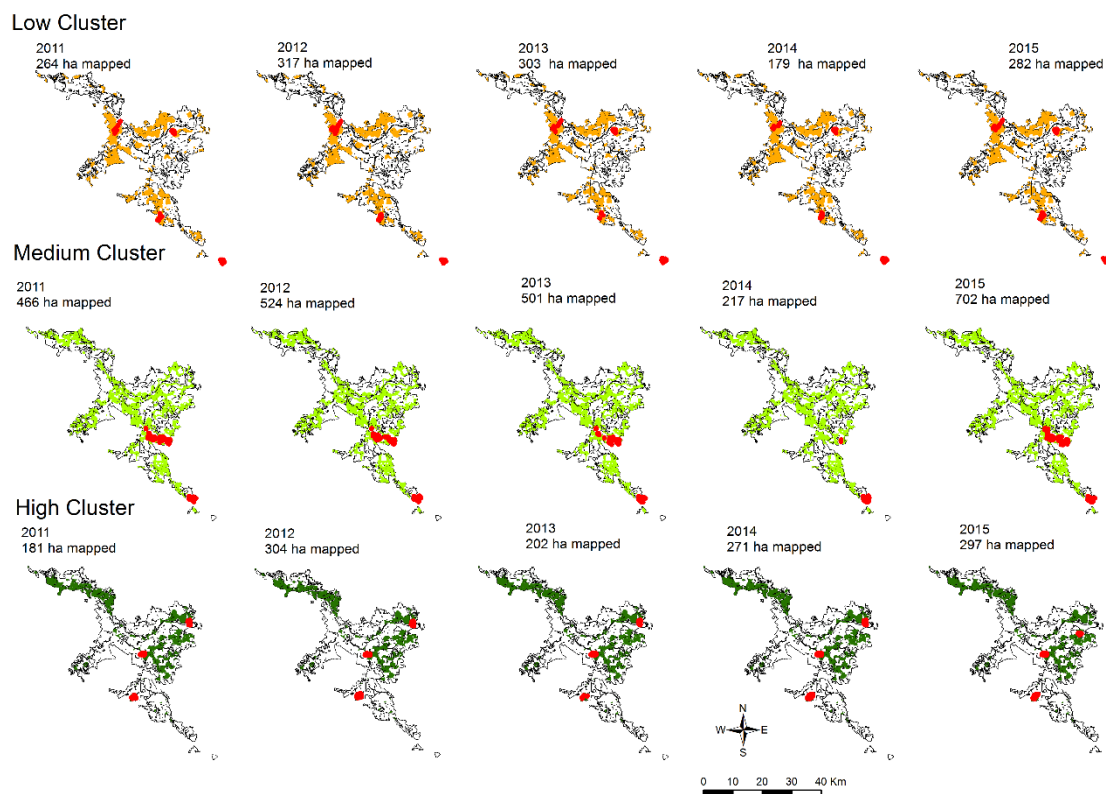
Figure 21.   Locations of Yield map analysis for a farm in the Herbert River on either (a) a block, or (b) a farm basis.
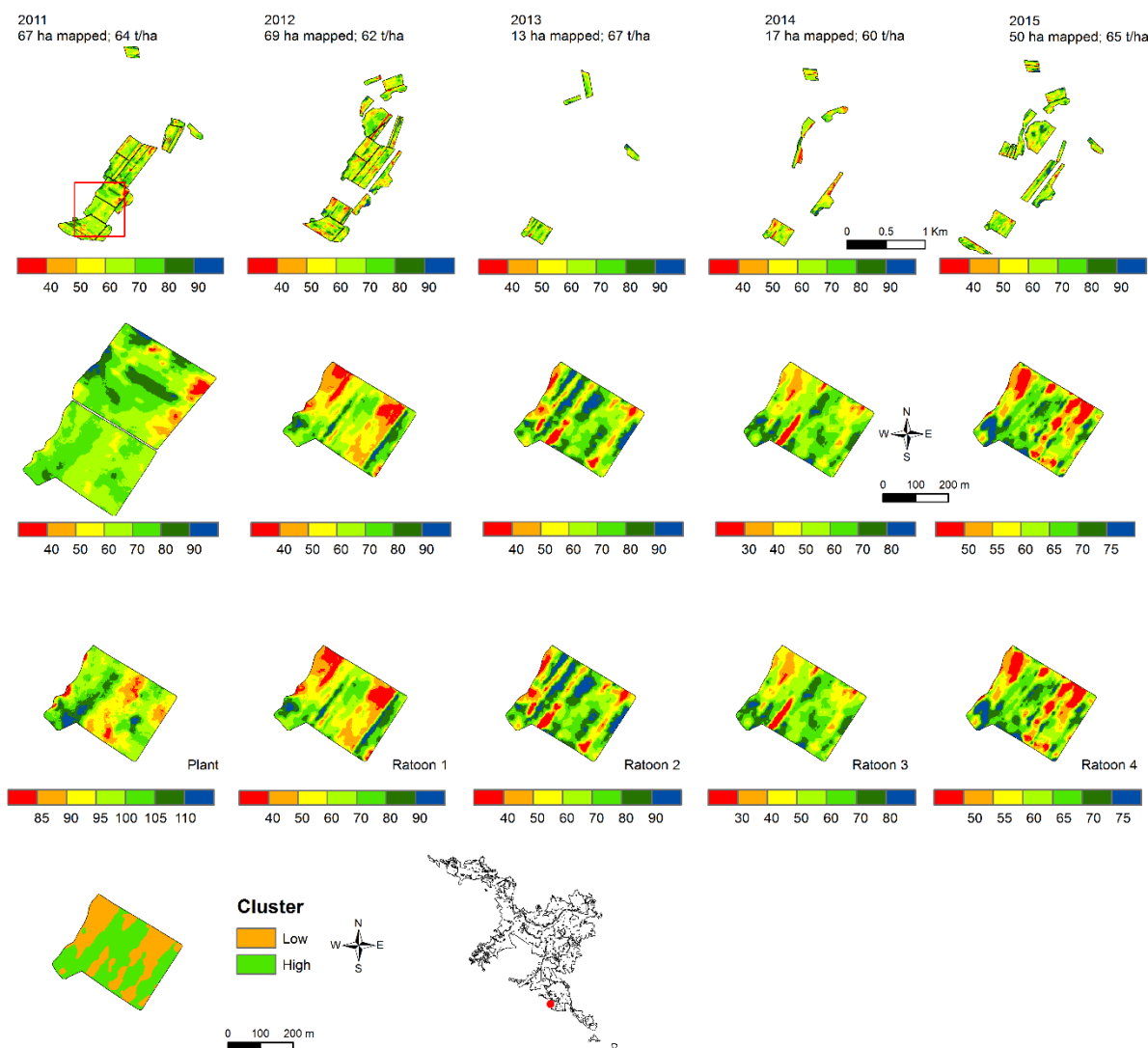
Figure 22. Analysis of yield variation at the farm (top row), block (second row) and sub-block (third and fourth rows) scales for an exemplar farm from the low yielding cluster identified in Fig. 12. This is farm no. 3 in Table 3. The text at the top of each year column indicates the area for which mappable data were available, and the mean yield of first ratoon for that area. Note that the colour legends are not necessarily the same for each map.

tendency for both block boundaries and their identifying numbers to change when blocks are re-planted, presumably due to farmers changing varieties, the within-block variety mix changing leading to a re-definition of sub-block areas, or significant time gaps in the harvesting process which may sometimes lead to a break of several weeks between the commencement of harvest in a given block and its completion (Bramley and Jensen, 2013). Table 2 illustrates the consequences of this kind of discontinuity for yield map availability as it affected the analyses reported here, whilst Table 3 summarises the results of our analysis of farms and sub-blocks from the clusters shown in Fig. 12 and illustrated by Figs. 22-24.

