THE BALLISTICS OF SEPARATION OF FERTILISER BLENDS AT WIDE BOUT WIDTHS

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Abstract.
In recent years some New Zealand arable farmers have experienced crop striping when spreading blended fertilisers. These farmers have not necessarily experienced the phenomenon prior to upgrading spreading equipment, capable of spreading to tram lines spaced at 30m plus. Fertiliser companies have been criticised as the blends used are no different to those used previously and in some cases have been recommended by the fertiliser companies' representatives.

Tram line spreading is generally very accurate. Spreaders are pattern type tested by manufacturers based on particle size, uniformity of particle size and bulk density, to achieve a pattern overlap which delivers the minimum spread variation possible, given the fertiliser particle parameters.

Spreading to a 30m tramline requires fertiliser particles to spread to at least 22.5m from each disc to allow for the required spread overlap, as spread overlaps of around 50% are common. To propel particles 22.5m from a height of 1.5m above ground requires them to be ejected at around $60ms^{-1}$. At these speeds blended fertilisers separate as their rate of deceleration through drag force is based on particle density, size and shape in order of importance. This paper quantifies the impact of drag force on typical fertilisers and demonstrates the relationship between increasing bout widths and greater separation of blends.

In addition a twin disk arable spreader was spread-pattern tested using the New Zealand Spreadmark test with typical high analysis fertilisers. Fertiliser particles discharging from the disks were filmed using high speed photometry and ballistic modelling, compared to the pattern test.

Keywords *Drag force, Ballistics, Blended fertilisers, Blend separation, in-field coefficient of variation, high speed photometry*

Introduction
In recent years arable farmers have been complaining to their fertiliser suppliers about striping in their crops. These complaints have received coverage in agricultural newspapers and magazines and radio broadcasts. Federated Farmers representatives allocated time for discussion of this issue at the May meeting of the Fertiliser Quality Council Forum.

The complainants have inevitably purchased modern top of the range twin disc spreaders with the ability to spread at an acceptable spread pattern at tram lines at or greater than 30m. These latest generation spreaders have increased tram or bout widths of spread from 20 – 24m, to 30 m thus reducing the number of tram lines and their disruption to the crop.

Spreading at a tram line of 30m requires a total spread pattern to be around 45m allowing for pattern overlap to achieve the accuracy required. Given that the spreading disks are around 0.5m - 1.5m above ground level then fertiliser particles must be discharged at some considerable speed.

Fertiliser customer representatives have often recommended product blends to reduce the number of fertiliser applications and deliver a proprietary nutrient mix that meets the needs of their customers. Their arable customers have continued to purchase these mixes and when spread at the correct settings to achieve a 30m tramline have experienced striping which previously at narrower tram lines has not occurred. Striping is a real economic issue as it is only visible at in- field coefficient of variation (CV) of around 40%, giving a yield reduction of at least 20%, (Mersmann *et al*, 2013) and (Yule and Grafton, 2013). This reduction in yield and economic impact on the fertiliser end user has resulted in the complaints, media coverage and the attention of the Fertiliser Quality Council.

The fertilisers being spread have not changed, the only change has been in the bout width distances the products are being spread. This suggests that the striping is due to the change in bout width as the specifications of the fertiliser have little changed and that it results from differences in ballistic properties.

There have been a number of case studies undertaken which demonstrate splitting of fertiliser blends resulting in uneven spread, of which (Miserque *et al*, 2008) and (Yule and Pemberton 2009) are examples. Whilst the elements which lead to separation are identified by (Miserque *et al*, 2008) and (Yule, 2011) to be particle or specific density, particle size and particle shape in that order of effect on the distance particles spread.

Spreader operators are required to undertake a bulk density test and establish mean particle size by use of a sieve box prior to setting the equipment for the correct bout width as specified in the manufacturers' tables. Blended fertilisers produce a bulk density and mean particle size which will differ from the ideal settings of both products if spread separately.

