THE INTERNATIONAL SOCIETY OF PRECISION AGRICULTURE PRESENTS THE
13th INTERNATIONAL CONFERENCE ON
PRECISION AGRICULTURE
July 31-August 4, 2016 • St. Louis, Missouri USA

Accuracy of Differential Rate Application Technology for Aerial Spreading of Granular Fertilizer within New Zealand

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A paper from the Proceedings of the
13th International Conference on Precision Agriculture
July 31 – August 4, 2016
St. Louis, Missouri, USA

Abstract. *Aerial topdressing of granular fertilizer is common practice on New Zealand hill country farms because of the challenging topography. Ravensdown Limited is a New Zealand fertilizer manufacturer, supplier and applicator, who are funding research and development of differential rate application from aircraft. The motivation for utilising this technology is to improve the accuracy of fertilizer application and fulfil the variable nutrient requirements of hill country farms. The capability of this system to apply fertilizer at the target rate within an intended boundary was measured in two trials. Collectors were placed in a grid and nested grid formation over two sheep and beef farms in the North Island, New Zealand. Granular fertilizer was applied at two rates on the farm. The collected fertilizer was weighed and geo-statistical kriging was completed over the trial area. This produces a proof of placement map. Proof of release maps are produced using recorded aircraft data.*

Proof of release maps are highly detailed compared to placement maps. Release maps are based on thousands of flight recorded data points, while placement maps were created using 130 – 180 collectors. The release maps showed a clear transitional boundary with a noticeable change in rate between the two zones. In contrast, the average application rate found from the ground truth trial was lower than expected. Therefore the proof of placement maps predicted under-application in the trial area. High speed photometry of a collector showed that the collector was not able to fully capture all particles. A significant number ricocheted off the inside surface of the collector and bounced out. The average collected application rates of each zone improved when collection error was considered. The CV ranged from 34% to 56% for each zone. Variable wind conditions contributed to variation in the spread pattern. Therefore, although the differential rate application system is capable of applying fertilizer at different rates, wind speed and direction have a significant impact on the ground distribution and will remain a limitation of the system.

Keywords. *Aerial spreading, accuracy, precision, differential application rate, granular fertilizer, New Zealand, geo-statistics, kriging*

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 13th International Conference on Precision Agriculture. Chok, S. E., Grafton, M. C. E., Yule, I. J. & White, M. (2016). Accuracy of differential rate application technology for aerial spreading of granular fertilizer within New Zealand. In Proceedings of the 13th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

Introduction

Ravensdown Limited, a New Zealand fertilizer manufacturer, supplier and applicator, is upgrading their aerial spreading aircraft with differential rate application technology (DRAT). The technology operates an automated hopper door based on the GPS location of the aircraft. Fertilizer application is a significant farm cost and conventional application typically applies one rate over the whole farm. However, soil fertility can vary significantly over a hill country farm (Gillingham and During, 1973). Therefore, differential rate application will allow for improved soil fertility management. Areas low in soil nutrients will be able to receive a higher application rate. On the other hand, areas with high soil fertility can receive a maintenance or sub-maintenance application rate. There is also the option of not applying any fertilizer over non-productive areas (i.e. roads, rivers). Murray and Yule (2010) showed that a differential rate application could increase a farm's cash surplus by 26% per hectare, under the most productive conditions.

Another benefit of a GPS controlled hopper door is that it can prevent off-target fertilizer application into neighboring farms. Murray (2007) showed that a non-GPS aircraft applied 16% (23 tonnes) of fertilizer outside of the application area compared to 6% (9 tonnes) from an automated hopper. This equated to 14 more tons of superphosphate spread in unintended areas when the hopper is pilot operated. The price of superphosphate at Ravensdown Limited is currently $NZ 330. Therefore pilot operated application unintentionally misdirected $NZ 4620 of fertilizer in the example presented. An automated system also improves safety since the pilot is able to focus on navigation and operation of the aircraft, and no longer has to operate the hopper door.

The coefficient of variation (CV) is used to determine the precision of a fertilizer application. It is the standard deviation of the application rate over the mean. Grafton et al. (2012) showed that an automated hopper door could improve the CV from 63 – 70% in conventional application to 44%. This is similar to CV values found in ground fertilizer application. The CV is affected by the flight configuration, wind conditions and fertilizer properties (Grafton et al., 2013). A low CV can be achieved by applying at a swath width that ensures a targeted overlap in the transverse spread pattern so that the average application rate is near the target rate. Non-GPS aircraft would need to rely on landmarks to reference their flight path, which increases the probability of missing areas and double application (Ballard and Will, 1971). In contrast, DRAT aircraft have GPS to aid in reducing the CV.

Geo-statistical methods can help in the interpretation and presentation of spatial data. Kriging, a geo-statistical tool, interpolates discrete spatial data to produce a continuous layer. It applies the relationship that collected data points closer to the estimated intermediary point have more weight than those far away. A semi-variogram quantifies the spatial correlation between collected data points (Montero et al., 2015) to improve the accuracy of the interpolation. The semi-variance can be plotted against the lag distance (average squared difference of values separated by the lag distance). Best results are achieved when the data is normally distributed and is stationary (reaches a lag distance where mean and variance does not vary).

