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Evaluating the Profitability of a Soil Sensor-Based Variable Rate Applicator for on-the-go Phosphorus Fertilization

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ABSTRACT

Variable rate (VR) phosphorus (P) fertilization aims at improving fertilizer use efficiency and environmental impacts by varying fertilizer rates according to the needs of each zone within a field. This study evaluates the profitability of an on-the-go VR fertilization of phosphate (P_2O_5) in grain corn yield using visible (VIS) and near infrared (NIR) soil sensor-based VR applicator. This evaluation was considered in two different soil phosphorus levels (high & very high with minimum & no fertilization, respectively), which are the common phosphorus levels in Belgian agricultural fields. A previously developed VIS-NIR model was used to predict the extractable phosphorous (Pal). An experimental field divided into two zones according to soil P levels, namely, Zone 1 (high Pal level of 55 mg 100 g^{-1}) with 2 plots and Zone 2 (very high level of Pal of 63 mg 100 g^{-1}) with 3 plots. In these five plots VR of phosphate (P) was adapted using the VR applicator. For each plot, the amount of uniform rate (UR) P need was also obtained using the traditional soil test phosphorus (STP). The overall P application in each plot using the VR approach was compared with the corresponding UR. Amount of P applied with VR fertilization depended upon the initial level of Pal. Compared with the STP recommendation for UR application, in Zone 1 with high level of P, VR provided a positive fertilizer return of 1.5 kg P ha^{-1}, (0.96 € ha^{-1}), whereas in Zone 2 with very high level of P, VR led to a negative fertilizer return of 16.37 kg P ha^{-1} (10.52 € ha^{-1}). Compared with the UR fertilization plots, 305 kg ha^{-1} corn net return was obtained in Zone 1, which introduced a revenue of 33.54 € ha^{-1}. However, in Zone 2 there was a loss of 324.6 kg ha^{-1} introducing a cost of 35.73 € ha^{-1}. The results showed that the on-the-go VR fertilization of P based on a VIS-NIR sensor is profitable in fields with high level of phosphorus. However, the profitability of this system should also be investigated in fields with medium, low and very low levels of P levels, which are not the case in most of the fields in Belgium.

Key Words: Precision agriculture; Soil spectroscopy; Variable rate; Phosphorous; On-the-go fertilization; Soil sensor

INTRODUCTION

Precision farming (PF), or site-specific management, assists farmers in making precise management decision for different cropping systems throughout the world (Koch & Khosla, 2003). Site-specific management recognizes the spatial variability associated with the most fields under crop production (Thrikawala *et al*., 1999). Identifying variables plays the important role in PF to vary or tailor the rate of inputs such as soil moisture content (Mouazen *et al.,* 2005) for seeding, weed detection for herbicide application (Jafari *et al*., 2006; Mohammadzamani *et al.,* 2009), soil resistance for energy requirement (Abbaspour-Gilandeh *et al.,* 2006) and soil nutrients for fertilizer application (Maleki *et al.,* 2008a). Identifying field variability with traditional soil test phosphorus (STP) for the improvement of phosphorus (P) management has been widely investigated and adapted by crop producers for many years (Nielsen & Bouma, 1995; Franzen & Peck, 1995; McIntyre, 1967). The STP can be used at various scales and has been essentially adapted for site-specific management (Mulla & Schepers, 1997). Studies on the spatial variability of STP have revealed large within-field variability (Wibawa *et al.*, 1993; Chambardella *et al.*, 1994; Chan *et al*., 1994; Mallarino, 1996; Geodenken *et al*., 1998; Mallarino & Wittry, 2000) and between fields variability (Carr *et al.*, 1991; Wittry & Mallarino, 2004). Phosphorus managers are interested in within-field variability although monitoring larger scale P variability is important for larger scale agricultural and environmental planning purpose (Klatt *et al*., 2003). Hammond (1993) also estimated potential differences in crop yield response or amount of fertilizer applied by experiments on uniform or variable P fertilization based on STP variability. Although, most of these studies show a potential benefit from variable rate

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(VR) P fertilization, many suggested that large benefits would be achieved only with very dense soil sampling, which is often beyond densities that could be economically afforded by producers of extensive crops (Mallarino & Schepers, 2005).