This paper uses ballistic modelling to identify fertiliser ballistic characteristics, so that bout widths which may result in blends splitting can be identified; so that products can be categorised in the distance they will travel at discrete spreading speeds. In addition the paper identifies the speeds fertiliser particles need to travel to produce a bout width of 30m when delivered from a height of 1.5m.

Material and method

Samples of fertilisers commonly sown by arable farmers were collected from Ravensdown's Aramoho store. The products selected were; monoammonium phosphate (MAP), di-ammonium phosphate (DAP), Ammonium sulphate (crystals), urea, Potassium chloride (KCl) and single superphosphate (SSP). A random sample of about 0.5Kg of each product was taken to be placed through a standard Fertiliser Quality Council sieve box and for the particles to be examined so that their cross sectional area, volume and approximate drag coefficient could be established (Anon, 2013). Particle densities for the products were taken from product specification material data information.

This information is required for ballistic modelling. The drag force on a particle is:

$$Fd = \frac{1}{2}\rho v^2 cdA$$

Where:

- $\rho = 1.2kgm^{-3}$ the density of air at 0 velocity at standard temperature and pressure.
- v is the velocity of the particle
- cd is the drag coefficient of the particle
- A is the cross sectional area of the particle
- v_f is the final velocity
- v_i is the initial velocity

By dividing force by the particle mass which was determined by the mean particle volume divided by the specific or particle density which was determined by the product specification material data information (Pers.comm, M. J. Manning, GM Research and Development, Ravensdown Fertiliser Co-op, 12 June, 2013), the acceleration a of the particle is determined, through differentiation and anti-differentiation the distance D a particle will travel can be determined.

$$a = \frac{1}{2}\rho v^2 cdAm^{-1}$$

$$K = \frac{1}{2}\rho cdAm^{-1}$$

$$\Delta a = 2vKt$$

$$v_f = (v_i - Kv_i^{\ 2})dt$$

By taking small increments of time the distance travelled in each increment is given by

$$D \approx v_i - (Kv_i^{\ 2}\Delta t)dt \quad Lim v_i > 0$$

Integrating the velocity time function reveals the distance travelled horizontally. However as the result is an exponential function both in terms of velocity and time then the result is only accurate when changes in time are extremely small. This issue is mitigated by calculating the time a particle will travel, which is a function of the height and gravity and undertaking iterative calculations at short time intervals. As particles in the vertical plane start from rest and the height is 1.5m, then the time particles travelled can be approximated with the assumption of drag force in this plane being close to zero.

The time particles are in motion is then:

$$t \approx \sqrt{\frac{2h}{g}}$$

To achieve an accurate calculation of the distance fertiliser particles will travel at a given speed the distance was calculated by integrating and accumulating the distance travelled by ten iterations, by taking the time for the particles to travel before landing, a little over half a second and integrating at time intervals of $0.1t$, which is both, Δt.

The SSP has a heterogeneous range of particle size, whereas the other fertilisers were homogenous, for this reason although the mean particle diameter was 2.9mm, the particle range was also examined so 1.00mm and 4.7mm particles were also modelled.

The input values are shown in Table 1.

Table1: Input parameters for ballistic modelling.

	Ammonium Sulphate	KCl	MAP	DAP	Urea	SSP 1.0mm	SSP 2.9mm	SSP 4.7mm
cd	0.8	0.8	0.8	0.8	0.47	0.6	0.6	0.6
P (Air Density Kgm^{-3})	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
A cross sectional Area m^{-2}	$4x10^{-5}$	$1.05x10^{-5}$	$7.5x10^{-6}$	$5x10^{-6}$	5×10^{-5}	$3.9x10^{-7}$	$3.3x10^{-6}$	$8.7x10^{-6}$
Mean Particle mass kg	$1.4x10^{-5}$	$7.0x10^{-5}$	$3.2x10^{-5}$	$1.9x10^{-5}$	$2.7X10^{-5}$	$1.2x10^{-6}$	$2.8x10^{-5}$	$1.2x10^{-4}$
Particle Density Kgm^{-3}	1,769	2,942	1,800	1,619	1,320	2,200	2,200	2,200
K	.136	.071	.11	.123	.072	.123	.042	.026
T s	.55	.55	.55	.55	.55	.55	.55	.55

Results

The horizontal pattern spread of the fertiliser particles as defined in Table 1 are shown in Table 2 assuming the particles do not have spin, which can either increase or decrease the distance spread, depending whether top or back spin is imparted when spread.