Kriging generates proof of release maps from aircraft data. Data for release maps is readily available and abundant. Therefore release maps are well defined but are not a good prediction of the ground fertilizer distribution. Parameters, such as wind conditions, the forward motion of particles and topography, are not considered in a proof of release map. Proof of placement, created from collector data, considers these factors but is limited by the sample size required to produce a reliable output layer of a large area.

This paper will seek to evaluate the capability, accuracy and precision of the differential rate application system for Ravensdown Limited. There will also be an assessment of the sampling methods undertaken and whether kriging is a suitable method of data interpretation and representation for aerial topdressing trials. Results pertaining to accuracy and precision have been previously published in the 2016 proceedings of the New Zealand Hill Country Symposium (Chok et al., 2016b). The section on proof of release maps was published in the 2016 New Zealand Fertilizer and Lime Research Center workshop proceedings (Chok et al., 2016a).

Methodology

Collectors

The collectors used for aerial trials cover an area of 0.5 m^2 and is approximately 1.2 m in height when assembled. It has three parts: stand, cone and collar. Fertilizer collected over the area is funneled to a plastic bag attached by a rubber band at the bottom of the cone (Figure 1). There are 179 collectors available for trials.

Figure 1: Two assembled collectors with sample bags attached.

High speed photometry taken of a single collector during aerial trials found that a significant percentage of fertilizer particles bounce out of the collectors (Table 1). Three slow motion videos were analyzed for urea and superphosphate by counting the number of particles that enter and exit the rim of the collector. Different fertilizer types gave different results and this could be attributed to their hardness. The percentage was used to correct all collected data. However, three videos are not sufficient in finding the percentage's true variance; therefore data presented here is an estimate.

Table 1: Fertiliser type and their percentage of particle bounce (PPB).

	Particles bouncing out (%)			
Fertilizer type	Video 1	Video 2	Video 3	Average
Urea	12.5	27.0	8.0	15.8
Superphosphate	8.6	4.1	4.6	5.7

Experimental Trials

A ground truth trial was carried out at Limestone Downs (February 2014), Port Waikato, New Zealand with 136 collectors. Limestone Downs is a coastal hill country farm with large variations in topography. The collectors were loosely arranged in an incomplete grid because the area on the eastern side of Figure 2 had to be excluded due to cattle being present that were disrupting the collectors. In the grid, collectors were placed 70 m apart. An additional seven groups of five collectors were placed randomly in the grid to determine spatial variance. The total trial area was 61 ha. Wind conditions were not measured on the day; however there was a noticeable westerly wind. Superphosphate was applied at 250 kg/ha inside the shaded block and 500 kg/ha outside (Figure 2).

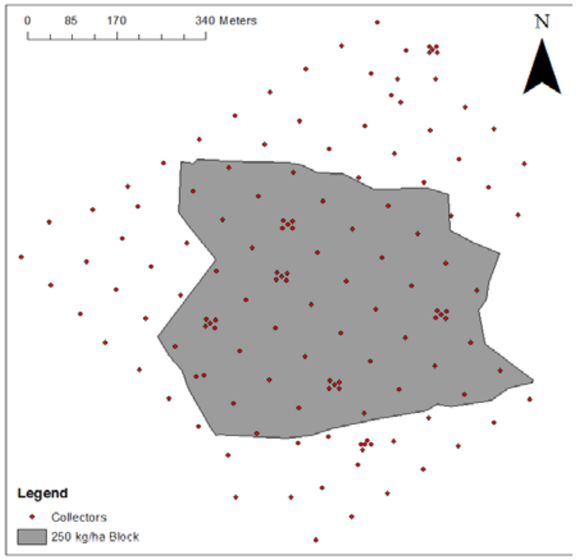

Figure 2: Final sampling design for Limestone Downs.

A nested grid sampling design was used at Longview (April 2015), Waitotara, New Zealand. Longview is a coastal farm with gentle slopes. Collectors were placed 2, 25, 50 and 150 m apart in a branching tree configuration. The distances collectors were placed from each other were used to determine the amount of spatial variation:

- Between application zones
- Between two flight paths/swath widths
- Within a swath width

One hundred and sixty-five collectors were placed over 30 ha. Twenty three collectors had to be excluded because there was precipitation on the collector which was not fully dried before the sample bag was attached. Wind speed and direction was measured using an anemometer. Wind speed averaged 0.9 m/s with a range of 0.17 m/s to 1.97 m/s in a north-easterly direction. A blend of superphosphate, Flexi-N (a urea coated with magnesium oxide to prevent chemical reaction with superphosphate), Maxi Sulphur Super (single superphosphate with additional sulphur injected in the granule) and other trace elements were applied at 284 kg/ha outside the shaded blocks and 162 kg/ha inside the shaded blocks, which are predominantly sand dunes (Figure 3).