The potential of improving profitability due to VRP application depends on identifying areas, where additional P inputs will increase revenue on a scale that is greater than the added cost and/or identifying areas, where reducing P inputs will decrease costs on a scale, which is greater than potential revenue reduction correlated with lower yield. Traditional uniform applications (UR) result in the most cases in over and under application of P in various parts of the field due to within field variability. For site-specific P management the grid soil sampling should be as small as possible. Most current research on VR fertilization is based on taking one soil sample per hectare with the assumption that soil nutrient content does not vary within this area. Nevertheless, VRP based on the traditional STP for areas of 1 ha cannot be justified and the cost of VRP using traditional STP will offset the excess revenue if grid soil sampling is used for less than 1 ha. Therefore, VRP can only be efficient if sufficient number of P measurement per unit area can be provided at low cost. The soil sensor-based VR fertilization system developed by Maleki *et al.* (2008a) was successfully operated for P application for maize planting. They managed to monitor within-field variability of soil P using the data collected on-the-go by an optical visible (VIS) and near infrared (NIR) soil sensor installed at the front of the fertilizer applicator. The soil P variations (CV) across the experimental field ranged from 5-51%. They reported significant difference in yield between plots received VR treatment, while compared with plots received UR treatment. However, the profitability of the implementation of this fertilization system in fields with different level of P was not investigated.

Some results on cost, revenue and returns associated with VR application have been reported (Lowenberg-DeBoer & Aghib, 1999; Yang *et al.*, 1999 & 2001; Wittry & Mallarino, 2004). However, the profitability of new-developed VR fertilization system are not investigated yet. The objective of this study was to estimate the profitability of using the VIS-NIR soil sensor-based VR fertilization system of phosphate in a field with two zones with different average levels of soil P, which are the typical P levels for soils in Belgium.

MATERIALS AND METHODS

Soil sensor-based variable rate fertilization system. The soil sensor-based VR fertilization system (Maleki *et al.*, 2008a) developed at Department of Biosystems, Division of Mechatronics, Biostatistics and Sensors (MeBioS), Catholic University of Leuven, Leuven, Belgium was used in this study for P application during maize planting (Fig. 1). The applicator includes a four rows pneumatic planter (ED302, AMAZONE, Oldengerg, Germany) with a fertilizer unit compartment. The granular fertilizer rate could be varied using an electrical actuator (LINAK & Co., UK) controlled by a LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) program (National Instrument, USA, ver 6.1) using the soil P information collected on-the-go by the VIS-NIR soil sensor (Mouazen *et al.*, 2005). This sensor was installed on the planter tool-bar at 0.91 m ahead of the fertilizer outlets and was coupled with a VIS-NIR fibre-type spectrophotometer (Zeiss Corona 45 visnir 1.7, Germany) that measured soil reflectance spectra in the range from 305 to 1711 nm. The methodology for evaluation of this distance has been explained in previous study (Maleki *et al.*, 2008b)

The positions of soil scanning were recorded using a DGPS Trimble® AgDGPS 132 receiver, although, for a sensor-based VR application system this positioning system is not necessarily required. This DGPS recording was mainly used to study the yield response to different levels of P and phosphate application in each field spots.

The calibration model of ammonium lactate extractable phosphorus (Pal) developed by Mouazen *et al.* (2007) was used in this study to predict Pal during on-the-go measurement of soil VIS-NIR spectra. This calibration model was based on fresh (wet) soil samples collected from many fields in Belgium and northern France, representing a wide range of soil moisture content, textures and colours with a correlation coefficient (R) of 0.92 and 0.86 for the calibration and validation stages, respectively. The phosphate recommendation rate was based on the model developed by Maleki *et al.* (2007).