Important Note: Table 3 is produced for purely illustrative purposes to show the process of refining fertilizer N rates on a zone basis using yield mapping and soil testing; based on the available data which, as with Fig. 20, we do not regard as deriving from a sufficient number of years, we do not consider the zone delineation (Figs. 22-24) to be robust. It also lacks supporting soil or terrain information (e.g. Fig. 1). The potential N savings listed should therefore be regarded as purely indicative.

Notwithstanding this important caveat, along with the desirability of conducting field experiments on-farm to guide refinement to fertilizer management at the within-farm and -block scale, Table 3 is useful in highlighting that the greatest risk of excess N application when fertilizer rates are based on DYP is on lower yielding farms, an observation consistent with that of Webster et al. (2016). Until such time as sufficient robust yield map data are available to support zone delineation and variable rate fertilizer management, Table 3 highlights the potential benefits, in terms of reducing the risk of N loss offsite, of using a BYP-based application of 6ES as illustrated in sections 6.1 and 6.2.
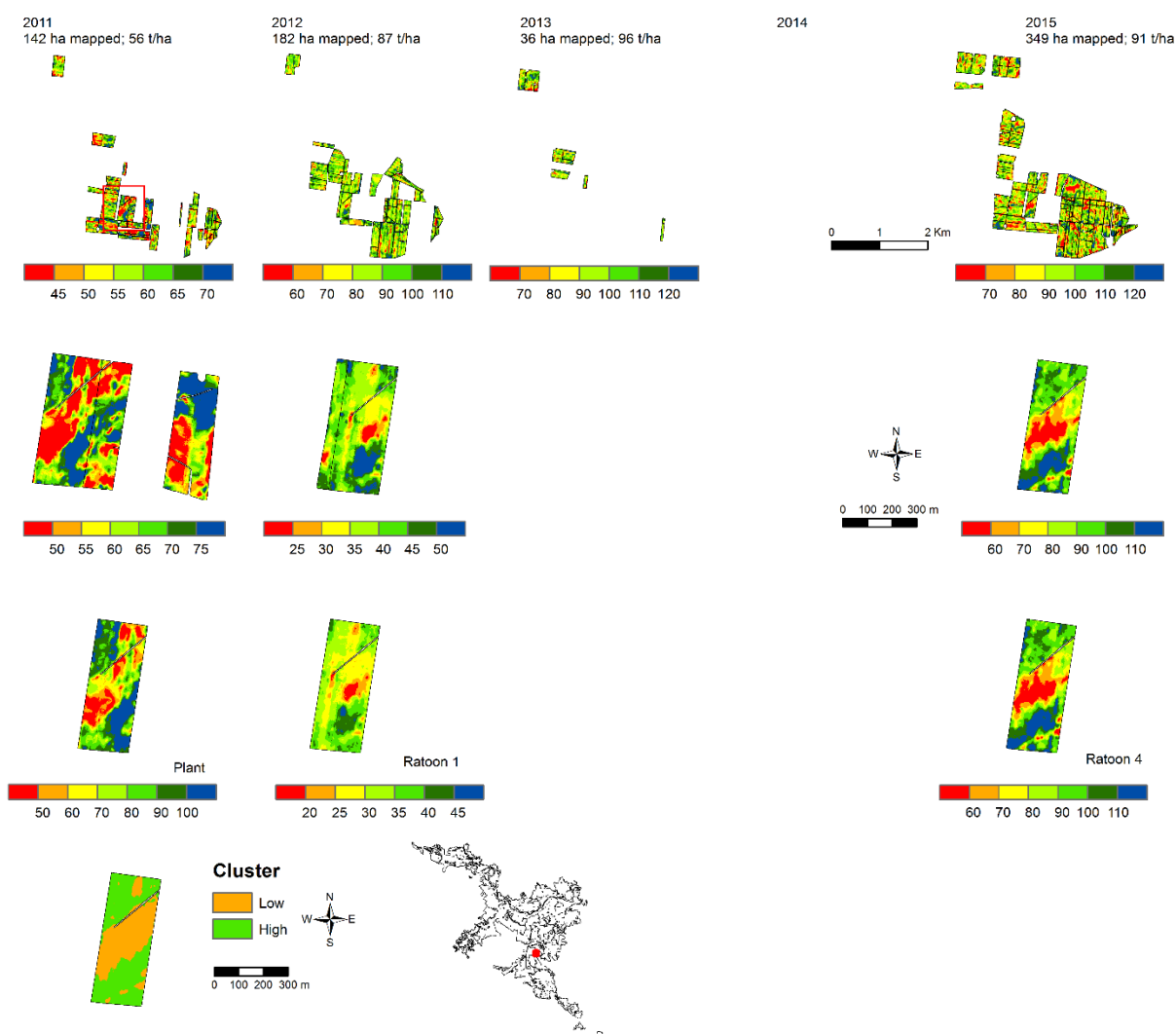
Figure 23.   Analysis of yield variation at the farm (top row), block (second row) and sub-block (third and fourth rows) scales for an exemplar farm from the medium yielding cluster identified in Fig. 12. This is farm no. 8 in Table 3. The text at the top of each year column indicates the area for which mappable data were available, and the mean yield of first ratoon for that area. Note that the colour legends are not necessarily the same for each map.

