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The accuracy of farm machinery for precision agriculture: a case for fertilizer application

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Abstract

Work quality, capacity and reliability are important criteria for design and evaluation of farm equipment. With the introduction of precision agriculture, the ability to adapt to spatially variable soil and crop conditions, becomes an additional aspect. A calculation method is developed to find the precision of site specific fertilizer application. The variance between the required rate, RR, and the applied rate, AR, is used as a measure for precision. The theory of geo-statistics is used for variance calculation. Spreading patterns are evaluated for different levels of field variability, positioning accuracy and resolution of the required application rates. The shape of spreading patterns had small influence. The effect of the accuracy of positioning systems depends on the resolution of the required application rates and of the working width of independently controlled sections of the spreaders. The study shows how machine design depends on the resolution of field information.

Keywords: Fertilizer application, precision agriculture, geo-statistics

Introduction

Modification of agricultural practises according to spatial variability within agricultural fields will benefit the economic and environmental aspects of farming (Robert *et al.*, 1993). Precision Agriculture is an accepted term for such practise and stands for an integrated package of techniques. This will increase efficiency of inputs, realize less pollution and improve energy utilization while income of farmers is maintained with competitive prices.

Technology in precision agriculture.

A technological push made precision agriculture a realistic option. The relation of soil and crop characteristics and field operations to their geographical location is crucial for precision agriculture. The development of receivers for the Navstar Global Positioning System (GPS) and the Global Navigation Satellite System (GLONASS) made this possible (Krüger *et al.*, 1994). Other sensor techniques are in development for data collection on soil and crop characteristics. Yield mapping technology is developed and available for combinable crops (Murphy *et al.*, 1995), while work is initiated for other harvesting techniques (Rawlins *et al.*, 1995). Yield mapping is essential to validate all the assumptions on potential yields used during formulation of the site specific prescriptions. Investigations are done to measure soil nitrogen (Adsett & Zoerb, 1991), soil organic matter (Suddeth *et al.*, 1991), weed population (Thomson *et al.*, 1991) and tillage resistance. Remote sensing is used to determine the crop biomass and the leaf area index. Satellite and aircraft are used as platforms to monitor crops (Bouman, 1995), but research is being carried out to use agricultural vehicles during normal field operations for these measurements (Reusch & Heege, 1996).

All data collection and location specific control of the operations are made possible by developments in computer and communication technology. Electronic control units and actuators change machine settings for location specific treatments. Communication buses are used to exchange data between micro controllers on agricultural equipment (Hofstee & Goense, 1994, 1996) and communication protocols are used for the data exchange between the mobile systems and the management information system on the farm (Goense, 1996).

The accuracy, speed, resolution and quantity of data associated with mentioned technologies depend on cost. Accurate measuring or dosing will in some cases require changes in the construction of the machine. For design of agricultural machinery it is necessary to judge the effect of accuracy on the agronomic aspects, to justify increased cost.

Location specific fertiliser application is one of the first techniques used in precision agriculture. Good application of fertilizer granules, which means even distribution in the case of broadcasting or correct placement in relation to a plant row or individual plant, is relevant for uniform and location specific fertilizer application. In the latter case also the ability to vary the rates following the location specific requirements in the field, is important. Distribution technique, accuracy of the positioning system and the resolution in which required rates are made available will influence this ability.

A variety of fertiliser spreaders are available for broadcast fertiliser application. The twin disc centrifugal spreader with working widths up to 32 m, the reciprocating spout broadcaster with widths to 12 or 18 m and the pneumatic spreader that eventually can control sections of 3 to 6 m, are the most important ones. Development of a new generation of spreaders with even smaller, independently controllable, sections can be considered.

Fertilizer spreaders have spreading patterns that differ in size and in shape. The reciprocating spout broadcaster has a sharp pyramid shape, a two-disc centrifugal spreader used in this study has a less sharp pyramid shape, and for a pneumatic spreader a roof like shape is assumed. With location specific fertilizer application, variations are introduced on purpose by adjusting the rate, to realise application rates that are as close as possible to the required ones. Required application rates can be specified either for an area or for a point. The field can be divided in grid areas; rectangle areas following a certain grid, or in polygons; areas of any shape of which the borders are described by polylines. Points in a field can also be systematically arranged following a grid, called gridpoint, but can also be located over the field in any pattern, in which case they are called pattern points. (Goense *et al.*, 1996). The different types of objects for which determined application rates are specified can be presented in different resolutions. Narrow or coarse grids can be used for grid areas and grid points and in the case of polygons it is possible to describe many areas with small differences in required application rates or fewer areas with larger differences.

The objective of this particular study is to develop a method to calculate the effect of application technique on the precision of site specific fertiliser application and to present the results. Accuracy will be expressed as the deviation between the required rate (RR) and the applied rate (AR).

The calculations for different levels of variability of the field, study the following aspects:

A. The effect of different widths and shapes of spreading patterns.
B. The resolutions in which the required application rates are made available.
C. The accuracy of the positioning system.

Materials and methods

Components of Fertilizer Application Systems

The following subsystems of site specific fertilizer application influence accuracy;

- spatial variability of required application rates and the method of presentation,
- the distribution patterns of fertilizer spreaders and
- the accuracy of the positioning system.

Application Rates

Location specific recommendations are subject of current research and no overall strategy is developed yet. Actual soil fertility, actual crop conditions in case of fertilizing after crop emergence, the expected yield and fertiliser efficiency are some of the variables that can play a role in determining the required application rate. The mentioned variables are soil dependant and their value will vary by location. Determination of the value of these variables will have uncertainty, the effect on crop response will be influenced by the weather and other, not known, factors and introduce additional uncertainty. The recommended application rates therefore have a certain level of uncertainty. This uncertainty is however not considered in this study because the effect of application techniques is the main interest. It is assumed that the set point application rate for the specified point in the field is the true estimator for the required application rate of that point without variance.