Experimental fields and VR application. A 2 ha field situated in Lovenjoel, 30 km east of Brussels, Belgium was prepared for corn planting. The texture according to the USDA soil classification was silt loam. Two zones (Fig. 2), namely, Zones 1 and 2 were selected inside of the field and these two zones were divided into two and three plots, respectively. In each plot of Zone 1, four tractor runs could be operated, whereas in each plot of Zone 2, only two tractor runs could be operated. The planter-applicator width was three meter wide. For each zone of the field, a traditional STP was carried out to estimate the UR during corn planting. About ten soil samples were collected from 0.10-0.20 m depth and well mixed before they were sent to the soil service of Belgium for analysis and recommendation of phosphate (P) application. These recommended UR rates were solely considered as a basis for economical analysis of VR fertilization method. The rest of the field, consisting of two plots (plots 6 & 7) located directly beside Zone 1 (with equal area & shape to those in Plots 1 & 2) were received an UR based on the soil test recommendation and the overall yield average of these Plots (plots 6 & 7) of the field was compared with others plots. The fertilizer applicator was filled with triple super phosphate (0-45-0). Each sampling cell of approximately 4 m^2 (1.25 by 3 m) received an application rate according to the Pal level obtained by soil sensor for this cell. The application rate was adapted in 5 kg P ha^{-1} intervals. The planter was adjusted for 100,000 seeds per hectare for sowing maize (*Zea mays* L.) in 0.75 m wide rows. Although the travelling speed for row-crop planting is about 5-6 km h^{-1}, the planter-applicator was driven at a travel speed of 2 km h^{-1} gathering average soil spectrum throughout approximately 1.25 m distance intervals, while travelling across the field. The entire field received a uniform rate of 180, 150 and 70 kg ha^{-1} of nitrogen, potassium and magnesium, respectively.

Grain yields. Four field runs (4 by 3=12 m; planter width was 3 m) were considered during corn planting within each plot. Grain corn yield was geo-referenced and determined in all plots with an 8 rows combine harvester equipped with a DGPS (CR 960 New Holland) and an impulse type based yield monitor. The 8 rows (6-m wide) of each plot were harvested in one pass and yield records were obtained at about 1.35 m intervals. The yield in the 6-m centre of plots 1 and 2 was recorded, whereas the entire width of each plot in Zone 2 could be harvested in one combine pass (Fig. 2).

Maize yield versus soil phosphorus. To compare the yield with the P fertilization within the VR treatment plots a labVIEW program was developed to match the corresponding cells of soil P detected by the soil sensor during the maize planting with the nearest yield data points. The DGPS coordinates recorded on both implements was used to match the position of the Pal and corresponding yield within a field spot.

From each treatment about 35 samples were randomly selected and the analysis of variance was performed to compare the yield of both treatments, VR and UR.

RESULTS AND DISCUSSION

The coefficient of variation of the P values per plot based on the data collected by on-the-go VR sensor ranged from 33 to 67% across the field (Table I). The coefficient of variation (CV) can be used as an index for the degree of the variation in a given area. This index has been widely used in precision agriculture by many researchers (Dhillon *et al.*, 1994; Boland & Wilson, 1994; Raun *et al.*, 1998). This indicates the ability of the on-the-go applicator in capturing the variability existing across the field and applying corresponding rate, while travelling across the field.

Economic benefits from VR application can be derived from increased yields and/or saving in reduced inputs. The VR fertilizer strategy employed in this study did not economically reduce fertilizer use efficiency. The UR application recommended by STP revealed that the application rate was 30 kg P ha^{-1} for plots 1 and 2 in Zone 1 (high level of Pal of 55 mg $100g^{-1}$), whereas no fertilizer application was recommended for plots 3, 4 and 5 in Zone 2 (very high level of Pal of 63 mg $100g^{-1}$). The average soil Pal predicted from the on-the-go soil spectra shows that plots in Zone 2 had very high initial Pal and this is higher than for plots in Zone 1 (Table I). Compared with virtual UR (recommended using STP, but not applied) application of P in the same plots, only plot 1 received less fertilizer, while using on-the-go VR approach, whereas plots 3, 4 and 5 received more P. Although, Plot 2 received an identical rate compared with UR (30 kg ha^{-1}), the fertilizer rate varied from 5 to 95 kg P ha^{-1} with the VR strategy (Table I). The amount of P applied during VR fertilization as compared to UR fertilization depends on the initial level of Pal. With a very high level of Pal as in Zone 2, more fertilizer is distributed with VR application compared with UR application. In Zone 1 with high level of Pal, P might be either smaller (plot 1) or equal (plot 2) to UR application. Generally, a considerable variability in fertilizer application was observed in all plots. The minimum and maximum application rates of 0 and 95 kg P ha^{-1} were observed among experimental plots. A wider range in fertilizer application was observed even in high initial Pal plots (plots 1 & 2) and ranging from 0 to 70 and 5 to 95 kg ha^{-1}, respectively. The strategy used for VR phosphorus fertilizer application shows slightly improvement in fertilization use efficiency. This is because some of the soil P values were higher than the total P needed. These higher rates increased the overall means of soil P for VR treatment. However, the technique leads to higher profit probably because of the ability of capturing those areas in which P is more required and could not be supplied by UR treatment.