2011
47 ha mapped; 83 t/ha

2012
94 ha mapped; 97 t/ha

2013
109 ha mapped; 97 t/ha

2014
100 ha mapped; 80 t/ha

2015
104 ha mapped; 88 t/ha

Plant   Ratoon 1   Ratoon 2   Ratoon 3   Ratoon 4
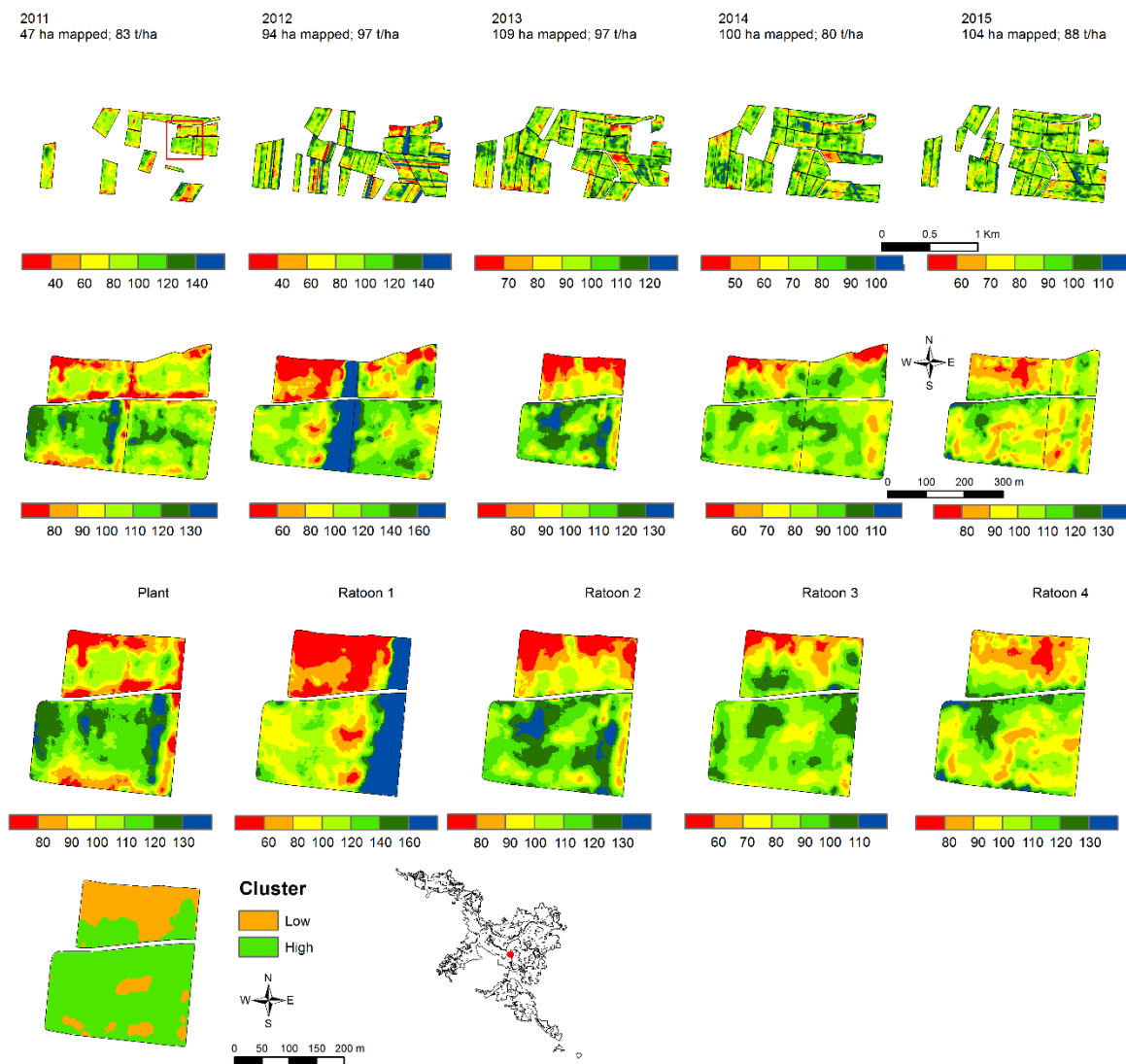
Figure 24. Analysis of yield variation at the farm, block and sub-block scales for an exemplar farm from the high yielding cluster identified in Fig. 12. This is farm no. 10 in Table 3. The text at the top of each year column indicates the total area for which mappable data were available, and the mean yield of first ratoon cane for that area. Note that the colour legends are not necessarily the same for each map.

Inspection of Figs. 20 and 22-24 shows that, based on the available data and in contrast to Figs. 9 and 11, there is apparently much less stability in patterns of yield variation at the within-farm scale than at district scale. Indeed, it is striking that having followed the process described in section 5.2, and given the coverage of the HCPSL yield mapping effort, we were only able to analyse 12 out of the 24 farms initially selected for the within-farm analysis. Only three of these had useable yield monitor data for each year in the 2011-15 period. Doubtless, there are many more farms in the Herbert River district with a complete yield monitor record; these were missed by the farm selection process chosen here (section 5.2). However, Jensen et al. (2010) and Bramley and Jensen (2013) have highlighted both the fallibility of the yield monitoring systems used to collect these Herbert yield monitor data and also their susceptibility to the vagaries of the multi-event harvesting process and to consignment errors. In this work, whilst we did not make use of the process described by Bramley et al. (2017) for filling in gaps in the yield map record (to do so would have entailed an enormous amount of additional work in the absence of an automated tool for this process), we have

Table 2.   Summary of yield map data successfully processed using the methodology described in section 5.2[A]

Farm	Cluster[B]	Mapped area (ha)					Ratoon 1 adjusted cane harvest (tonnes)					Calculated yield (t/ha)					Years missing
		2011	2012	2013	2014	2015	2011	2012	2013	2014	2015	2011	2012	2013	2014	2015	
1	L	35	65				1193	3364				34.4	51.9				3
2	L	22	109	91	41	133	1226	7478	5986	2787	10036	55.7	68.3	65.4	67.8	75.7	0
3	L	67	69	13	17	50	4302	4301	876	1003	3236	64.1	62.4	67.3	59.8	65.3	0
4	L	73	74	123	74	31	3844	4593	8837	5694	1573	52.5	61.9	72.0	76.7	50.4	0
5	L	67		76	46	69	2617		4285	3484	5315	39.2		56.5	75.0	77.0	1
6	M	110	26	225		114	5030	1808	15608		9179	45.5	69.6	69.5		80.3	1
7	M	96	94	89	10	45	4884	7307	6567	657	3961	51.0	78.1	73.9	68.1	87.9	0
8	M	142	182	36		349	7928	15773	3498		31772	55.7	86.7	96.1		91.2	1
9	M	117	223	151	208	194	8890	18794	11018	16306	13900	75.8	84.4	73.1	78.5	71.6	0
10	H	47	94	109	100	104	3935	9097	10552	7972	9118	83.5	97.0	97.1	79.5	87.6	0
11	H	62	105	80	75		4662	9471	6953	8462		74.6	90.3	86.6	113.3		1
12	H	71	105	31	96	108	7408	9526	3039	10872	12016	104.1	90.8	96.8	112.9	111.2	0

[A]In most cases the mapped area is far less than the whole farm area, due to (a) not all sub-blocks being harvested in any one year, (b) yield monitor data missing, too sparse or with CV too low indicating likely sensor failure, (c) mill data (tonnes or area) missing, or (d) blocks with either a ratoon number > 4 or standover cane which was excluded from processing.

[B]Here, 'cluster' refers to the district-scale yield zones identified in Fig. 12.

Table 3. Summary of within-farm scale yield analysis and potential implications for targeted fertilizer management using 6ES compared to current practice based on DYP[A].