The differences between required and applied application rates depend for site specific application among other factors on the spatial variability of the required rate and can, like other spatial variables, be described by a semi-variogram. The basic assumption is that the variability of values measured by observations in space varies with the distance between observations (Journel & Huijbregts, 1978). This dependency is described in a variogram function that gives the semi variance 2γ as a function of lag distance h.

$$\gamma(h) = \sum_{i=1}^{n(h)} \frac{[(Z(x_i) - Z(x_{i-h})]^2}{2n(h)} \tag{1}$$

where
$\gamma(h)$ = semi-variance for distance between samples h
$Z(x_i)$ = the observed value at point x_i.
$n(h)$ = the number of observed pairs at distance h.

Several models exist for semi-variograms. In this study calculations are made for the exponential model, but the developed calculation method in itself is independent of the used semi-variogram model. The exponential model is represented by the following two equations:

$$\gamma(h) = C + a(1-e^{-bh}) \;\; if\, h > 0.0 \tag{2}$$

$$\gamma(h) = 0.0 \;\; if\, h > 0.0 \tag{3}$$

Where
$C + a$ = the maximum semi-variance, the sill and
C = the nugget, the variance between points at a distance that approaches zero.

The mutual distance h at which the sill is reached is called range. An exponential model reaches its sill only asymptotically. A 'practical' range of b= 3/range is used, where $1\text{-}e^{-3}$ corresponds with 0.95 (Journel & Huijbregts 1978).

Different levels for the range are used to express the variability of the field. In one particular experimental field in the Netherlands, the ranges for N-content were in the order of 150–250 m (Gijsbers, 1996), but smaller ranges are also reported. Hergert *et al.* (1995) report an average range of 85 m for Nebraska, but ranges varied among the individual sites from 40 to 275 m. The required application rates are apart from soil N-content, based on spatial variable soil parameters. Ranges between 36 and 256 m are studied. The level of the sill is set at 100 percent and the nugget at 5 percent. It is assumed that technical limitations for the equipment to realise the changes in required application rates are not present. For that reason, percentages are used as the measure for variability.

Electronic control units with sufficient computing power for real time kriging are not realistic at present. Therefore either the values of the original sample points are passed to the application system, or the values obtained by interpolation by the management computer. Interpolated data can be made available in any resolution, but storage and data processing capacity limit the useful resolution. In this study required rates as values for grid points with different resolutions, being multiples of 1.0 m, are evaluated.

Distribution Patterns of Fertiliser Spreaders.
The following distribution patterns of fertiliser spreaders are studied;

- Theoretical spreaders with square, pyramid shaped distribution areas (Figure 1a)
- Theoretical spreaders with square, flat shaped distribution areas (Figure 1b)
- Sections of a pneumatic spreader with rectangular distribution areas. Measurements for a two dimensional spreading pattern of this type of spreader are