The exercise demonstrates which commonly applied blends are likely to separate when applied at wide bout widths. Although spread patterns are dependent on the rotational velocity of the spinner and the point of discharge, which effects the horizontal pattern by CosØ. However, to produce a spread pattern overlap particles must be spread at around 1.5 bout width, when CosØ =1. For the results of modelling horizontal spread by fertiliser type, see Table 2.

Table 2: Distances typical fertiliser particles will travel when ejected at various speeds, in a horizontal plane

Horizontal velocity	Ammonium Sulphate (m)	KCl (m)	MAP (m)	DAP (m)	Urea (m)	SSP 1.0mm (m)	SSP 2.9mm (m)	SSP 4.7mm (m)
60ms^{-1}	17.0	21.8	18.8	17.9	23.6	17.9	24.0	25.2
50ms^{-1}	15.3	18.6	16.6	16.0	19.8	16.0	20.0	20.9
40ms^{-1}	13.1	15.1	13.8	13.5	15.8	13.5	16.0	16.5
30ms^{-1}	10.2	11.3	10.6	10.4	11.7	10.5	11.7	12.0
20ms^{-1}	6.9	7.3	7.0	6.9	7.4	7.0	7.5	7.6
10ms^{-1}	3.1	3.2	3.2	3.1	3.2	3.1	3.2	3.3

Case Study

The aim of the case study is to compare ballistic modelling of fertiliser particles ejected from a Kuhn Axis twin disk spinner, with measurements from a Spreadmark (New Zealand Fertilser Quality Council, 2013) pattern test.

Materials and Methods

Two homogenous high analysis fertilisers Nitrophoska12-10-10 (12.0%,N 8.8%,P 10.0%,K 0.4%,S 1.2%,Mg 4.6%,Ca) by weight and DAP (17.6%,N 20.0%,P 1.0%,S) (were sieve tested as per BS-410-2, (2000), see Figures 1and 2.

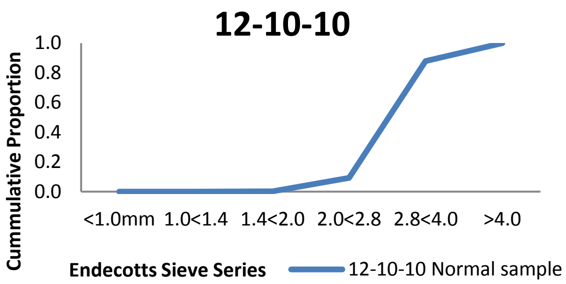

Figure 1: Cumulative sieve test Nitrophoska 12-10-10

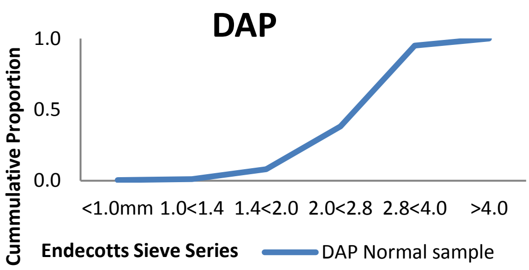

Figure 2: Cumulative sieve test DAP

The ballistic attributes of the two products were calculated from representative samples taken from the 500kg bags of each product which was spread tested, see Table 3.

Table 3 Ballistic properties of spread tested samples

Property	12-10-10	DAP
cd	0.55	0.6
P (kgm^{-3})	1.2	1.2
A (m^2)	$7.07X10^{-6}$	$4.91X10^{-6}$
M (Kg)	$1.6X10^{-5}$	$1.3X10^{-5}$
K	0.146	0.136

The Kuhn Axis spreader was mounted on a New Holland tractor and important features related to ballistics were measured. High speed photometry, at eight hundred and one thousand frames per second was used to help analyse the fertiliser being spread from the disks, see Figures 3 and 4.