Yield cluster[B]	Farm	HCPSL Prod. Zone[C]	Yield zone[D]	Area (ha)	Mean yield of 1st ratoon					Soil N mineralization discount (%)		Dominant soil[F]	Suggested N rate (kg/ha)			Potential saving[I] (kg N/ha)
					2011	2012	2013	2014	2015	HCPSL soil tests[E]	1:5,000 soil survey[F]		HCPSL soil tests[G]	1:5,000 soil survey[G]	DYP[H]	
Low	1	Lann. E	NA	17.0	33	**51**				12.5	6.25	Sandy clay	63	67	140	77
	2	Lann. E	L	3.2	43	**53**	49			14.3	6.25	River Bank	64	70	137	56
			H	4.8	60	**78**	75						94	102		
	3	Bamb. W	L	3.2	**63**	54	60	51	57	9.6	NA	NA	80		145	59
			H	4.0	65	70	71	66	**72**			NA	91			
	4	C-Roll	L	7.2	49	56		**63**	42	12.7	NA	NA	77		140	46
			H	4.8	58	65		**98**	63				120			
	5	F'home	L	4.7	39		58	**68**	68	19.3	6.25	Silty clay	89	77	145	47
			H	2.6	40		54	93	**94**	19.3	12.5	Clay	115	106		
Med	6	B'rock	L	15.3	44		**68**		63	15.2	NA	NA	81		136	38
			H	14.5	51		74		**98**	15.0			117			
	7	B'rock	L	2.7	47	74	69	69	**83**	17.0	NA	NA	97		133	31
			H	2.7	54	84	80	67	**93**	16.9			108			
	8	Helen's H	L	4.6	45	**77**			74	15.2	NA	NA	91		136	26
			H	6.0	64	95			**105**	14.6	NA	NA	124			
	9	C-Roll	L	3.3	**68**		62	61	58	9.9	NA	NA	86		144	43
			H	4.4	81		79	**89**	79	9.9	NA	NA	112			

Table 3.   Cont.

Yield cluster[B]	Farm	HCPSL Prod. Zone[C]	Yield zone[D]	Area (ha)	Mean yield of 1st ratoon					Soil N mineralization discount (%)		Dominant soil[F]	Suggested N rate (kg/ha)			Potential Saving[I] (kg N/ha)
					2011	2012	2013	2014	2015	HCPSL soil tests[E]	1:5,000 soil survey[F]		HCPSL soil tests[G]	1:5,000 soil survey[G]	DYP[H]	
High	10	H'leigh	L	1.9	67	57	**79**	66	77	19.3	6.25	Silty clay	87	101	129	17
			H	4.6	92	**111**	103	84	92	19.3	6.25	Red loam	122	142		
	11	Hal FM	L	1.1		85	76	**103**		20.3	6.25	River bank	114		128	6
			H	2.2		92	91	**118**		20.3	6.25	River bank	126			
	12	Yuruga	L	2.6		83		**97**	96	8.5	NA	NA	124		146	8
			H	3.1		100		**125**	121	8.5	NA	NA	151			

Notes:

[A]This table is produced for purely illustrative purposes as to the process of refining fertilizer N rates on a zone basis using yield mapping and soil testing; based on the available data, which we do not regard as sufficient, we do not consider the zone delineation which underpins the Table to be robust.
[B]Yield clusters as identified at regional scale (Fig. 12).
[C]Productivity zones used by HCPSL: Lann E. – Lannercost Extension; Bamb. W – Bambaroo West; C-Roll – Coolbie Rollingstone; F'home – Foresthome; B'rock – Blackrock; Helen's H – Helen's Hill; H'leigh – Hamleigh; Hal FM – Halifax four mile; Yuruga - Yuruga
[D]Yield Zone as identified by block-scale cluster analysis (e.g. Fig. 20); L denotes 'low'; H denotes 'high'; in both cases, 'low' and 'high' are used purely as relative terms to differentiate the zones.
[E]Discount to the N fertilizer rate derived from the soil N mineralization potential as estimated from soil carbon analysis (Fig. 8).
[F]Soil types and discounts to the N fertilizer rate derived from the soil N mineralization potential as estimated from soil carbon analysis conducted as part of a 1:5,000 soil survey (Wood et al., 2003; Figs. 3, 6).
[G]Recommended N fertilizer rate derived from 6ES using the maximum yield achieved per zone over the study period and discounting for soil N mineralisation potential based on either soil testing[E] or soil survey[F].
[H]Recommended N fertilizer rate derived from 6ES and DYP
[I]Estimated potential N saving obtained by subtracting the total amount of N applied using 6ES, maximum zone yield and discounting for soil N mineralisation potential based on soil testing[E] from the recommended N fertilizer rate derived from 6ES and DYP[H] amortised over the total block area to a kg N/ha basis. See note A.

tried to remove as many of the effects of harvesting and yield monitor errors by working with data that were normalised on a per harvest event basis. Yet the lack of temporal stability in patterns of yield variation seen in Figs. 22-24 indicates some problems with the data at our disposal. That said, we have been able to derive yield zones in these examples, the veracity of which would be greatly enhanced by more data, as illustrated in Fig. 1. It is to be hoped that, with the increasing commercial availability of new yield monitoring technology, growers of sugarcane will be able to implement targeted management on a more robust basis in the future. In the meantime, the within-farm scale results presented here, and especially in Table 3, should be viewed with circumspection, whilst in the short-medium term, the district scale analysis presented in sections 6.1 and 6.3 offers a more robust basis for location-specific application of 6ES.

6.4. Yield variation at scales intermediate between the district and farm

The apparent mismatch between the mapped yield variation (e.g. Figs. 9, 11-15) and the 'Productivity zones' used hitherto by HCPSL (Fig. 2) has already been highlighted. The original intention (Fig. 2) was to focus our yield monitor analysis on three areas of interest (AOI) deemed reflective of these productivity zones. However, given the results reported, this was not considered appropriate; Fig. 25 highlights the reasoning for this. As can be seen, the AOIs are not discrete to any yield cluster and indeed, each of them contains at least some land with a membership in each of the three clusters.