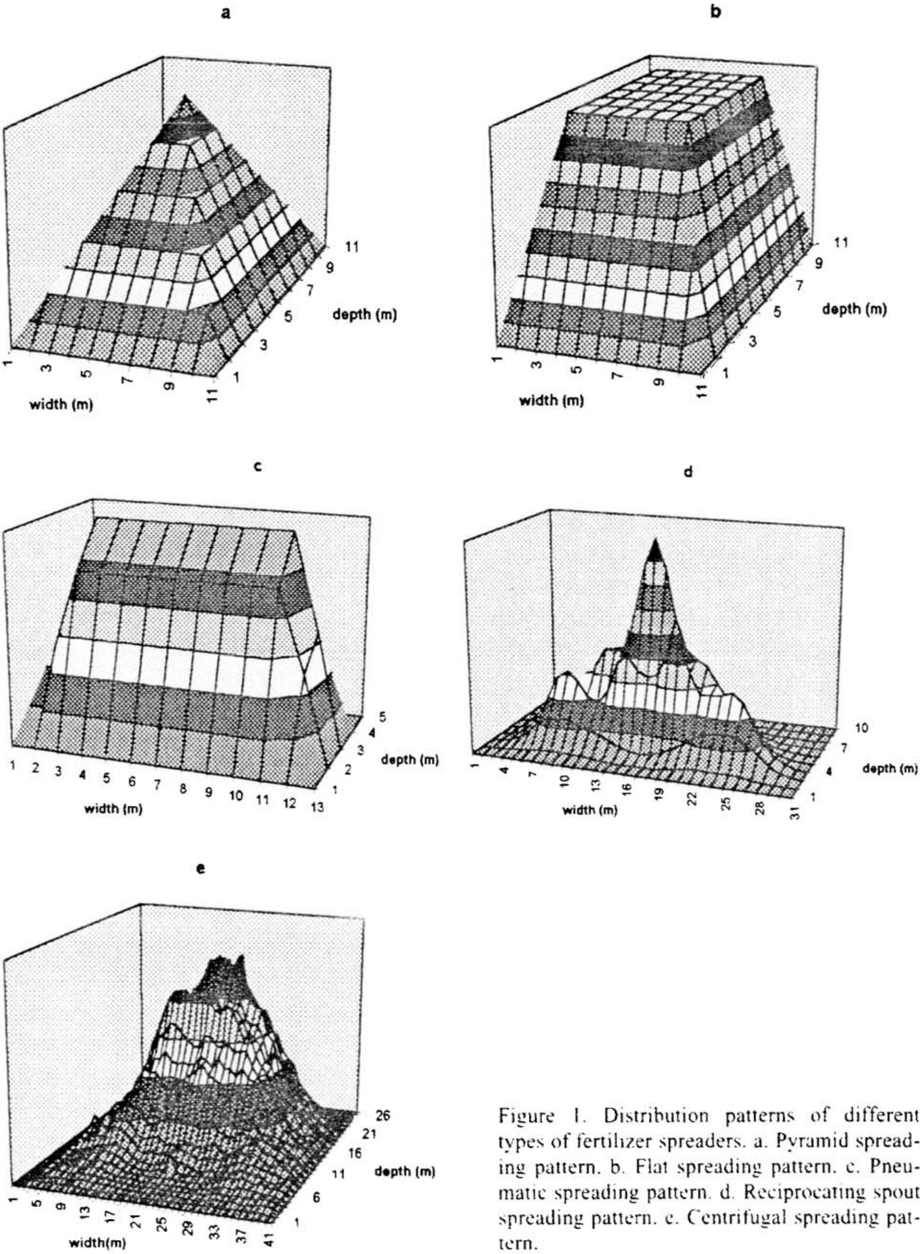

Figure 1. Distribution patterns of different types of fertilizer spreaders. a. Pyramid spreading pattern. b. Flat spreading pattern. c. Pneumatic spreading pattern. d. Reciprocating spout spreading pattern. e. Centrifugal spreading pattern.

not available yet. The estimated shape of the distribution pattern is that of an asymmetric roof (Figure 1c). The depth of the surface area is 3 m, while calculations are made for different widths (Table 1).

- A reciprocating spreader that has a distribution area of 29 m wide and 8 m deep. The measured distribution is given in Figure 1d, and can be described as a sharp cone like distribution. The effective width is 12 m.
- A two-disc centrifugal spreader with a distribution area of 41 m width and 25 m deep. The measured shape of this type of centrifugal spreader is cone-like (Figure 1e). The effective width is 18 m.

The dimensions of the spreading patterns, with their effective width, are presented in Table 1. The spreading patterns are two dimensionally described by the relative distribution for areas in a grid of 1.0 × 1.0 m. The distribution pattern of the hypothetical spreaders and their effective width is such that the standard deviation of the total spreading pattern is 0.0. For the reciprocating and centrifugal spreader, standard deviations are 1.6% and 3.3%. These standard deviations are lower then found in tests of this type of spreaders, because the measured data is smoothed. This is done because the main interest is the effect of the pattern shape and dimension of the pattern.

Positioning

The Global Positioning System (GPS) has now the best potential as an agricultural location system (Stafford & Ambler, 1994). Differential GPS code receivers are widely used. Improvements in code receiver technology have improved accuracy; prices of carrier phase enhanced receivers might reduce sufficiently that they can be considered for use in agriculture. Measurements with a six-channel DGPS code re-

Table 1 The dimensions of the surface areas of the evaluated distribution patterns of different types of fertilizer spreaders for the corresponding effective working widths.

	Type of fertilizer spreader							
	Pyramid	flat	pneumatic		reciprocating		centrifugal	
effective width (m)	length and width (m)	length and width (m)	length	width (m)	length	width (m)	length	width (m)
1.0	1.0	1.0						
2.0	3.0	3.0						
3.0	5.0							
4.0		5.0	3.0	5.0				
6.0		7.0	3.0	7.0				
7.0	13.0							
12.0		13.0	3.0	13.0	8.0	29.0		
13.0	25.0							
18.0							25.0	41.0
24.0		25.0	3.0	25.0				
25.0	49.0							

ceiver showed that deviations from true position could be reasonably well described with a normal distribution and had standard deviations of 1.7–2.4 m in the North-South and East-West direction respectively (Van Bergeijk *et al.*, 1996). In this study positioning with accuracies represented by a standard deviation of 0.0, 0.5, 1.0 and 2.0 m in both directions is evaluated.

Calculation of Applied Fertiliser Rates

Applied rates are calculated for grid areas with a resolution of 1.0 m, the resolution used to describe the two dimensional spreading patterns. Calculations are made for discrete 'steps' of 1.0 m and passes on an effective width that are multiples of 1.0 m. The orientation of the spreading pattern and field coordinate system are the same and the areas of the pattern are exactly positioned above the field areas in each step.

Sources of Variation

Deviation between required application rate *RR* and applied application rate *AR* can be due to:

a. Deficiencies in the distribution patterns due to incorrect overlap, a shape of a single-pass distribution pattern, that has an optimum effective swath width, with a coefficient of variation that is larger than 0.0, and irregularities in the shape. These variations would also occur with uniform application and perfect control of the application rate. The distribution patterns for the reciprocating spout broadcasters and the centrifugal spreaders have this source of error.
b. The deviation by selecting only one application rate at a certain moment for all areas under the spreading pattern. These areas require most likely different rates but receive a fraction of one selected rate. A simple algorithm is chosen that uses the required rate under the centre of gravity of the spreading pattern as application rate. No evaluation is made yet of other alternatives like a weighted average of the required rates under the spreading pattern.
c. The variance of the required application rate itself. This aspect is not considered yet.
d. Positioning errors in the x and y direction. The system assumes the centre of gravity of the spreading pattern to be on a certain position for which it takes the required rate. In reality it is on another position that might require another rate.