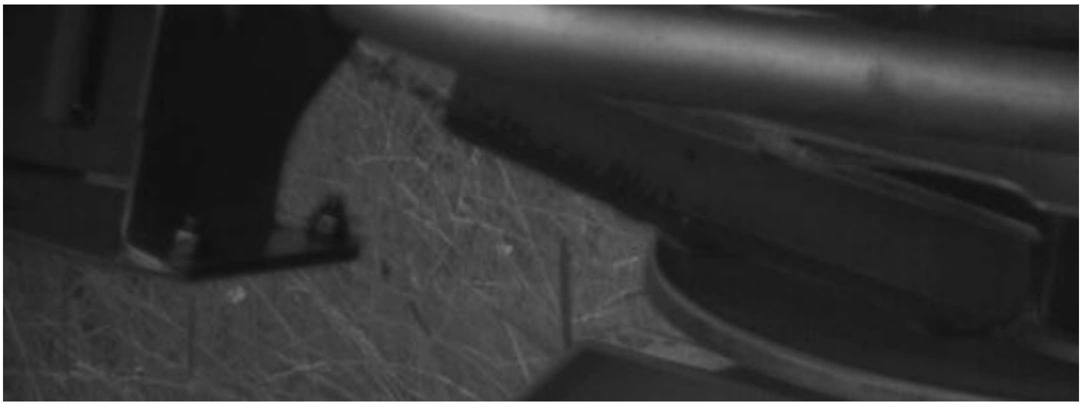

Figure 3: Long vane spinner 0.285m spreading Nitrophoska 12-10-10 at 1083 revolutions per minute, a still photograph from high speed photometry

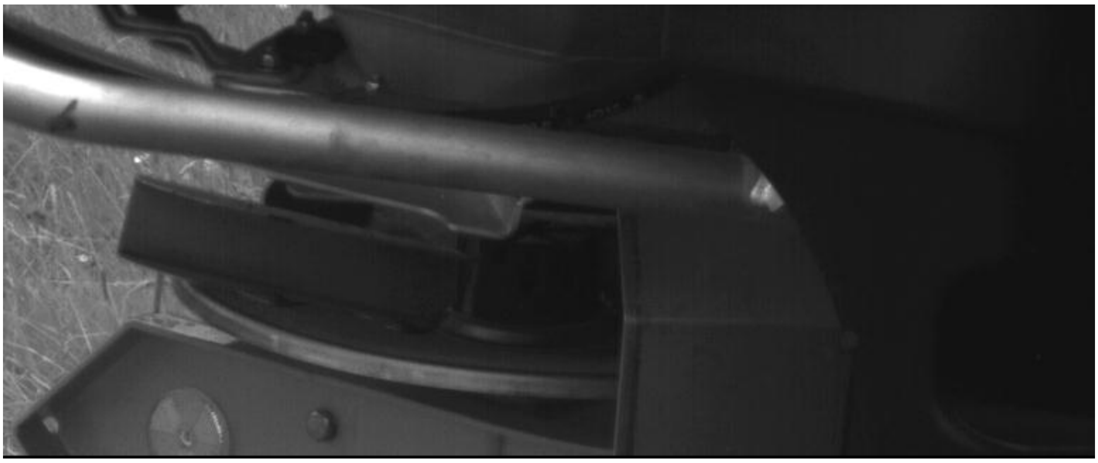

Figure 4: Short vane spinner 0.215m spreading Nitrophoska 12-10-10 at 1083 revolutions per minute, a still photograph from high speed photometry

The measured ballistic properties of the spreader are displayed in Table 4.