Because the crop yields are greatly affected by many factors such as annual weather, soil properties, moisture content, crop rotation and infestations of weeds, it may be difficult to obtain reliable profitability potential of VRP. Therefore, comparing the effect of VR and UR on yield may not lead to clear conclusions. For this reason, many research studies of VR applications use a yield goal using UR application (Ferguson *et al.*, 1996). The corn yield results for the five experimental plots situated in Zones 1 and 2 are presented in Table II. Average yield among different plots varied between 7.49 and 8.44 t ha^{-1} for VR treatment, while in UR plots (plots 6 & 7) an average yield of 8.12 t ha^{-1} was obtained. This means that, it is difficult to see the yield differences because the differences in fertilizer application were generally small and large yield variability existed in all experimental plots. It can be seen (Table II) that plots 3 and 4 had lower yield compared with UR plots (plots 6 & 7) in which they received 30 kg ha^{-1}. Therefore, it seems that plant utilizes P available in fertilizer better than P already available in the soil. However, the research conducted by Eghball *et al.* (2003) showed that corn can effectively uptake soil P and significantly decrease the level of soil P over several years although they did not mention that any possible yield loss is to be expected due to no fertilization. They reported that lowering soil P level from 26.5 mg 100 g^{-1} to 15 mg 100 g^{-1} (that is used as the critical level by some states in United States) would require only 5 years of corn if no additional P is applied. The crop response to P fertilization was reported to be very considerable, when the

Table I. Comparison of applied variable rate (VR) and theoretical recommendation for uniform rate (UR) application of phosphate (P_2O_5)

Plot	Phosphorus (mg 100 g^{-1} dry)		Uniform rate phosphate (kg P_2O_5 ha^{-1})	Variable rate phosphate (kg P_2O_5 ha^{-1})			
	Uniform rate [a]	Variable rate		Min	Max	Mean	CV (%)
1	55	44 [b]	30 [c]	0	70	27	44
2	55	42	30	5	95	30	50
3	63	55	0	0	30	14	56
4	63	47	0	10	40	22	33
5	63	56	0	0	30	13	67

[a] The uniform rate application was estimated based on laboratory soil phosphorus test (STP) and recommendation of Belgium Soil Service
[b] Phosphorus predicted on-the-go by soil sensor for VR only
[c] recommended by Belgium Soil Service

Table II. Summary statistics of corn grain yield obtained in five experimental plots using on-the-go variable rate P fertilization system

Plot	Yield (t ha^{-1})			CV (%)
	Min	Max	Mean	
1	1.11	12.19	8.41	22
2	1.47	11.48	8.44	19
3	0.81	11.90	7.85	18
4	0.83	11.71	7.49	23
5	1.39	10.93	8.16	14

Table III. Economical analysis on fertiliser application, while using the on-the-go variable rate phosphate fertilisation as compared to traditional uniform fertilisation in two experimental plots with high level of phosphorus