Calculation of applied rates

A certain considered area in a field, *a*, accumulates in discrete steps *s*, in the direction of driving, during one pass, or in the case of overlap during more passes, *p*, a certain amount of fertilizer AR_a. The amount received by area *a* in each step in each pass, $Fr_{a,p,s}$ is the fraction of the total deposited flow that during that step in that pass is deposited above the field area *a*. The deposited flow is, as discussed before, based on the required rate of the field area that is during that step in that pass positioned under the centre of gravity of the spreading pattern, $RR_{cg,p,s}$. When the required rates are made available in the highest possible resolution, the centre of gravity has for each step (X direction) during each pass (Y direction) a specified required rate. The applied rate for the field area AR_a can then be calculated as:

$$AR_a = \sum_{p=1}^{p=P} \sum_{s=1}^{s=D} RR_{cg,p,s} * Fr_{a,p,s} * \frac{EW}{\Delta X} \qquad (4)$$

Where

AR_a = Applied rate on the considered field area a.

P = Number of passes made over the area under consideration.

p = Index of the actual pass

D = Depth of the spreading pattern in steps.

s = Step in driving direction.

$RR_{cg,p,s}$ = Required application rate of the field area that is, during step s in pass p, under the centre of gravity of the spreading pattern.

$Fr_{a,p,s}$ = The fraction of the total deposited amount of fertilizer, that is distributed above the considered field area a, during step s in pass p.

EW = effective working width of the spreading pattern (m)

ΔX = length of one step in the driving direction, i.e. X direction.

The applied rate AR, the required rate RR and the fraction Fr depend on position. The required rate is specified for positions in the field coordinate system and will in further elaboration of equation 4 be expressed relative to the position of the considered area $a(Xf_a, Yf_a)$ as function of pass p, effective width EW, step s and step size ΔX.

The fraction that is distributed above the considered area a during step s in pass p, is determined by the two dimensional spreading pattern that is described as fraction for the positions (Xs, Ys) in the coordinate system of the spreading area.

The fraction deposited above the considered area during step s in pass p, $Fr_{a,s,p}$, becomes, when expressed in the coordinate system of the spreading area as $Fr(Xs, Ys)$:

$$Fr(-\Delta X*(s-1), Offset(p)) \qquad (5)$$

where

$Offset(p)$ = $BaseOffset + (p-1) * EW$

and $BaseOffset$ = distance in the y direction between the reference point of the spreading pattern and the considered area in the first pass.

An area has, in the direction perpendicular to the driving direction, a specific position relative to the position of the spread pattern in its first pass. This position is represented by the *BaseOffset* and, because the considered area must represent all areas in the field, calculations must be made for all possible base offset's. That is from the maximum base offset; the width of the spreading area, to the minimum base offset; the width of the spreading area minus effective width (Figure 3.).

The result of positioning errors, *ErrorX* and *ErrorY*, is that the required application rate will be based on a possibly false position.