Table 4 ballistic properties of spreader common to both fertilisers

Properties	Constants
Vane long (m)	0.285
Vane short (m)	0.215
ω rotational velocity ($rads^{-1}$)	18.05
Exit velocity large vane (ms^{-1})	32.5
Exit velocity short vane (ms^{-1})	24.5
Elevation angle of delivery (degrees)	15
Horizontal initial velocity long vane (ms^{-1})	31.4
Vertical initial velocity long vane (ms^{-1})	8.4
Horizontal initial velocity short vane (ms^{-1})	23.7
Vertical initial velocity short vane (ms^{-1})	6.3
Height of disks above ground level (m)	0.7
Apex long vane (m)	4.3
Apex short vane (m)	2.75
Height apex of parabolic flight long vane (m)	4.3
Height apex of parabolic flight short vane (m)	2.75
Time of flight long vane (s)	1.8
Time of flight short vane (s)	1.4

Parabolic flight

The Kuhn Axis spreader delivers fertiliser in a parabolic flight path, which contains a vertical as well as a horizontal component. The vertical component is Sin 15° of the exit velocity, which is a little over 25% of the horizontal component. Although, the vertical component is also subject to a drag force, the drag in the upwards direction is opposite and almost equal to the drag in the downwards component of flight, so at the speeds and period in fertiliser delivery from this spreader assuming a vertical drag force of 0, and gravity is the only acceleration in this plane is a valid approximation.

Thus the time to the parabolic apex is the exit velocity in the vertical plane divided by acceleration of g:

$$t \approx \Delta v / g$$

The distance to the apex is the area under the velocity time graph and total time of flight includes the time of descent which requires the apex height to be known.

$$d \approx \frac{\Delta v}{2} t$$

$$t \approx \sqrt{\frac{2h}{g}}$$

Predicted results

The predicted spreading distances, for the mean particles, of the fertilisers is shown in Table 5. Actually as the Kuhn Axis is a twin disk spreader the total spreading distance without any overlap is twice the distances shown in table 5, assuming still conditions.

Table 5 Particle spreading distances from each vane

	12-10-1-0	DAP
Distance long vane large particle size (m)	21.9	20.1
Distance short vane large particle size (m)	12.9	13.5
Distance long vane mean particle size (m)	18.7	19.2
Distance short vane mean particle size (m)	12.4	12.6
Distance long vane small particle size (m)	14.4	17.7
Distance short vane small particle size (m)	10.9	12.1

Results Spreadmark pattern test

Both fertilisers were pattern tested over 3 rows of eighty, 0.5m x 0.5m trays with insets in accordance with the Spreadmark method and analysed using Spreadmark version 16, analysis software. Although, the Spreadmark method requires still conditions; wind speed less than 15kmhr^{-1} a little over 4ms^{-1}, the conditions on the testing day, ranged from 1 – 8ms^{-1} cross wind. The test was undertaken to assist research using borrowed equipment on a specific day, so the tests were undertaken and the effects of a crosswind measured on the test patterns, to achieve a CV (standard deviation of spread/ mean) of 15%, see Figures 5-7.

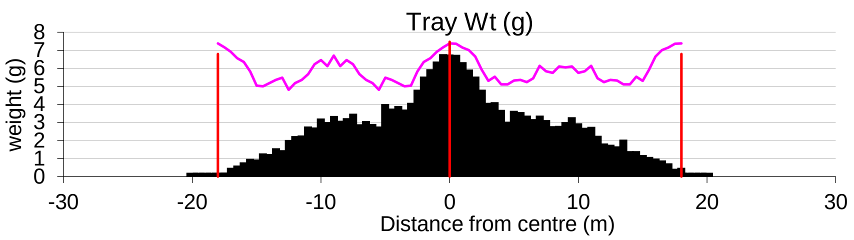

Figure 5a: Chart shows the shape of spread pattern, where horizontal lines show bout spacing to achieve pattern overlap to achieve a 15CV, the pink line represents a to and fro pattern as tested.