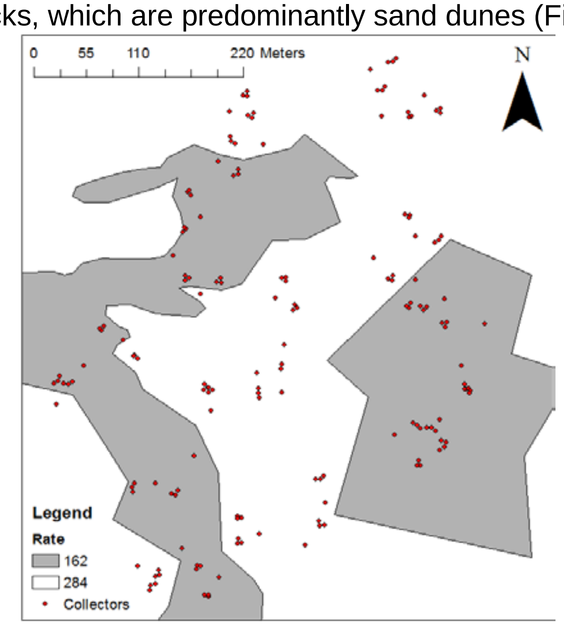

Figure 3: Sampling design for Longview.

In both trials, a Pacific Aerospace Cresco 600 was fitted with a hydraulic hopper door and Satloc's Intelligate G4 system (Hemisphere GPS, Phoenix, Az). The same pilot completed both trials and flew in a racecourse configuration (overlapping circles that intersect the application areas). The collected sample bags were weighed and an application rate was calculated using the masses and the area of the collectors.

Aircraft Data

Aircraft data, such as hopper door opening, aircraft ground speed, altitude and location, is recorded every 0.2 s. Approximately 5000 aircraft data points were available for Limestone Downs and 2500 points for Longview. The Beverloo equation (Beverloo et al., 1961) was used to estimate the mass flow rate (M), in kg/s from the aircraft based on the hopper door opening (B) in m.

$$M = LK\rho g^{\frac{1}{2}}\left(B - k\bar{d}\right)^{\frac{3}{2}} \tag{1}$$

L is the length of the hopper door, K is an aircraft constant, k is a fertilizer constant, ρ is the fertilizer's bulk density, $\bar{d}$ is the mean particle diameter and g is acceleration due to gravity. The aircraft application rate can be calculated using the mass flow rate, swath width and aircraft velocity. Each recorded point represents an area that is dependent on aircraft speed and the swath width, in these trials that was approximately 14 m by 16 m. The mass flow rate predicted by Beverloo's equation has error as it does not consider the effect of aircraft velocity, the interaction of air and the hopper door or the design of the actual hopper. Therefore the Beverloo predicted application rates should be taken as estimates. Work is on-going to determine the magnitude of error and better methods of estimating the application rate.

Geo-statistical Analysis

ArcGIS 10.1 has a geo-statistical analyst tool wizard, which was used in this paper to produce semi-variograms and to complete kriging. The penta-spherical model was fitted to all data and ordinary kriging was carried out.

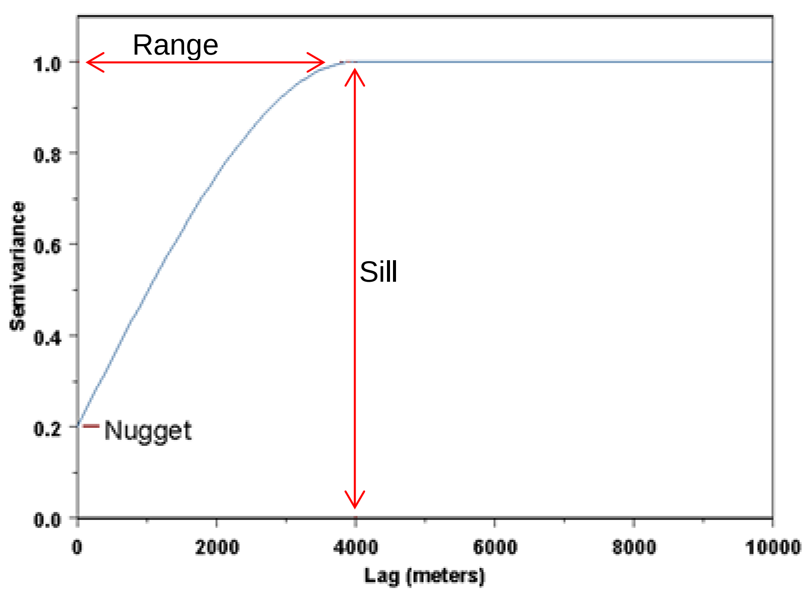

Figure 4: Annotated semi-variogram adapted from Bohling (2005).

The sloped section of a semi-variogram indicates that a relationship exists between two points at distance. This means they are spatially auto-correlated (Bohling, 2005). To get a well-represented output layer, it is important to sample sufficiently at distances along this slope. The sill is where the data is no longer spatially auto-correlated (Figure 4). The distance needed to reach the sill is called the range, and the y-intercept is the nugget effect. It represents background variation that could not be quantified due to sampling design and measurement error.

Limestone Downs collector semi-variogram has the largest nugget effect, which indicates that placing collectors 70 m a part is not suitable (Figure 6A). Aircraft data also has a significant nugget effect because the recorded flight points are a minimum of 14 m apart but it is likely that there are significant correlations at shorter distances (Figure 5). Compared to collector data, the semi-variogram for aircraft data is better modeled because there was more spatial data available from aircraft (Figure 5 and 6).