Plot	Variable rate phosphate (kg P_2O_5 ha^{-1})	Uniform rate phosphate (kg P_2O_5 ha^{-1})	Fertilizer return, (kg P_2O_5 m^{-2})	Plot area (m^2)	Fertilizer saving (kg P_2O_5)	Fertilizer saving (€)
1	27	30	0.0003	3600	1.08	0.69 [a]
2	30	30	0	3600	0	0
			Total	7200	1.08 [b]	0.69 [b]

[a] price of triple super phosphate (0.45% P_2O_5) is 0.29 € kg^{-1}
[b] the overall average of fertiliser return is 1.5 kg P_2O_5 ha^{-1} for an income of 0.96 € ha^{-1}

STP level in fields is very low, low and medium (Wittry & Mallarino, 2004), where the fertilizer should be applied in higher rates. Soil chemical P can also lead to variability in yield by influencing the total amount of P in soils, the fraction available to crops and possible losses in the root zone (Mulla & Schepers, 1997). However, no correlation between the mean plot yield and mean application of P could be made, perhaps due to the other influencing factors. It is shown in this study that the VR approach does not appear to be profitable, when a field has a very high STP as in Zone 2. Generally, in Belgium, most arable fields have moderately high (33% of total area), high (36%) and very high (14%) levels of STP (Hanotiaux & Vanoverstraeten, 1990; Vanden Auweele *et al*., 2000). This means that the response of crop to P can be considerable in 86% of the arable area in Belgium. Therefore, the range of the crop response to P can be expanded to very low, low medium and high level of P, instead very low, low and medium reported by recent research (Bundy *et al.*, 2005). This new finding is attributed to the large number of samples (about 2200 soil scan ha^{-1}) used for adopting the fertilization. Furthermore, the VR strategy will be most profitable, where large differences in STP levels exist within a field, more specifically in fields having both low and high levels of soil P (Wittry & Mallarino, 2004). The least profitable situation for VR strategy was reported to be in fields containing mainly high and medium STP (Wittry & Mallarino, 2004), which is similar to the experimental plots used in present study. In Belgium, STP greater than 30 mg 100 g^{-1} is categorised as high level (Vanden Auweele *et al*., 2000). Further investigation is needed to compare VR and UR approaches for very low and medium P because STP in the present study was in the high and very high level. Fig. 3 shows the relationship between the maize yield and initial soil Pal within the VR treatment plots. As it can be seen the yield decreased, when initial soil P increased. Note that the rate of fertilization decreases as Pal increases and this trend eventually suggests not applying any P. It seems that the VR is more efficient, where the initial level of soil Pal is at intermediate levels (Pal of 35-45 mg 100 g^{-1}). This needs also further investigation to be conformed. Comparing Fig. 3 with Fig. 4, it can be concluded that the optimum yield can be reached at soil P levels of 45 mg 100 g^{-1}. Results of the present research show that for areas with higher levels of P for which no application is suggested, a small amount of application is still required to achieve maximum yield. This finding is inline with another research carried out by Sawyer and Mallarino (1999 & 2002), who reported from long-term

Table IV. Economical analysis on fertiliser application, while using the on-the-go variable rate phosphate fertilisation as compared to traditional uniform fertilisation in three experimental plots with very high level of phosphorus

Plot	Variable rate phosphate (kg P_2O_5 ha^{-1})	Uniform rate phosphate (kg P_2O_5 ha^{-1})	Fertilizer return (kg P_2O_5 m^{-2})	Plot area (m^2)	Fertilizer saving (kg P_2O_5)	Fertilizer saving (€)
3	14	0	-0.0014	1260	-1.76	-1.13
4	22	0	-0.0022	870	-1.91	-1.23
5	13	0	-0.0013	540	-0.70	-0.45
			Total	2670	-4.37 [b]	-2.81 [b]

[a] price of triple super phosphate (0.45% P_2O_5) is 0.29 € kg^{-1}
[b] the overall average of extra fertiliser is 16.37 kg P_2O_5 ha^{-1} with extra fertiliser cost of 10.52 € ha^{-1}

Table V. Revenue of the corn yield over the experimental plots, when using the on-the-go variable rate (VR) phosphate fertilisation system compared to uniform rate (UR) application on two experimental plots with high level of phosphorus