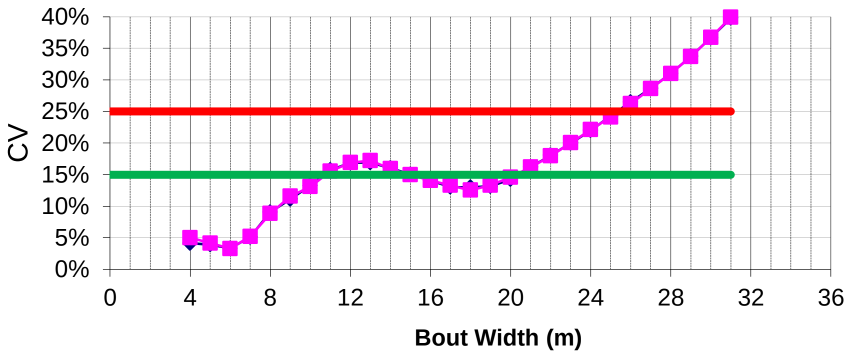

Figure 5b: Spread pattern test still conditions, Nitrophoska 12-10-10, bout width 21m. The green horizontal line represents the 15% CV line required for fertilisers containing N, the pink line the to and fro spread pattern

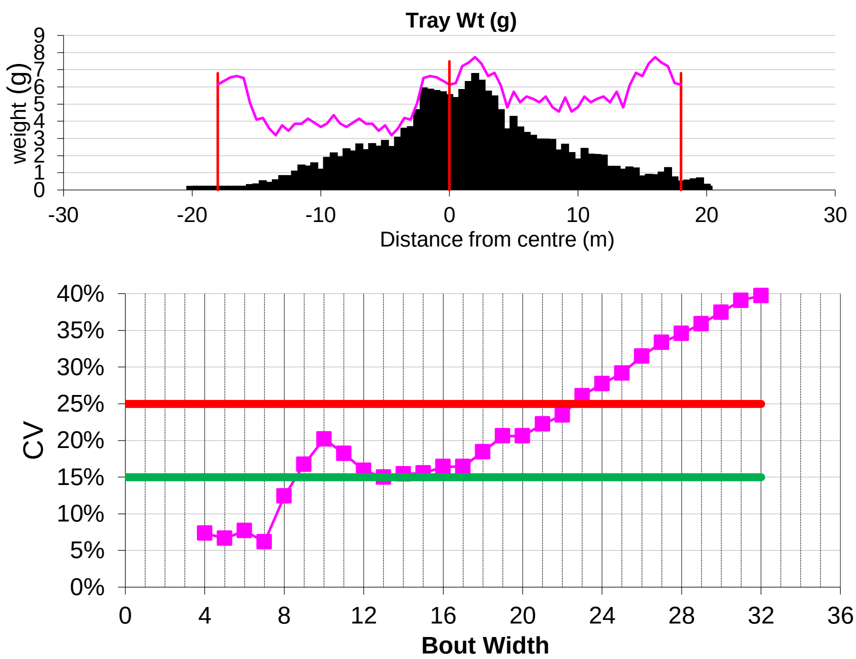

Figure 6: Spread pattern test in 6ms^{-1} cross wind, Nitrophoska 12-10-10, bout width 14m.