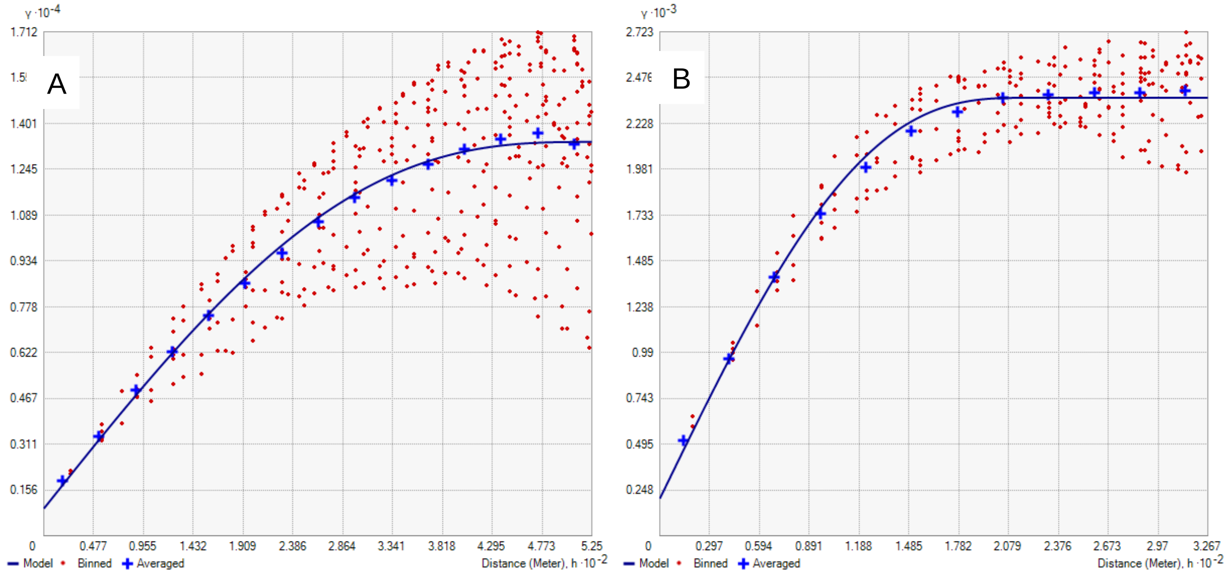

Figure 5: Semi-variogram of aircraft data from Limestone Downs (A) and Longview (B).

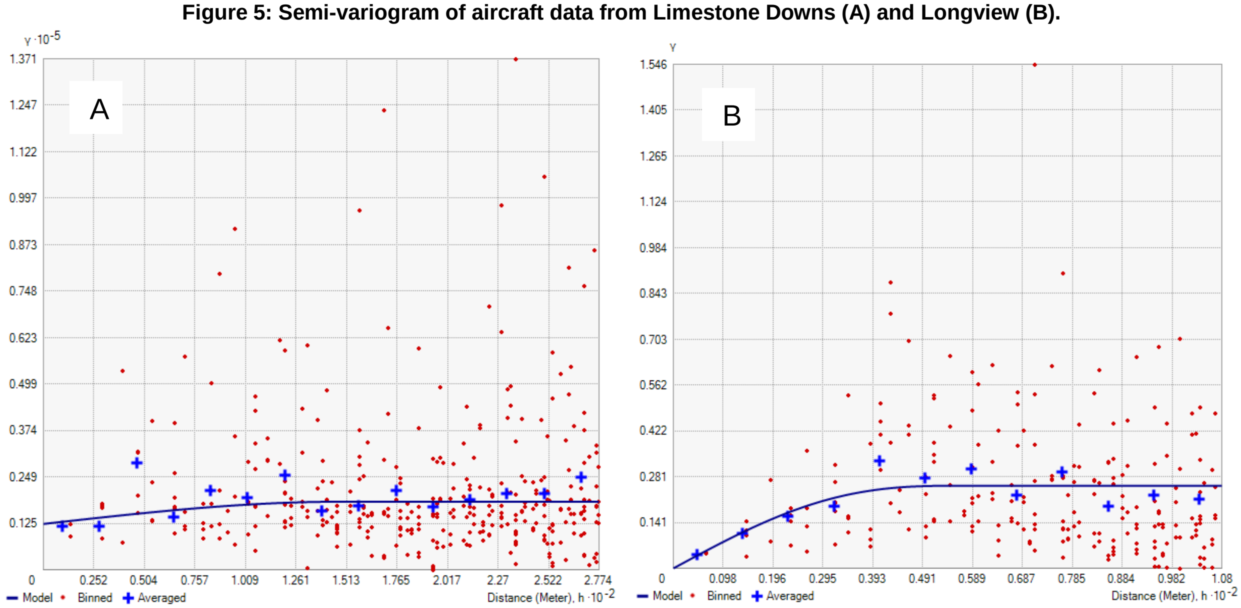

Figure 6: Semi-variogram of collector data from Limestone Downs (A) and Longview (B).

The semi-variograms for collector data at Limestone Downs and Longview have a sinusoidal sill, which represents cyclicity in the data (Pyrcz and Deutsch, 2003). Applied fertilizer creates a normally distributed pattern. Overlap of flight paths, using the swath width, should average the application to the target rate. However, this is difficult to achieve with variability in wind conditions and aircraft operation; therefore cyclicity occurs.