The part of Equation 4 that determines the required application rates under the

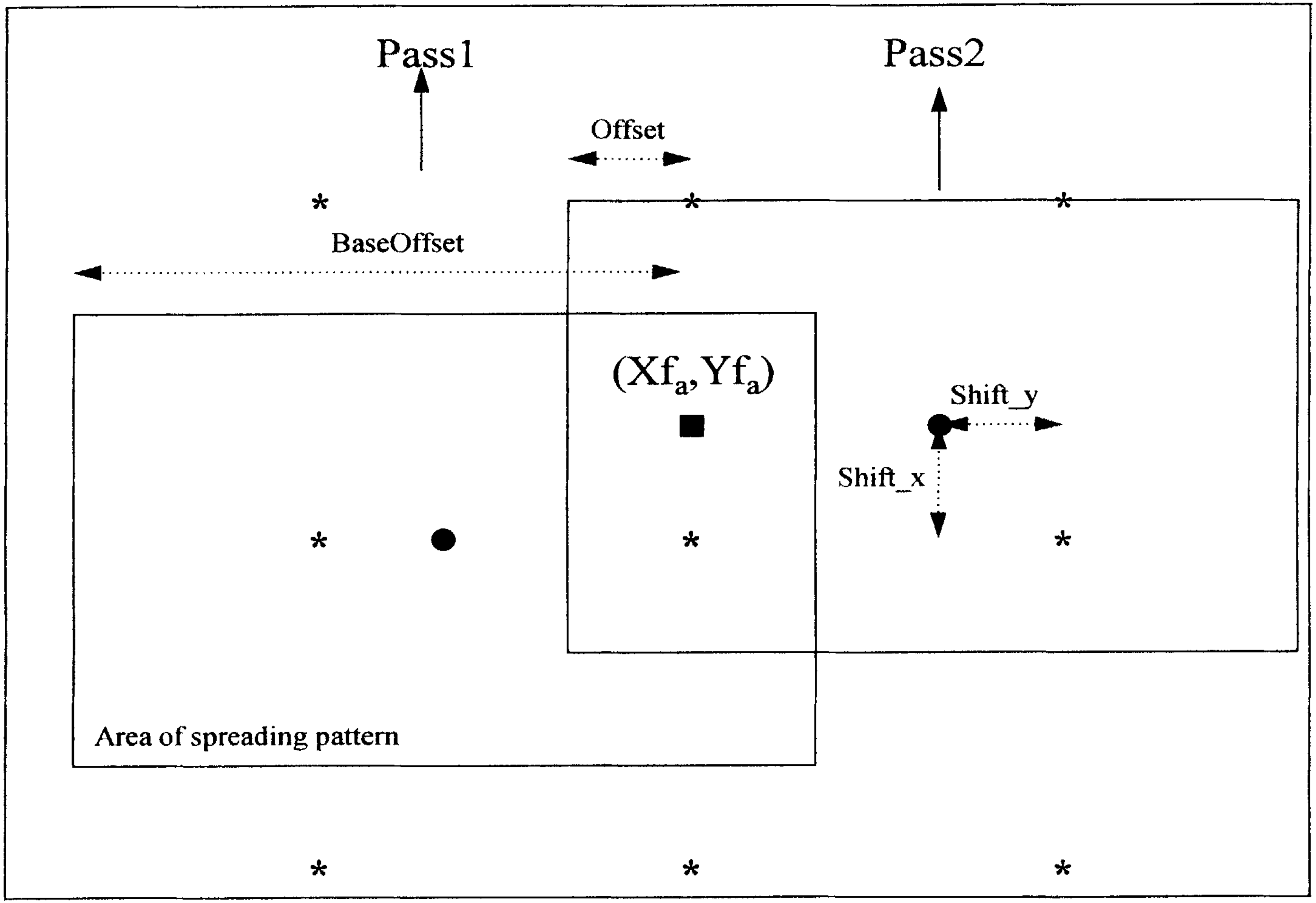

Figure 2. Graphical representation of the surface area covered by a spreading pattern at a certain time moment (step) during two passes, spreading on a particular area (■) located at position Xf_a, Yf_a. The applied rate is based on the (*) gridpoint, nearest to the (●) centre of gravity of the spreading pattern.

centre of gravity at step s in pass p, $RR_{cg,p,s}$ becomes, when expressed in field coordinates (Xf, Yf):

$$RR(Xf_a + \Delta X^*(s-1)+Xs_{cg} + ErrorX, Yf_a + BaseOffset + EW * (p-1)+Ys_{cg} + ErrorY \tag{6}$$

Where

Xs_{cg} and Ys_{cg} = The x and y position of the centre of gravity in the spreading patterns coordinate system.

Required application rates are made available in a grid with a certain resolution, *Res*, the distance between the grid points. The required rate *RR* will be based on the area for which a required rate is specified that is nearest to the centre of gravity of the spreading pattern, including positioning error. Variables *ShiftX* and *ShiftY* represent the distance between the position of the centre of gravity Xf_{cg}, Yf_{cg} and the grid point for which the rate is made available, Xf_{gp}, Yf_{gp}. The position $(Xf_a+ShiftX \pm m*Res, Yf_a+ShiftY \pm n*Res)$ with values for whole numbers of m and n, that is nearest to the position in Equation 6 is used for the required rate.

Calculation of Variance

In geo-statistics, a distinction is made in the treatment of areas, often called blocks, and of points. When data is available for areas, like in our case the data on the fractions of the two dimensional spread patterns, the inner block covariance must be considered. This can algorithmically be done by calculations based on a finite number of points within the block. The spreading patterns and the field are divided in areas of 1 × 1 m. which is found small enough in respect of field variability to justify that these areas are treated as one point.

The sums over the index p for pass and s for step are, for ease of presentation, replaced by one index q such that $\sum_{q=1}^{q=n}$ *replaces* $\sum_{p=1}^{p=P}\sum_{s=1}^{s=D}$.

The expression, $Fr(-\Delta X^*(s-1), Offset(p))^* \frac{EW}{\Delta X}$ is replaced by $F(q)$.

The required rate used to control the spreader in each step of a pass is replaced by RR(q).

The Equation 4, modified by Equations 5 and 6 can then be rewritten as

$$AR(Xf_a, Yf_a) = \sum_{q=1}^{q=n} RR(q)*F(q) \tag{7}$$

The deviation between the required application rate, *RR*, and the applied application rate, *AR*, represents the accuracy of location specific fertilizer application. The variance of the difference between the required application rate and the applied application rate is used as a measure for that accuracy. The estimate of that variance for a certain area Xf_a, Yf_a can be calculated from Formula 8;

$$
\begin{aligned}
Var &= E\left[(RR(Xf_a,Yf_a) - AR(Xf_a,Yf_a))^2\right] \\
&= E\left[\left(RR(Xf_a,Yf_a) - \sum_{q=1}^{q=n} RR(q)*F(q)\right)^2\right] \\
&= E\left[(RR(Xf_a,Yf_a))^2\right] \\
&\quad - 2E\left[RR(Xf_a,Yf_a) * \sum_{q=1}^{q=n} RR(q)*F(q)\right] \\
&\quad + E\left[\sum_{q=1}^{q=n}\sum_{r=1}^{r=n} RR(q)*RR(r)*F(q)*F(r)\right]
\end{aligned}
\tag{8}
$$

The index r is equivalent to q.

The three different terms of formula 8 are treated separately.

For the first term, one can state that the estimate of the variance of a regionalised variable, like an application rate for a specific point in the field, $RR(Xf_a, Yf_a)$, is equal to the estimate of the variance of that variable RR in that field. The first term therefore yields:

$$
\mathrm{E}[(RR(Xf_a,Yf_a))^2] = \mathrm{E}[\,RR^2] \tag{9a}
$$

In the second term, the fact that there is covariance between the points $RR(Xf_a,Yf_a)$ and $RR(q)$ is used. This covariance is expressed in the semi-variance $\gamma(h)$ for those points. The values for $\gamma(h)$ are based on the applied semi-variogram model with the respective ranges.

$$
-2E\left[RR(Xf_a,Yf_a)\sum_{q=1}^{q=n} F(q)*RR(p)\right] = -2E[RR^2] + 2\sum_{q=1}^{q=n} \gamma(Xf_a,Yf_a),q) \tag{9b}
$$

Also, in the third term, the fact that there is covariance between the point p and q is used.

$$
\begin{aligned}
&+E\left[\sum_{q=1}^{q=n}\sum_{r=1}^{r=n} F(q)*F(r)*RR(q)*RR(r)\right] \\
&= \sum_{q=1}^{q=n}\sum_{r=1}^{r=n} F(q)*F(r)*E[RR(q)*RR(r)] \\
&= E[RR^2] - \sum_{q=1}^{q=n}\sum_{r=1}^{r=n} F(q)*F(r)*\gamma(q,r)
\end{aligned}
\tag{9c}
$$

In combining the three expanded terms, the variance of the field points itself falls away and the following formula for the variance between required and applied rates remains.

$$2\sum_{q=1}^{q=n}\mathrm{Fr}(\mathrm{q})*\gamma(Xf_a,Yf_a),q)-\sum_{q=1}^{q=n}\sum_{r=1}^{r=n}Fr(q)*Fr(r)*\gamma(q,r) \qquad (10)$$

This formula is used to find the variance between applied rate and required rate for one point in the field.