Notwithstanding the aforementioned concern, during the early phase of the project, we attempted to use yield monitor data to explore yield variation at a 'sub-district' scale using the AOIs as exemplar sub-districts. Fig. 26 shows a set of maps produced for AOI A (Fig. 25). The top row of maps in Fig. 26 shows yield maps for a selected field in the AOI, and also for the farm (middle row of maps) of which the field shown in the top row forms a part. The bottom row of maps shows the result for
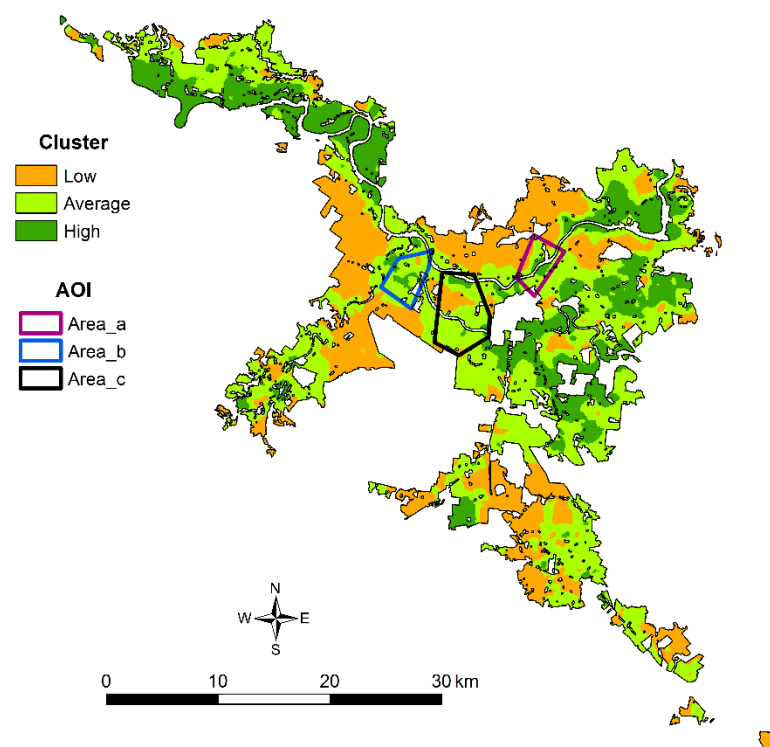
Figure 25.   Areas of interest (AOI; Fig. 2) mapped onto the clusters derived from mill records of block/sub-block yield (Fig. 12).
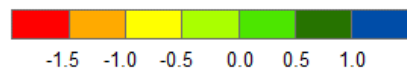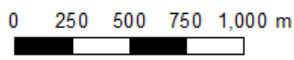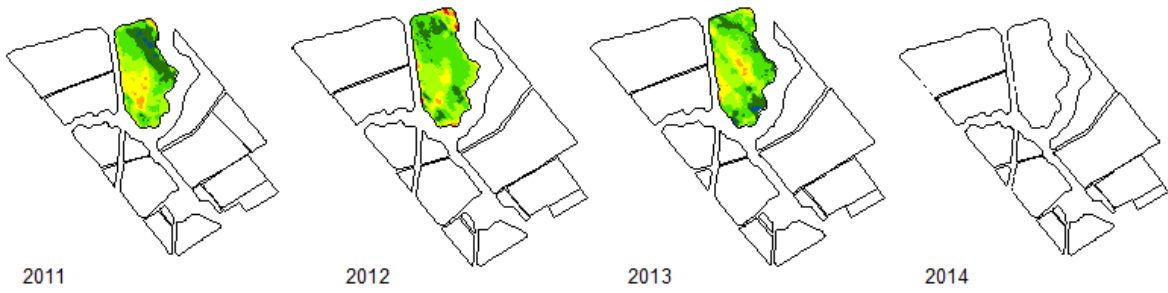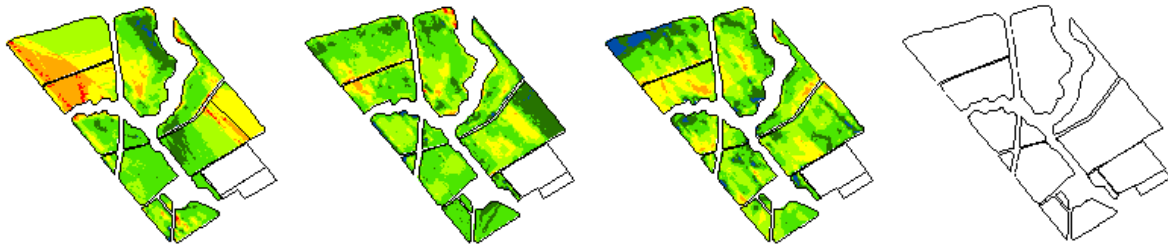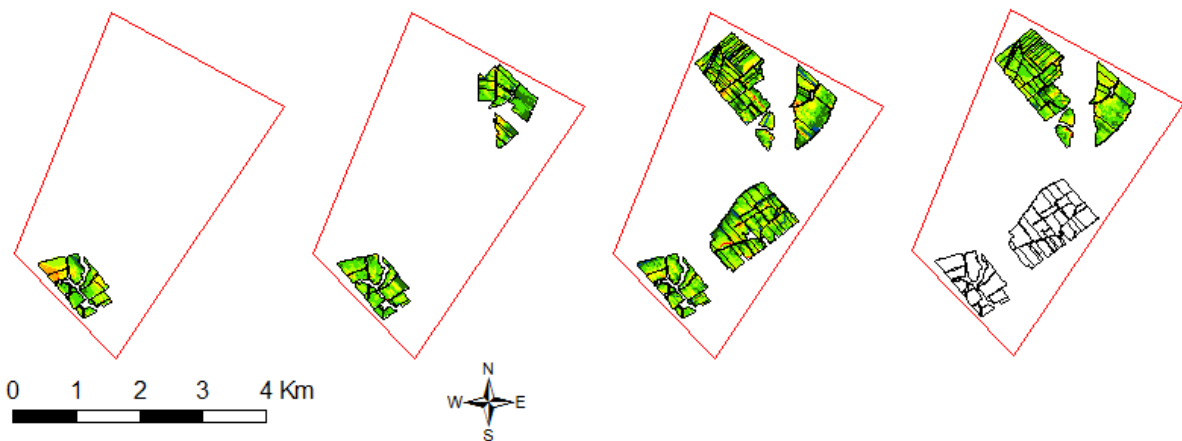
Figure 26. Normalised yield maps for AOI A. Note that the scale of the bottom row of maps is different to that of the top and middle rows. The legend for each row of maps is the same and has units of standard deviations.

the entire AOI. As can be seen, no yield monitor data were available for the selected farm in 2014, although data were available for adjacent properties.

Knowing the standard deviation of yield (obtained from the yield normalisation process) and the mean yield for the field (obtained from the mill tonnage and knowing the field area), the normalised data can be back-transformed to t/ha. The results of back-transforming the maps shown in Fig. 26 to a t/ha basis are shown in Fig. 27. Thus, in the case of the selected field (top row of maps), the back transformation has been done using the Mill tonnage for that field recorded in the cane block layer. For the scale of the whole farm (middle row), the back transformation has been based on the mean yield for the farm and a value of the standard deviation for yield obtained by calculating a mean value of the coefficient of variation (CV) for yield from all the harvest event-based CVs obtained when the data were initially normalised on a per-harvest event basis. The same approach was used at the 'sub-region' scale of the whole AOI. In Fig. 27, the same legend has been applied to each row of maps; deviation at this scale is heavily influenced by the availability (or otherwise) of similar amounts of data for each year. We think a sensible solution to this problem is to not use yield monitor data to generate maps at scales broader than the farm and to rather rely on sub-block mill data for generation of such maps (sections 6.1 and 2). Pragmatically, it is also a fact that a farmer using yield monitor data does not do so at scales broader than his/her farm. Accordingly, no further attempt was made to explore yield variation at scales intermediate between the farm and district as a whole.