Results and Discussion

Accuracy, precision and capability of differential rate application technology

The data measured from collected samples show that under application occurred at both trials by between 18 – 38% (Table 2). This could be due to poor calibration between the hopper door and the application rate, collection error or variable wind conditions. It is possible to increase the accuracy by calibrating the hopper door opening to the target application rate. Carrying this out at the start of a farm application could help to account for topography and localized wind conditions. Quantifying the variance in the collector's error and improving collector design will also improve accuracy.

Table 2: Summary collector data for Limestone Downs and Longview.

	Limestone Downs		Longview	
Intended application rate (kg/ha)	500	250	284	162
Average measured application rate (kg/ha)	308.0	203.4	198.4	120.3
Difference between intended and measured average rate (%)	38.4	18.6	30.1	25.7
Standard Deviation (kg/ha)	174.4	103.0	68.8	63.8
CV (%)	56.7	50.6	34.7	53.0

The standard deviations show that precision improved at Longview when compared with Limestone Downs (Table 2). Comparing this system to a pilot operated hopper door applying a blanket rate (CV = 63 - 70%), the CV found in the trials is lower (CV = 35 - 57%). Although the CV has improved over conventional blanket aerial application, Ravensdown Limited would like to achieve CVs between 30% and 35%. Methods of achieving this include selecting a suitable swath width, ensuring that there are parallel flights lines over the application area and maintaining a consistent flight operation. Spreadmark is a voluntary New Zealand accreditation scheme for ground and aerial fertilizer applicators (NZFQC, 2016). It sets standards for the precision of fertilizer application. Applicators must achieve a CV of 15% for nitrogen based fertilizers in ideal test conditions (i.e. little to no wind, flat area) and 25% for all other fertilizers. Therefore fertilizer applications on farm begin with a CV of 15 – 25% and localized variables, such as topography and wind conditions, increase the CV. This means consistently achieving a CV of 30 – 35% will be challenging but is possible if the effect of localized variables is minimized.

Table 3: ANOVA test for collector distance and application rate from the Longview trial.

Groups	Count	Sum	Average	Variance
5 m	76	12316.72	162.0621	5640.565
25 m	37	5709.571	154.3127	8396.464
50 m	19	3108.874	163.625	4563.783
150 m	10	1489.572	148.9572	2454.15

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between groups	2925.115	3	975.0384	0.162203	0.9216275	2.670203
Within groups	829550.5	138	6011.235			
Total	832475.6	141				

A one-factor analysis of variance (ANOVA) test on the relationship between collector distance and application rate at Longview showed that the means were not significantly different. This suggests that the variation within data points of the same distance is similar to the variation between distance groups (Table 3). Therefore, all groups experienced the same variation. This variation could be attributed to collector error or changes in wind conditions. If it is assumed that all collectors experienced the same percentage of particles bouncing out then the variation is caused by wind. Wind conditions are uncontrollable and difficult to model. Macfarlane *et al.* (1987) showed that cross wind speeds of 0.44 – 3.5 m/s could result in application rates of 4 – 270 kg/ha. The intended mean application rate for the trial was 100 kg/ha. Therefore wind could significantly impact the transverse spread pattern and was a likely contributor to differences in the target and measured application rates reported here. Fertilizer spreading in little or no wind would decrease the CV, but these conditions are unlikely to occur in New Zealand hill country.

Figures 7A and 8A are the proof of release maps for Limestone Downs and Longview, respectively. The release maps show an identifiable change in application rate at the treatment separation boundaries. This indicates that the differential rate system made an adjustment in the hopper door as it approached/crossed the boundary. The flight direction can also be observed in the high application rate zone since there are strips of different colors. The placement maps do not show the treatment separation boundary because there were insufficient collectors (Figures 7B and 8B). This also leads to large areas of interpolated points that do not capture the variation in aerial spreading. This is truer for Limestone Downs' placement map than Longview's.