Plot	Variable rate yield (t ha^{-1})	Uniform rate yield average (t ha^{-1})	Yield return (kg m^{-2})	Plot area (m^2)	Yield return (kg)	Yield Return (€)
1	8.41	8.12	0.029	3600	104.4	11.48[a]
2	8.44	8.12	0.032	3600	115.2	12.67
			Total	7200	219.6 [b]	24.15 [b]

[a] price of corn yield is 0.11 € kg^{-1}
[b] yield return is 305 kg ha^{-1} with return of 33.54 € ha^{-1}

Table VI. Revenue of the corn yield over the experimental plots, when using the on-the-go variable rate (VR) phosphate fertilisation system compared to uniform rate (UR) application

Plot	VR yield, (t ha^{-1})	UR yield average (t ha^{-1})	Yield return (kg m^{-2})	Plot Area (m^2)	Yield return (kg)	Yield Return (€)
3	7.85	8.12	-0.027	1260	-34.02	-3.74
4	7.49	8.12	-0.063	870	-54.81	-6.03
5	8.16	8.12	0.004	540	2.16	0.23
			Total	2670	-86.67 [b]	-9.54 [b]

[a] price of corn yield is 0.11 € kg^{-1}
[b] yield loss is 324.6 kg ha^{-1} with loss of 35.73 € ha^{-1}

(11 years) research results, that the economic return to P application is low at high or very high STP levels. Similarly, our finding in this study led to the same conclusion that high STP values are not a prerequisite for high yield. If there is a known level of phosphorus in the soil and a realistic yield goal or expected yield, it is possible to apply some phosphate fertilizers to achieve higher yield. But, optimal yield depends also on other factors namely, weather conditions, other nutrients etc. which made it difficult to have a general conclusion from the 2 ha experimental field of the current study.

Compared with phosphate variation (CV of 33-67%), corn yield had lower variation (CV of 14-35%), when using the on-the-go applicator for P fertilization. The variation of yield in plots 6 and 7 were 23 and 41% in which UR P treatment was used. This result is inline with the finding by Wittry and Mallarino (2004), who reported that, the VR method tended to reduce yield variability in most fields under study. Further experimentation is required to explain the effect of VR application on uniformity of crop yield. Compared with UR application, Zone 1 received slightly less fertilizer, while using VR technique (Table I). The overall average of fertilizer reduction in Zone 1 was 1.5 kg P ha^{-1} with price 0.96 € ha^{-1} (Table III). Plots 3, 4 and 5 in Zone 2 received more P with VR application as compared with the virtual UR application rate (Table IV). The total cost of the extra VR fertilizer application compared to virtual UR application was about 10.56 € ha^{-1} (the current price of triple super phosphate is 0.29 € kg^{-1} in the Belgium market).

To calculate the net return, a comparison was carried out between yield of plots received VR fertilization and average yield of the two plots of UR application. An extra yield of 305 kg ha^{-1} was obtained (Table V) with VR application compared to UR application plots (8.12 ton ha^{-1}) at 5% of probability, which resulted in an extra income of 33.54 € ha^{-1} to be attributed to the use of the on-the-go VR fertilization system. Surprisingly, the yield in Zone 2 with VR fertilization was markedly lower than the yield of plots received UR fertilization (Table VI). This might be attributed to the situation of the Zone 2, which is surrounded by woods that may inhabit the solar radiation. Furthermore, this condition also leads to more wet conditions, leading to diseases (fungal, etc.) thus reduced plant growth and yield. The results arising from this study showed that the yield has a decreasing trend with increasing initial level of P, which was the case of the most areas in Zone 2. The net return of plots due to extra yield of VR compared to that of UR fertilization can be a basis for

Fig. 1. Soil VIS-NIR sensor-based variable rate phosphorus applicator (Maleki *et al.*, 2008a) used in this study; (a), planter and fertiliser applicator (AMAZONE, ED302); (b), sensor and penetration unit; (c) DGPS antenna; (d), electrical actuator; (e) roller for closing the trench made by penetration unit