Calculating Procedure

The average variance is calculated with equation 9 in steps of 1 m for all possible base offsets, all possible shifts in X and Y direction and for positioning errors between $-3*SD$ and $+3*SD$. The average is calculated by weighting the positioning error with their probability from a normal distribution with standard deviation *SD*. The distance from all areas on which the applied rate is based to the considered area and their mutual distances are used to compute the respective γ's from the exponential semi-variogram model.

Results

Calculations are made for the spreading patterns listed in Table 1 (for ranges of 32, 64, 128 and 256 m to represent field variability, for resolutions of required application rates of 1, 3, 6, 12 and 24 m and for standard deviations of positioning of 0.1, 0.5, 1.0 and 2.0 m).

Near-perfect positioning, a *SD* of 0.1 m, and application rates in the highest possible resolution of 1.0 m, results in no variance for the spreading pattern of 1.0 × 1.0 m. The effect of an increase in effective working width depends on field variability as expressed by the semi-variogram range (Figure 3a-d). Pyramid shaped spreading patterns and then flat ones show little difference in variance. Pyramid shaped ones have a slightly lower variance, which can be explained by the fact that the highest fractions are deposited near the centre of gravity, the position on which the applied rates are based. The reciprocating broadcaster and, to a lesser extent, the centrifugal spreader have a more pronounced pyramid shape, which explains why their variances are lower. The theoretical spreading pattern for the pneumatic spreader shows a higher variance then the other pattern types for larger working widths of 12.0 and 24.0 m. This can be explained by the relatively high fraction on the outer sides of the rectangular pattern.

The effect of positioning accuracy for different working widths is shown for the pyramid shaped patterns in Figures 4a-d with required application rates available in a resolution of 1 m.

Standard deviations between 0.1–2.0 m do not affect the variance of independently controlled working widths of more then 12m. The effect is large for working widths of 3m or smaller. A working width of 1 m and low positioning accuracy results in high variances. Positioning equipment with a standard deviation of 1–2 m has, with high resolutions of required application rates, an optimum working width of 2 or 3m, depending on field variability.

The effect of the resolution of the required rates is shown for the pyramid shaped patterns with near perfect positioning in Figures 5a-d. A high resolution of applica-