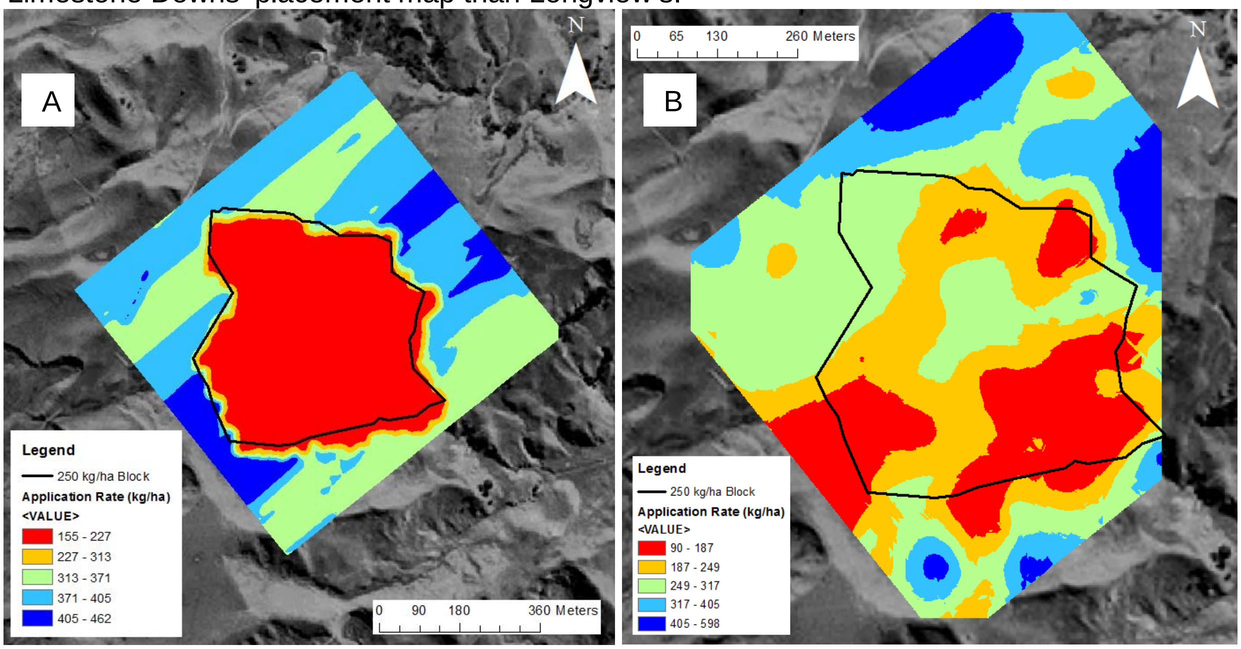

Figure 7: Proof of release (A) and placement (B) maps for Limestone Downs.

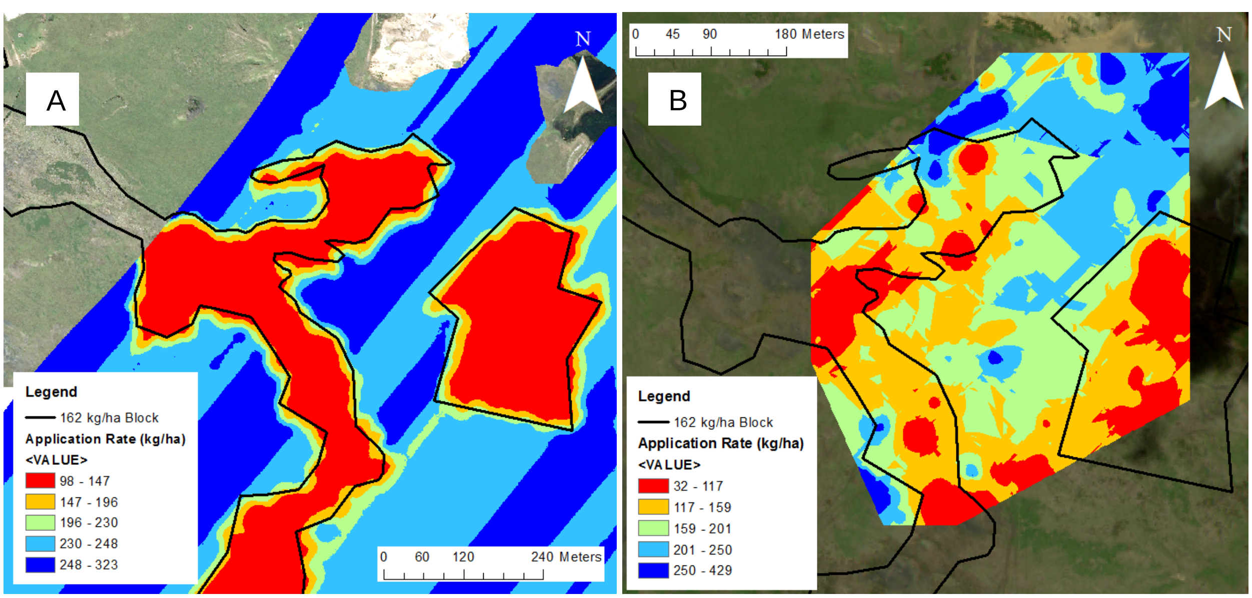

Figure 8: Proof of release (A) and placement (B) maps for Longview.

A one way analysis of variance (ANOVA) test of the collector data set was undertaken to determine if the averages of the two application zones differed for both trials. Limestone Downs and Longview both had a highly significant result ($P<0.001$), which indicates that differential rate system is able to recognize the treatment separation boundary line and adjust the hopper door opening to apply two rates. This is the most important measurement parameter for the differential rate application system because the capability of the system to change application rates is new to aerial spreading and the primary purpose of the installation. Improvements in accuracy and precision are a by-product of an automated hopper door and GPS, and are still limited by aerial spreading variables, such as fertilizer quality and wind conditions.

Assessment of sampling methods and kriging

Figures 9 and 10 are plots of the collected/recorded data against the predicted value. These are produced during cross-validation of the data where points are systematically removed and predicted for (Johnston et al., 2001). There are two distinct areas in Figure 9 (proof of release) because of the two application zones. The majority of values from the proof of release maps fall along a 1:1 line, which means the predicted values are well correlated with the aircraft recorded application rate. Points that deviate from the 1:1 line are near treatment separation boundaries.