Fig. 2. Experimental field with 5 plots selected for variable arte (VR) fertilization of phosphate (P_2O_5) during corn planting

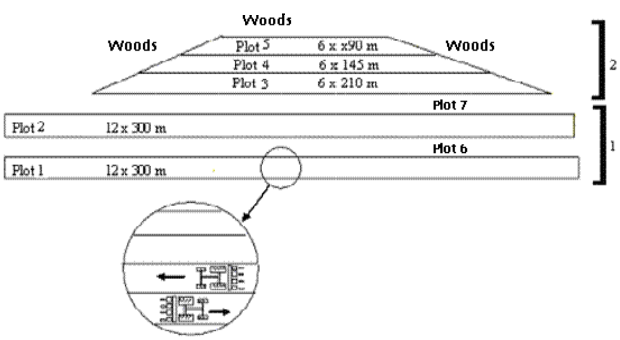
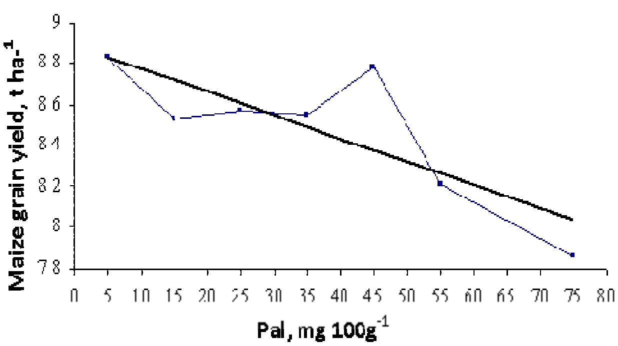
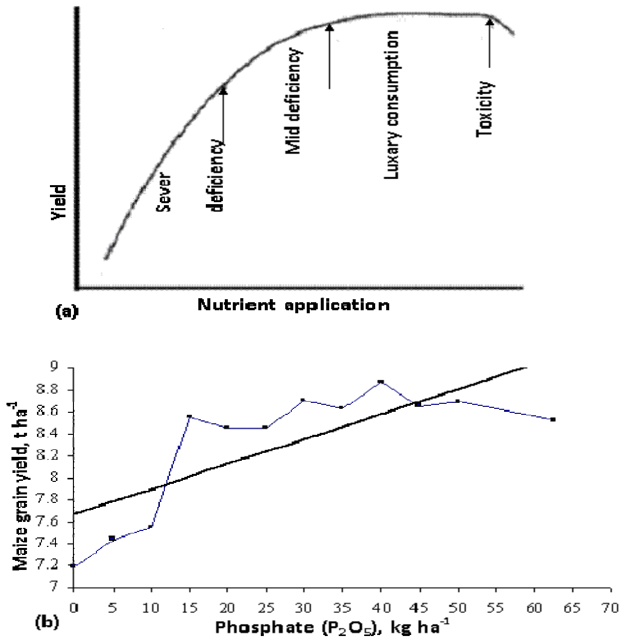


Fig. 3. The relationship between yield and initial soil phosphorus in area designated for variable rate application



the evaluation of VR profitability. The overall income gained from Zone 1 (with high level of initial Pal) was 34.5 € ha^{-1}. In the very high level of P zone, this is a negative cost of 46.25 € ha^{-1}, which arises the question of adopting

Fig. 4. (a) A typical curve showing yield response to added nutrient (Bock & Sikora, 1990) and (b) the relationship between phosphate (P_2O_5) application and yield in area designated for variable rate application



VR fertilization of P in very high P. The capital cost of the new developed applicator is not included in the calculation now as it should be, when the system becomes commercially available.

In Belgium, the cost of a standard soil test for essential soil nutrients including P is 53 €. This soil test is mainly based on samples collected from 2 ha and can be utilized for two successive years. For every extra STP per hectare, 481 kg more corn grain yield should be expected to compensate the cost of STP test. Nevertheless, VR application of P at a scale of 1 STP per ha requires more than one sample per hectare, which may not be an economical strategy if the traditional STP is used.