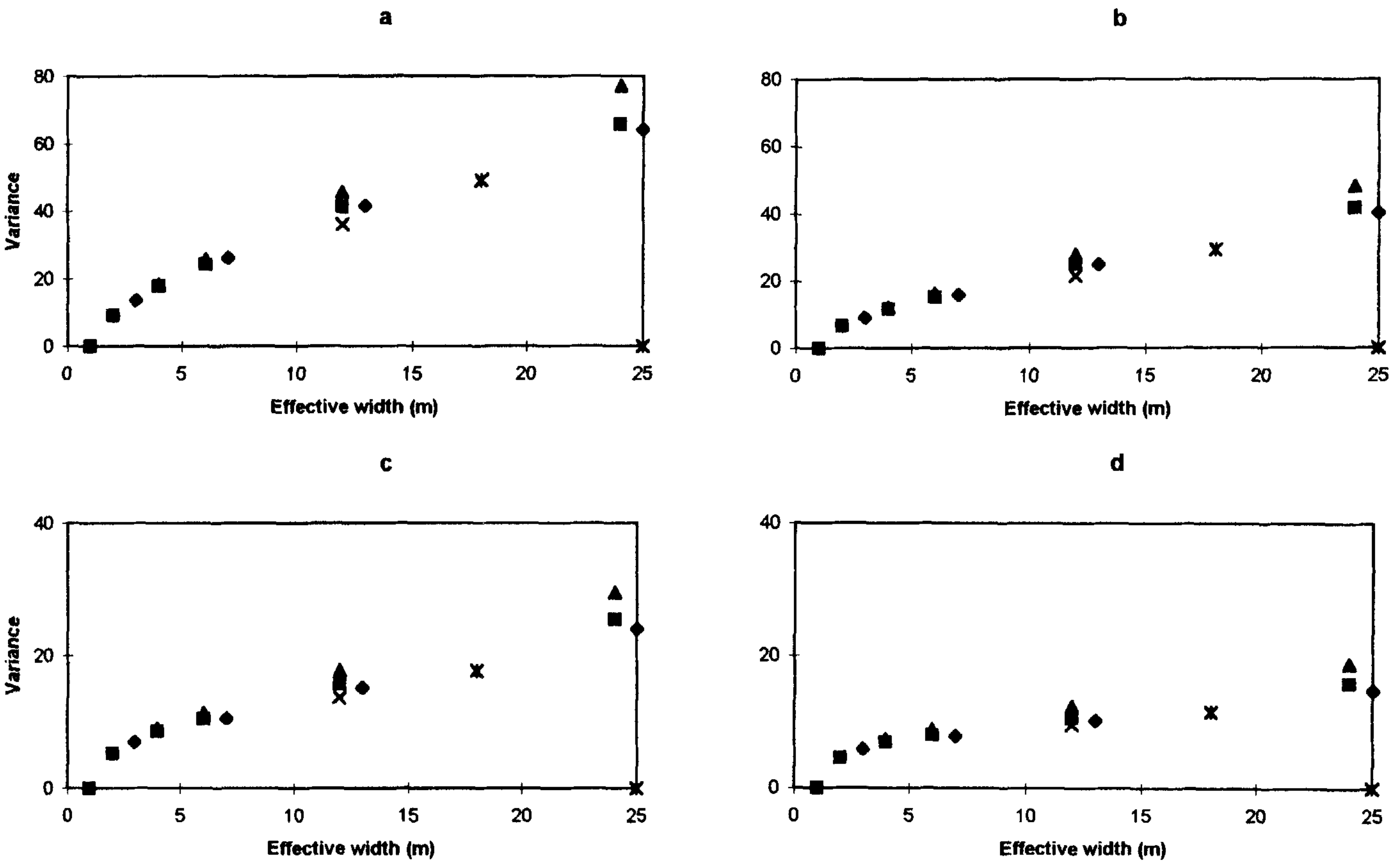

Figure 3. The variance between required and applied application rate, with perfect positioning and specifiction of the required rate in the highest resolution, for different types of spreading patterns and different levels of field variability as expressed by the range. (◆) Pyramid, (■) flat, (▲) Pneumatic, (×) reciprocation and (*) centrifugal spreading pattern.
a. Range of 32 m, b. Range of 64 m. c. Range of 128 m. d. Ragnge of 256 m.

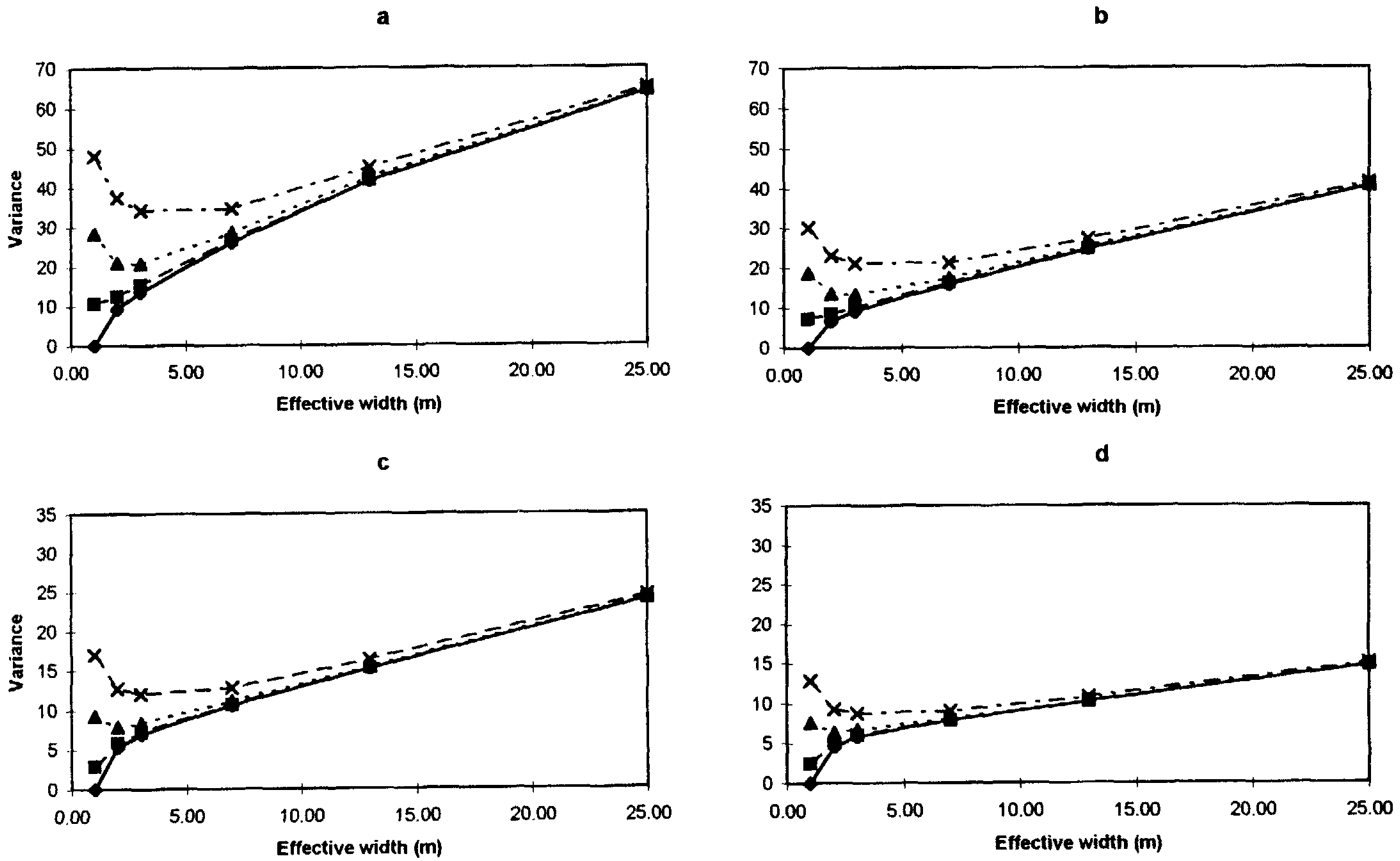

Figure 4. The variance between required and applied application rate for the pyramid type spreading pattern and specifiction of the required rate in the highest resolution , for different levels of positioning accuracy as expressed in the standard deviation SD and different levels of field variability as expressed by the range. (◆) SD = 0.1 m, (■) SD = 0.5 m, (▲) SD = 1.0 m, (×) SD = 2.0 m.
a. Range of 32 m, b. Range of 64 m. c. Range of 128 m. d. Ragnge of 256 m.