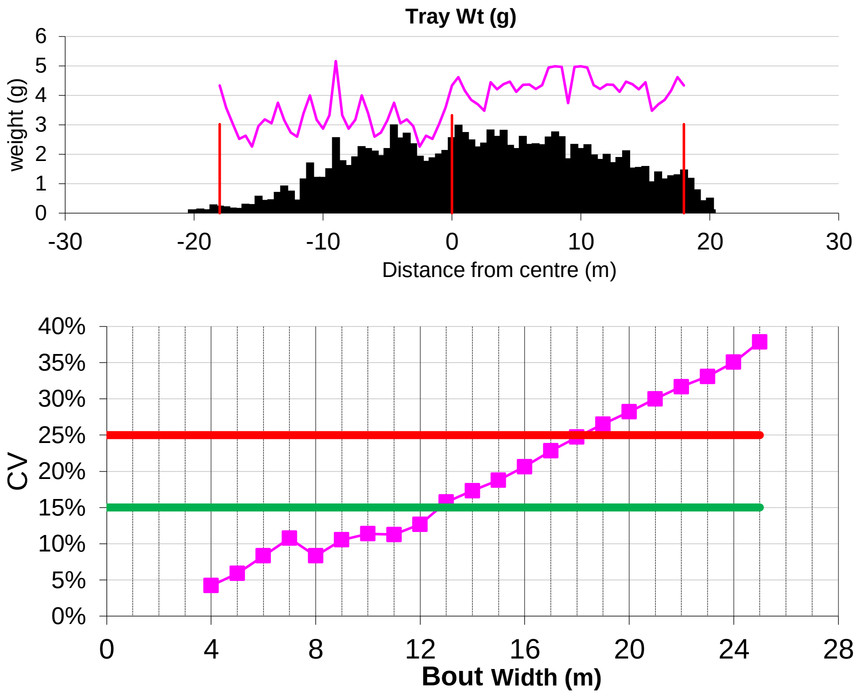

Figure 7: Spread pattern test in 6ms^{-1} cross wind, DAP, bout width 13m.

The effect of ballistic modelling a 6ms^{-1} cross wind was calculated and is displayed in Table 6.

Table 6 Shows effect of adding cross wind component to the ballistic model

Into 6ms^{-1} head wind	12-10-1-0	DAP
Distance long vane large particle size (m)	16.6	15.6
Distance short vane large particle size (m)	9.0	8.7
Distance long vane mean particle size (m)	14.7	15.0
Distance short vane mean particle size (m)	8.5	8.6
Distance long vane small particle size (m)	12.2	14.1
Distance short vane small particle size (m)	7.8	8.3
With 6ms^{-1} tail wind		
Distance long vane large particle size (m)	22.8	24.4
Distance short vane large particle size (m)	18.1	17.1
Distance long vane mean particle size (m)	22.2	22.9
Distance short vane mean particle size (m)	16.2	16.5
Distance long vane small particle size (m)	15.6	20.6
Distance short vane small particle size (m)	13.7	15.6

Discussion case study

It is apparent if good information is known about the spreader characteristics and the fertiliser particles ballistic properties being spread, then their disposition can be accurately predicted. For homogenous fertiliser particles this means that it should be possible to predict spreading bout widths and off sets for varying spreading machinery using different fertilisers.

Discussion in general

The result of the modelling demonstrates that as fertiliser particle velocities increase the greater the impact particle ballistics play in the distance they travel. Some common blends such as potassium chloride and ammonium sulphate have quite different ballistic properties which will lead to the products separating if sown together. Whereas, urea and potassium chloride appear to have similar ballistic properties, although quite different shapes and densities and may be suitable to blend.

Although single superphosphate is heterogeneous in particle size distribution, this should not lead to striping issues unless the particles are blended as the nutrient status should remain constant as long as the spreader is set up for the correct bout width.

Blended fertilisers will have a degree of separation at any speed or bout width. However, the separation at narrower bout widths is reduced with a consequently decreased impact on the in–field CV. This is evident as striping is not visible at in-field CV less than 40%, therefore as bout widths have increased to 30m some blends are separating sufficiently to produce this variation in spread.

Fertiliser ballistic differences start to become significant at between $30ms^{-1}$ and $40ms^{-1}$, for common materials with different physical properties. Therefore, unless mixes have similar properties then blends should not be sown at bout widths much greater than 20m.

Applicators contemplating spreading at bout widths greater than this should have their spreader tested for the material being spread and should stick to homogenous products, as proprietary mixes are likely to separate.

Although striping may not be evident there will still be a reduction in yield but the economic impact reduces exponentially as in-field cv reduces, (Mersmann *et al*, 2013) and (Yule and Grafton, 2013).

Conclusion

Farmers and farm advisors should be more aware of the ballistic properties of the products they use and recommend. They should also be aware that by blending products with differing ballistic properties then the in-field CV will increase and this will have an adverse impact on yield.

In many situations the saving in cost of increasing bout widths and reducing the number of applications by blending fertilisers, will be less than the reduction in income by reducing yield by increasing the in-field CV of the spread.

Farmers can avoid the need to apply several fertilisers along the same tramlines by soil testing early to establish the nutrients required for the crop scheduled for sowing. Then applying these nutrients by direct drilling, or broadcast sowing prior to crop establishment. Tramlines can then be set for side-dressing one product such as urea at the optimum bout width.

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