6.5. Other considerations

6.5.1. Ratoon yield decline

It is important to recognise that Fig. 15 reflects the estimated performance of first ratoon crops. Currently, no distinction is made between different crop classes in using 6ES as the basis for fertiliser recommendations, other than the separation between plant and ratoon crops; that is, no adjustment to the fertiliser recommendations is made based on ratoon number. Given our inability to accurately forecast the weather 12-15 months in advance, and the dependence of variation in mean district yield (and therefore yield potential) on seasonal climate variation (Muchow et al., 1997; Everingham et al., 2003), this seems a reasonable risk management strategy. On the other hand, Fig. 10 clearly indicates that, at least over the seven years of this study, fourth ratoon crops tended to achieve only 74% of the yield achieved by plant crops, and 80% of the yield achieved by first ratoon. Whether this observation justifies a 20% reduction in the rate of N applied to fourth, compared to first ratoon crops, is a matter for debate and further analysis, although it does perhaps highlight a need for understanding as to how this ratoon yield decline and associated reduction in NUE might be moderated. However, given an increased industry focus on environmental stewardship, this issue arguably warrants careful consideration. In particular, an assessment is needed of how real the ratoon yield decline effect (Fig. 10) really is. The tendency amongst growers to harvest older ratoons later in the season will tend to reduce potential yield (e.g. McDonald, 2006; Di Bella et al., 2008), yet experimental evidence (e.g. Wood, 1991; Thorburn et al., 2011) suggests that whereas plant and 1st ratoon crops tend to be the highest yielding, yields do not necessarily decline in older ratoons. Thus, Fig. 10, which did not include consideration of time of harvest/since previous harvest, can be regarded with some circumspection and applicable only to the present study. On the other hand, if industry practice is such that ratoon yield decline (Fig. 10) is a generally observed trend, the merits of fertilising fourth ratoon crops to the same level as first ratoon warrants evaluation, especially given the finding of Thorburn et al. (2015) that N fertiliser application rate was the only crop management factor that influenced NUE in ratoon crops. Opportunities for

Kriged by block

2011   2012   2013   2014

t/ha

40 50 60 70 80 90

0   250   500   750 1,000 m

Kriged by farm

Kriged by co - located blocks

0   1   2   3   4 Km

Figure 27.   Yield maps for AOI A expressed in t/ha.

soil amelioration aimed at moderating ratoon yield decline, so as to maintain profitability and NUE, might be a preferred alternative worthy of investigation.

6.5.2. Soil variation

Herbert cane growers are fortunate to have access to the 1:5,000 'Andrew Wood survey' which, to the knowledge of the project team, is unique in Australia in providing regional scale soil survey data at a scale that is consistent with the scale at which growers make management decisions (Bramley, 2017); typically Australian soil survey data is at much coarser scale (1:50 000-1:250 000). However, as noted in section 6.2, the 'Andrew Wood survey' does not cover the entire present cane growing area. For this reason, and also because of the need to provide appropriate support to 6ES when implemented in other regions which do not have soil survey data at fine scales, use was also made in this study of the soil testing program coordinated by HCPSL; whether similar programs run in other cane growing regions is not known. The soil test data were used in order to inform the discount to 'base' N fertilizer rates due to soil N mineralization potential which, along with potential yield, is a key input to 6ES. However, it is recognised that factors other than yield and N mineralisation potential may be spatially variable. Irrespective of yield variation, variation in soil and other biophysical factors may also lead to spatial variation in the risk of N loss (Thorburn et al., 2011), for example through leaching or volatilisation. Whether the requirement of 1.4 kg N/t cane (Keating et al., 1997), which underpins the 6ES recommendations (Schroeder et al., 2010), might also be subject to spatial variation is an open question. It is an important question however, given the suggestion that a lower N requirement may be appropriate (Thorburn et al., 2011), at least in some districts (Thorburn et al., 2015), leading to a relatively large proportional impact on recommended N fertiliser rates compared to discount factors such as N mineralisation. Evaluation of such factors in the pursuit of further improvements to NUE through refinement of the implementation of 6ES would therefore be warranted.

6.5.3. The pragmatics of yield monitoring to inform improved decision making on farm.

Section 6.3 highlighted the dearth of robust data that is available to support yield zone delineation, even in an area such as the Herbert which has taken the lead in the implementation of yield mapping in the Australian sugar industry; Jensen et al. (2010), Bramley and Jensen (2013) and Bramley et al. (2017) provide some of the reasons for this lack of data. However, the analysis conducted in section 6.3 has drawn attention to an additional problem which is highlighted in Fig. 28.

The farm shown in Fig. 28 has quite good coverage (up to 123 ha) of yield monitor data at the farm level, with the exception of 2015; at the block scale the coverage is somewhat less good and in fact none of the sub-blocks comprising this farm have yield map data available for all five study years. However, as can be seen, each sub-block is approximately 80 m wide but runs for over 1800 m. For yield mapping at the sub-block level following the protocol of Bramley and Jensen (2013), this presents a potential problem in biasing the map interpolation process along the orientation of the rows. More importantly, given that variation in the land underlying the farm is continuous, the benefit from examining and interpreting a yield map in concert with those from adjacent areas is missed when the focus is just at the sub-block level. Indeed, Fig. 28 is strongly suggestive of there being considerable merit in examining yield variation at the farm level. However, as the area of interest increases, so too does the complexity of map preparation given the need for data to be managed on a per-harvest event basis (Bramley and Jensen, 2013; Bramley et al., 2017). During the course of this work, code was written to greatly facilitate the discovery, extraction and processing of yield monitor data for farms such as that shown in Fig. 28. Meanwhile, SRA project 2014/028 (Jensen, 2017) developed procedures for assessing the quality of yield monitor data and its
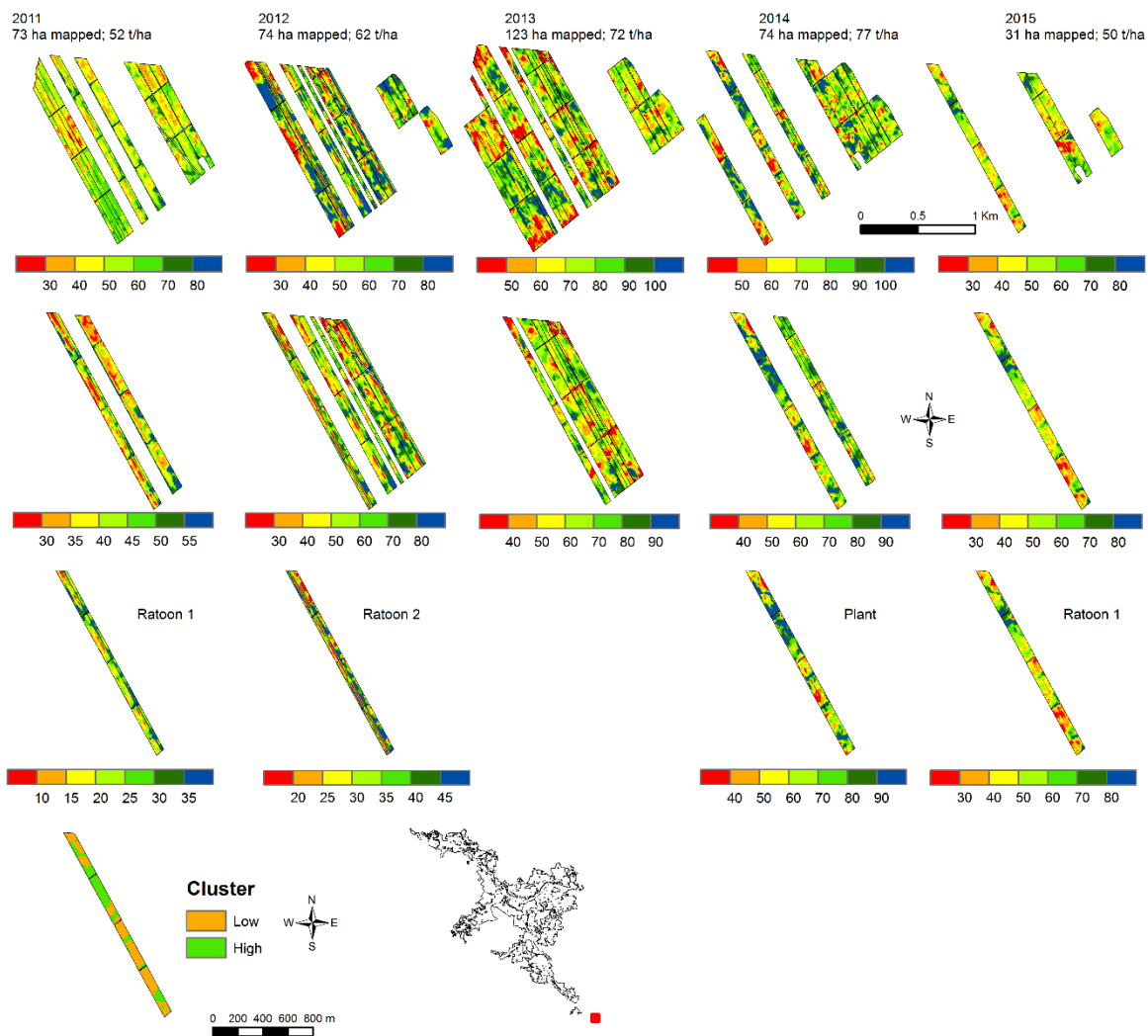
Figure 28.   Analysis of yield variation at the farm (top row), block (second row) and sub-block (third and fourth rows) scales for an exemplar farm (c.f. Figs. 22-24). Note that in spite of the total mappable area being large (123 ha in 2013), the fact that all sub-blocks are long and narrow presents difficulties for yield mapping. See text for further explanation.