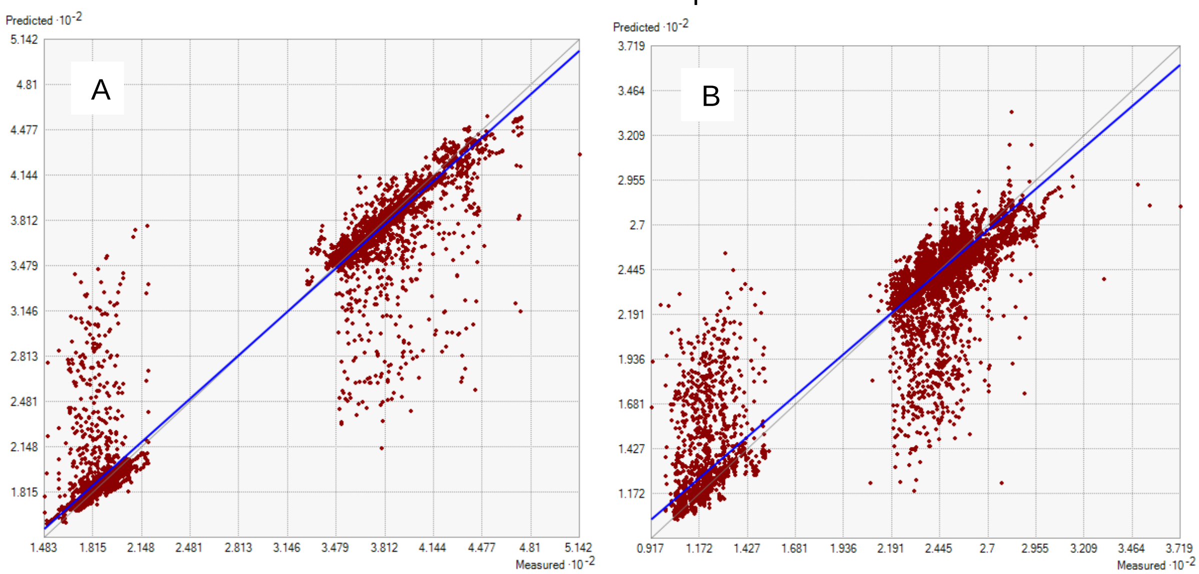

Figure 9: Error between predicted values and recorded aircraft values for Limestone Downs (A) and Longview (B).

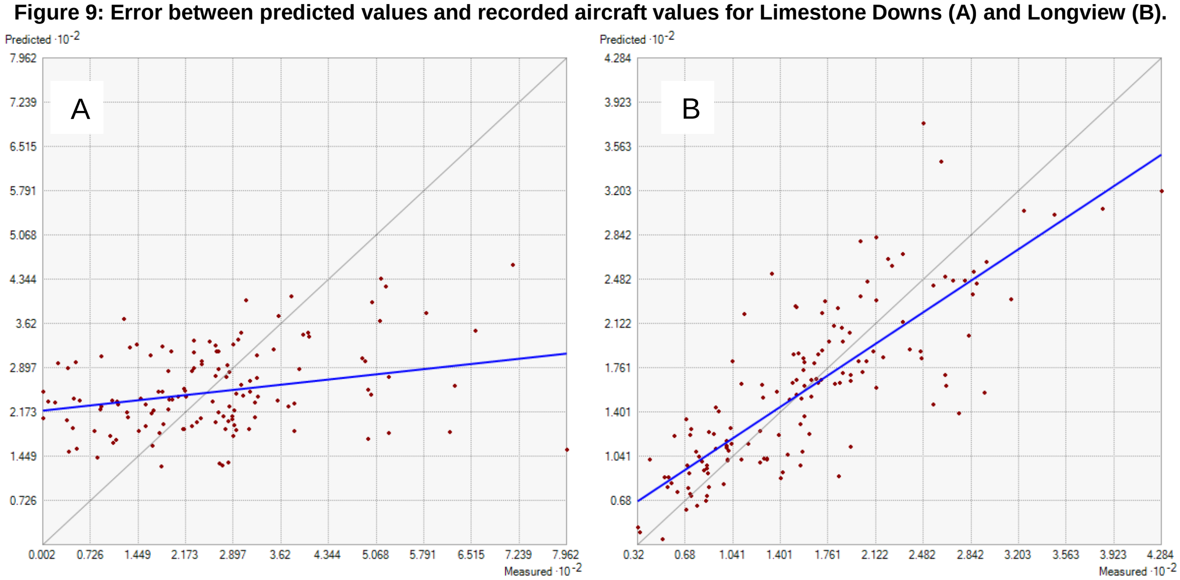

Figure 10: Error between predicted values and collector data for Limestone Downs (A) and Longview (B).

The difference between the predicted and collected data for the proof of placement maps was significant for Limestone Downs (Figure 10). There was under prediction of measured high application rates and vice versa. Although this is expected in kriging (Johnston et al., 2001), the magnitude of under/over prediction is significant. Longview's data set had better correlation to predicted values, and this is due to an improved sampling design.