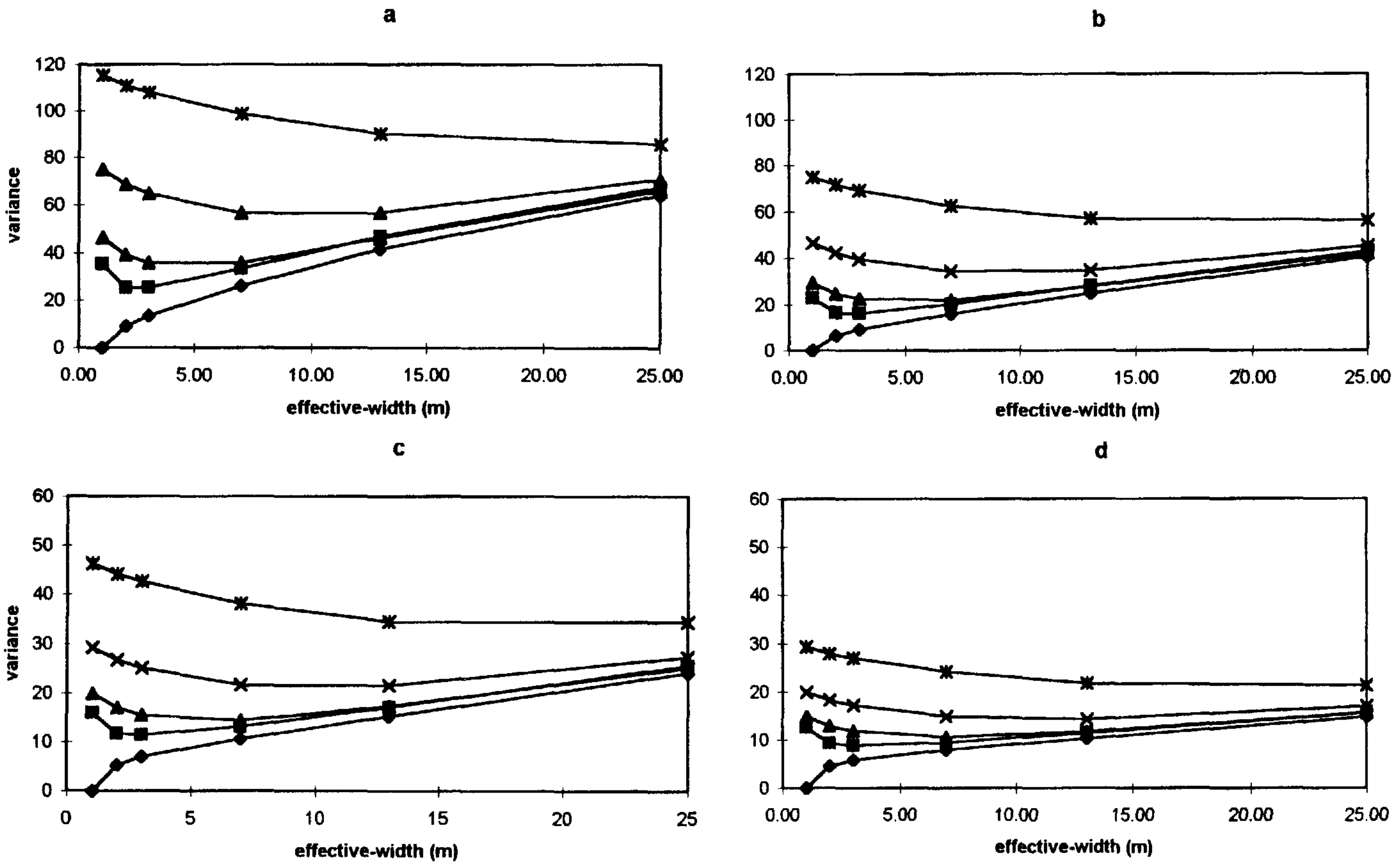

Figure 5. The variance between required and applied application rate for the pyramid type spreading pattern and perfect positioning, for specifictions of the required rate in different resolution, RES, and different levels of field variability as expressed by the range. (◆) RES = 1 m. (■) RES = 3 m. (▲) RES = 6 m. (×) RES = 12 m.(*) RES = 24 m.

a. Range of 32 m, b. Range of 64 m. c. Range of 128 m. d. Ragnge of 256 m.

tion rate set points results in lower variances between required and applied application rates. This positive effect is stronger at smaller effective working widths. The optimum effective working width is close to the size of the grid in which the required application rates are presented.

When less accurate positioning equipment is used in combination with higher resolutions, a small increase in optimum effective working width was found.

Discussion

The estimate for the variance between the required application rate and the realised application rate is very similar to the estimate of the kriging variance as used in geostatistics. In this study it is assumed that the variability of required fertilizer rates is characterised by the semi-variogram model $\gamma(h)$, where variability is a function of mutual distance.

Cone shaped spreading patterns have, with the simple algorithm used, a preference above flat ones in spite of the fact that their total spreading width is about twice the effective width. Spreading patterns with a high fraction on the outer sides of the pattern show the highest variance.

An effective working width for a fertilizer spreader that is equal to the resolution of the required fertilizer rates can be applied as a rule of thumbs. The practical consequence is that spending additional cost on adapting fertilizer spreaders, so that they have independently controlled sections with effective working widths of for example 6m, is justified only when the required fertilizer rates are available in a grid of 6 × 6m.

Positioning equipment that is more accurate then the present generation of DGPS code receivers is as far as fertilizer application is concerned only effective in those special cases where resolution of set point data and effective working widths come below 3m.

The resolution of the required application rates has the largest effect on the variance. Further study must reveal wether interpolation to higher resolutions, considering the variance of the estimator, reduces the variance between required rate and applied rate.

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