suitability for mapping. Bramley et al. (2014 and 2017) have also highlighted the benefit of 'filling in' gaps in yield monitor data – perhaps due to a sub-block being in fallow – by calculating an average normalised yield from the data that are available for other years. In such a way, continuous yield surfaces can be generated over larger contiguous areas. This is important given that the *k*-means clustering process used for zone delineation does not handle missing data.

Notwithstanding the caveats surrounding Table 3, it seems clear that on some farms, especially those in inherently low-medium yielding parts of the district, the expected reduction in N fertilizer rates when 6ES is applied at the within-farm scale, might be expected to be greater, compared to when DYP is used, than when BYP (Fig. 15) is used as the potential yield input to 6ES. Thus, whilst Fig. 19 and the work presented in sections 6.1 and 6.2 is strongly suggestive of a BYP-based implementation of 6ES delivering significant improvements to NUE and reductions in the risk of offsite N loss, pending availability of appropriate yield monitor data, implementation of 6ES at the within-farm, within-block or -sub-block scales can be expected to deliver further benefits. It should also promote enhanced grower profitability, both through savings in input costs, and also realisation of higher yields in those farms or zones where yield potential is highest. It is therefore suggested

that considerable value would accrue to NUE through both the promotion of PA (especially yield mapping) and in particular, through the development of a data processing tool which integrates the procedures used here with those developed in SRA project 2014/028 (Jensen, 2017) and the 'gap-filling' procedure of Bramley et al. (2014, 2017).

6.6. Recommendations

Further to the work described here, the following recommendations are made:

1. This project was a 'proof-of-concept' analysis of yield variation at district and finer scales. It has clearly demonstrated that DYP is not an appropriate basis for developing fertilizer recommendations for the sugar industry and that by implementing 6ES on a more location-specific basis, improvements to NUE and grower profitability might accrue. Since the mill data on which the within-district analysis (sections 6.1 and 6.2) depended are readily available in all Australian sugarcane growing districts, similar analyses could readily be undertaken in these other districts. It is recommended that SRA and/or Qld DEHP fund such an analysis. The CSIRO team which conducted this project would be interested in being considered for such work. A protocol describing the required process is provided at Appendix 4.

    a. In undertaking the present study, CSIRO and HCPSL spent a lot of arguably un-productive time negotiating access to the data required to complete the study. In conjunction with recommendation 1, it is suggested that SRA and/or Qld DEHP negotiate access to such data with the various relevant sugar milling companies.

2. The district scale analysis (section 6.1 and 6.2) made use of a unique 1:5,000 soil survey, along with a locally coordinated soil testing program to derive the discounts applied to 'base' N fertilizer rates due to soil N mineralisation potential. Whether such soil testing programs exist in other districts is not known. However, they could readily be established with the cooperation of productivity services companies (as is done by HCPSL in the Herbert) and assistance of Incitec-Pivot. It is therefore recommended that soil testing programs are established in each cane growing district. Such an initiative could usefully be combined with SRA-initiated work aimed at better understanding 'soil quality' in the sugar industry.

    As an adjunct to establishment of such soil testing programs, it is further recommended that:

    a. A small research project is established (or previous work reviewed) to examine the rate of accumulation (or loss) of soil carbon (C) in sugar soils so as to inform the question as to how many years of soil test data may be incorporated into a mapping exercise such as that shown in Fig. 8; clearly, more data leads to a more robust map of soil organic carbon content.

    b. Related to 2a, it would be valuable for the robustness of Fig. 5 to be established and, as necessary, an alternative regression relationship between soil organic matter content and the discount (%) to recommended N rates due to soil N mineralization potential established. Fig. 5 appears biased to a couple of small values, although these are medians calculated from a large number of soil analyses undertaken during the 'Andrew Wood' survey. A review of data collected during the development of 6ES would be a valuable starting point.

3. Closely aligned with 2, research is needed to examine spatial variability (between and within districts) in the following attributes (and/or the soil properties which control them) and its impact on NUE with a view to incorporating understanding of these into the location-specific implementation of 6ES:

    - The risk of N loss through leaching or volatilisation.
    - The crop requirement for N.
    - N uptake by the crop.

4. Anecdotal evidence suggests that some growers regard the 6ES recommendations based on DYP with caution since they represent a reduction in fertilizer use compared to previous practice. It is therefore to be expected that some of the implications of the work in this report will be regarded with much greater caution given an even greater reduction in N application rates is suggested. It is therefore recommended that a program of farmer demonstration trials be implemented to demonstrate the appropriateness (or otherwise) of the location-specific rates developed in sections 6.1 and 6.2. These should not be conventional small plot trials, but would much more appropriately involve the use of strip trials with treatments which include a zero application and a luxury application along with the revised suggested rate, in comparison with current farmer practice. The merits of this 'spatially distributed' experimental approach, in terms of the use it makes of spatial variability and the opportunities for more targeted further use generated by the spatial analysis of treatment effects are outlined by Bramley et al. (2013). The present project team would certainly be interested in assisting with such work.