Figure 11 shows the prediction standard error (PSE) for collectors at Limestone Downs and Longview. Prediction standard error is the square root of the prediction variance and indicates the uncertainty of an intermediary point (Johnston et al., 2001). If the collected data is normally distributed, the true value of any prediction should be within two times of the standard error for 95% of situations. Figure 11 shows predictions far from collected data have significant variances, which makes the overall map less reliable. Most of the area at Limestone Downs' had a PSE greater than 50, which means the variation of predictions could be ± 100 kg/ha. A significant area at Longview also had a PSE over 50. The high level of prediction standard error could be due to kriging error, collector error, changes in flow rate out of the hopper door, stochastic variability in aerial topdressing (noise) or a combination of these factors. Although Figure 11 is not able to indicate which of the errors/variability contribute to the standard error, it does show that kriging is not a suitable method for representing aerial topdressing trials as it is doubtful a representative sample size can be taken.

Future trials should seek to collect a complete data set on the system's accuracy, precision and capability without having the intention of kriging. Sampling can be done intensively over a small area, but this may not indicate the overall success of the application. Therefore a new sampling design is needed. One possibility is to replicate the sampling design done by Ballard and Will (1971), where there was a single line of 75 collectors perpendicular to the aircraft's flight path. This allowed for the collection of multiple transverse spread patterns, which would show the three levels of spatial variation in aerial spreading stated in the methodology.

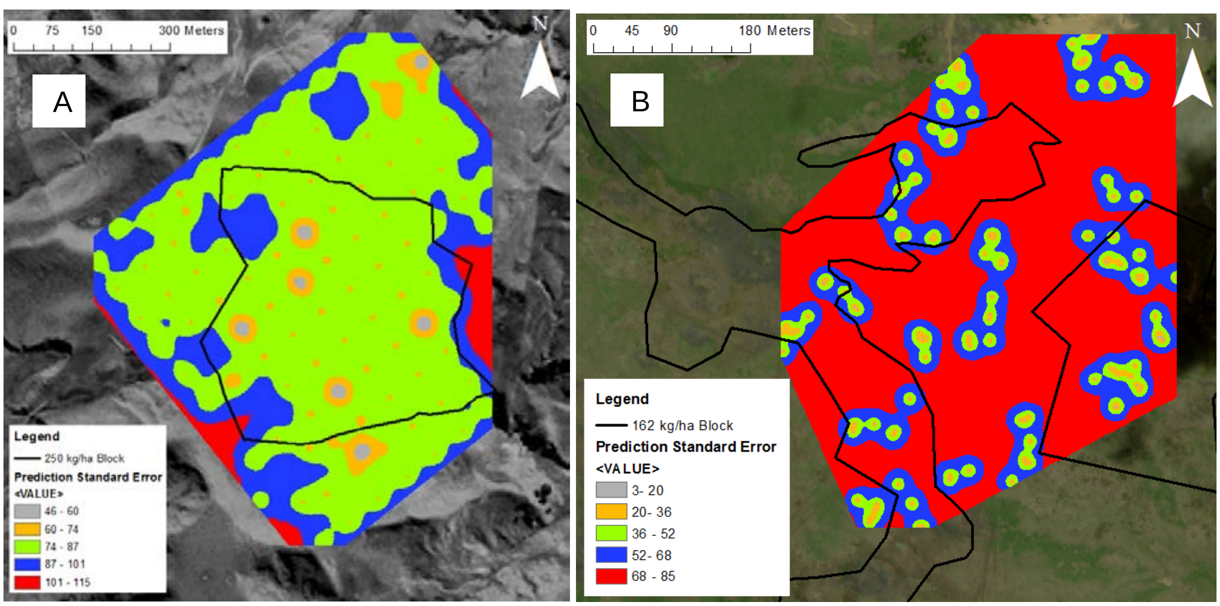

Figure 11: Prediction standard error maps for collector data at Limestone Downs (A) and Longview (B).

It should be noted that direct comparison between Limestone Downs and Longview cannot be made since trial areas and conditions differed. Replicates should be done at each farm but that is unlikely to occur because of resource and time constraints. It takes several days to set up a trial, depending on the topography, labor availability and vehicle accessibility. There is also a significant cost to each trial. However a final trial is planned for mid-2016 to test for accuracy and precision of the differential rate system. This trial will use improved collectors.

Conclusion

The two trials indicated that the differential rate application system under-applied fertilizer on the ground. However this could be due to collector error, poor calibration of the hopper door opening to the target application rate, variable wind conditions or a combination of all three. Precision has improved over conventional applications but it has not consistently reached Ravensdown's goal of a coefficient of variation of 30 – 35%. This could be improved through selecting a suitable swath width, ensuring parallel flights lines and maintaining consistent flight operation. The differential rate system was statistically tested and shown to be capable of applying two different application rates. Comparison of proof of release and placement maps showed they are significantly different. This is due to variable wind conditions and topography. Kriging collector data is not suitable for a large area because the variances between sample points are large, which makes the overall placement map unreliable. Therefore the sampling design should be changed for future trials.

Acknowledgements

The authors would like to acknowledge Ravensdown Limited for their funding and continued support of this project. We thank the Alma Baker Trust and Alf Harwood of Limestone Downs and David Pearce, the owner of Longview, for allowing these trials to be carried out on their properties.

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