5. Consistent with the discussion in sections 6.4 and 6.5.3, and to facilitate the realisation of benefits to NUE through the adoption of PA, especially as robust yield monitoring becomes more readily commercially available, it is recommended that the development of a yield monitor data processing tool be supported. This should integrate the procedures used in the present study with those developed in SRA project 2014/028 (Jensen, 2017) and the 'gap-filling' procedure of Bramley et al. (2014, 2017).

6. There is need for ratoon yield decline and any implications it has for fertilizer management to be better understood (see section 6.5.1). If, as seems possible, this is an artefact of grower practice, an extension program aimed at reducing ratoon yield decline through improved harvest management could yield useful benefits to NUE through higher yields of later ratoon cane being realised per unit input of fertilizer. On the other hand, if there is a clear physiological explanation for ratoon yield decline, then further research aimed at understanding how fertilizer N rates might be modified on a ratoon-specific basis would be warranted.

7. PUBLICATIONS

To date, the project has led to two publications (as follows; see also Appendix 2 and 3) the first of which was awarded the President's Medal (Research) at the 2017 conference of the Australian Society of Sugar Cane Technologists. It is anticipated that a further journal publication may be produced, a copy of which will be forwarded to SRA if and when available.

Bramley R, Ouzman J, Gobbett D 2017. Is district yield potential an appropriate concept for fertilizer decision making? Proceedings of the Australian Society of Sugar Cane Technologists 39, 67-76.

Bramley RGV, Ouzman, J, Gobbett, DL. 2017. Yield mapping at different scales to improve fertilizer decision making in the Australian sugar industry. Proceedings of the European Conference on Precision Agriculture, Edinburgh, July 2017. Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017, 8:2, 630–634.

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10.   APPENDIX

10.1.   Appendix 1 METADATA DISCLOSURE

Table 4   Metadata disclosure 1

Data	Herbert River mill statistics (2009-2015) and the 'Andrew Wood soil survey'
Stored Location	CSIRO Waite Campus / HCPSL
Access	Restricted – these data are the property of Wilmar Sugar and are not publically accessible without an appropriate licence for access being granted.
Contact	Rob Bramley / David Gobbett – CSIRO Raymond DeLai – Wilmar Sugar

Table 5   Metadata disclosure 2

Data	Soil test data for the Herbert River district
Stored Location	HCPSL with a copy at CSIRO Waite Campus
Access	Restricted – these data are the property of HCPSL and are not publically accessible without an appropriate licence for access being granted.
Contact	Lawrence DiBella – HCPSL Rob Bramley / David Gobbett - CSIRO

Table 6   Metadata disclosure 3

Data	Yield monitor data collected in the Herbert River district, 2011-2015
Stored Location	HCPSL with a copy at CSIRO Waite Campus
Access	Restricted – these data are the property of HCPSL and are not publically accessible without an appropriate licence for access being granted.
Contact	Lawrence DiBella – HCPSL Rob Bramley / David Gobbett - CSIRO

Table 7   Metadata disclosure 4

Data	All maps developed during this project
Stored Location	CSIRO Waite Campus
Access	These maps are available in .png format as used in this report. Maps derived from the data covered in Tables 1 and 2 are not available in raster format without the granting of an appropriate data licence from Wilmar sugar. Maps derived from the data covered in Table 3 are not available in raster format without the granting of an appropriate data licence from HCPSL.
Contact	Rob Bramley / David Gobbett / Jackie Ouzman - CSIRO

10.2.   Appendix 2

Bramley R, Ouzman J, Gobbett D 2017. Is district yield potential an appropriate concept for fertilizer decision making? Proceedings of the Australian Society of Sugar Cane Technologists 39, 67-76.

See attached pdf.

10.3.   Appendix 3

Bramley RGV, Ouzman, J, Gobbett, DL. 2017. Yield mapping at different scales to improve fertilizer decision making in the Australian sugar industry. Proceedings of the European Conference on Precision Agriculture, Edinburgh, July 2017. Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017, 8:2, 630–634.

See attached pdf.

10.4.   Appendix 4 - A protocol for estimating and mapping block yield potential from mill statistics.

It is assumed here that mill records are available in shapefile format with one file per mill per year, and that data are provided on a sub-block basis and that access to GIS, spreadsheet and statistical software is readily available. It is further assumed that the potential yield of each variety is the same and that the potential yield of re-plant cane is the same as that of plant cane. These assumptions can be modified at the analysts discretion, but doing so will require that the filtering (step 3) and normalisation process (step 4) is done in a manner consistent with any modifications.

1. For districts with more than one mill, for each year for which data are available, merge the data into a single per year file for the district.
2. For each year, generate cartesian coordinates for each data record based on the centroid of each sub-block.
3. Filter the data on the basis of crop class and retain data covering plant crops and for first, second, third and fourth ratoon crops. Discard data for ratoon crops older than fourth ratoon and standover cane. (Note that data for ratoons older than fourth ratoon can be retained at the discretion of the analyst).
4. For each crop class in each year, normalise the sub-block yield data to a mean of zero and standard deviation of one. This is done by calculating the district mean and standard deviation of yield and then from each individual yield record, subtracting the district mean and dividing the result by the district standard deviation.
5. Discard records with a value of normalised yield that is either greater than +3 or less than -3. Note that, for a normally distributed dataset, 99% of the data values lie within three standard deviations of the mean. Discarding those data records that lie outside this range is therefore a useful way of removing outliers and otherwise aberrant values.
6. Repeat step 4 (i.e. re-calculate the mean and standard deviation of the trimmed data set) and then step 5 iteratively, until all retained data meet the criteria stipulated at step 5.
7. Merge the shapefile boundaries of all sub-blocks to generate a single boundary for the cane-producing area in the district of interest.
8. From this single district boundary, generate a raster grid comprising pixels of 100 m x 100 m (i.e. 1 ha). Export this grid as required for use in kriging software.

9. For each crop class by year combination, interpolate maps of normalised yield onto the 100 m raster using local block kriging (Webster and Oliver, 2007). VESPER (Minasny et al., 2005) is recommended for this. The data cloud should be set to not less than 100 points (i.e. 100 sub-block records), exponential variograms should be used and blocks of 500 m (or 5 times the raster grid size if not 100 m).

10. Merge the normalised crop class-based datasets developed for each year to a single data layer and interpolate a further map summarising yield variation for the district as a whole independent of crop class.

11. Examine the resulting maps for consistency of patterns of spatial variation. This can be done through simple visual inspection or using the various methods described in the body of this report.

12. Assuming that the patterns of district-scale yield variation are deemed stable across years, back-transform the data to a first ratoon basis (or other crop class as required) using the reverse procedure to that described at step 4, knowing the mean annual yield of first ratoon cane (or of other crop classes as desired) and the mean value of the coefficient of variation (= [100 x standard deviation]/mean) of first ratoon yield across the mapped years.

13. For each pixel in the district raster grid, identify the maximum yield achieved over the period of data availability and use this to generate a map of maximum yield achieved. This map is then the surrogate for Block Yield Potential (BYP) and is used as the input to 6ES.

14. As desired, and for delivery of block-specific recommendations, the data can be exported on a sub-block basis using the coordinates generated at step 2.