A data analysis revealed that there was only 1% of the total area in plots 1 and 2 that received no fertilizer, whereas 47% and 30% of the area received 5-25 kg P_2O_5 ha^{-1} and more than 30 kg P_2O_5 ha^{-1}, respectively. Therefore, the UR recommendation of P based on STP (30 kg P_2O_5 ha^{-1}, Table I) represents only 22% of the total area in plots 1 and 2. In plots 3, 4 and 5 UR applications of 5-25, 30 and >30 kg P_2O_5 ha^{-1} were recommended for 81, 9 and 3% of the total area, respectively. Therefore, the UR fertilization is confirmed for 7% of the total area with very high Pal and no fertilizer is to be applied. Maleki *et al.* (2007) showed that the commonly used sampling methods (i.e., STP) cannot be representative for VR of P fertilization. This is inline with the finding of this study, which shows that STP based UR recommendation would only be proper for a small zone of the field area (7-22% of the field total area).

CONCLUSION

Although strategy used for VRP fertilizer application shows slightly improvement in fertilizer use efficiency, it leads to higher profit because of the ability of capturing those area in which P is more required. The phosphate fertilizer distribution was markedly variable and widely ranged from 0 to 95 kg P ha^{-1}. The cost of fertilizers applied by using VR applicator was lower for uniform rate (UR) in areas with a high level of P. However, in areas with a very high average level of P, the fertilizer application cost is higher than UR approach. The VR application of P may result in attenuation of the crop yield variation in case of high or very high level of STP. The VR application of P may in the end result in uniform soil P levels that also needs to further research. The results from this study demonstrated that VR P fertilizer application could increase crop yield and economic return and also reduce yield variability. However, these results are still preliminary and only reflect the performance of a particular fertilization strategy. Additional experiments are needed to test more VR strategies in more fields in which soil P widely and spatially varies.

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REFERENCES

Abbaspour-Gilandeh, Y., R. Alimardani, A. Khalilian, A. Keyhani and S.H. Sadati, 2006. Energy requirement of site-specific and conventional tillage as affected by tractor speed and oil parameters. *Int. J. Agric. Biol.*, 8: 499–503

Boland, M.D.A. and I.A. Wilson, 1994. Soil phosphorus testing: Studies on spatial variation of Colwell soil test phosphate. *Commun. Soil Sci. Plant Anal.*, 25: 2371–2384

Bundy, L.G., H. Tunny and A.D. Halvorson, 2005. Agronomic aspect of phosphorus management. *In*: Sims, J.T. and A.N. Sharply (eds.), *Phosphorus: Agriculture and the Environment*. Agronomy Monograph No. 46, ASA, CSSA and SSSA, 677 S Segoe Road, Madison, WI 53711, USA

Carr, P.M., G.R. Carlson, J.S. Jacobson, G.A. Nielson and E.O. Skogley, 1991. Farming soils, not fields: A strategy increasing fertiliser profitability. *J. Prod. Agric.*, 4: 57–67

Chambardella, C.A., T.B. Moorman, J.M. Novak, T.B. Parkin, D.L. Karlen, R.F. Turco and A.E. konopka, 1994. Field-scale variability of soil properties in central Iowa soils. *Soil Sci. Soc. America J.*, 58: 1501–1511

Chan, M.D., J.W. Hummel and B.H. Brouer, 1994. Spatial analysis of soil fertility for site-specific crop management. *Soil Sci. Soc. America J.*, 58: 1240–1248

Dhillon, N.S., J.S. Samra, U.S. Sadana and D.R. Nielson, 1994. Spatial variability of soil test values in a typic Ustochrept. *Soil Technol.*, 7: 163–171

Eghball, B., J.F. Shanahan, G.E. Varvel and J.E. Gilley, 2003. Reduction of high soil test Phosphorus by corn and soybean varieties. *Agron. J.*, 95: 1233–1239

Ferguson, R.B., C.A. Gotway, G.W. Hergert and T.A. Peterson, 1996. Soil sampling for site- specific nitrogen management. *In*: *Proc. 3rd Int. Conf. Precision Agric.*, pp: 13–22. Madison, Wisconsin: ASA/CSSA/SSSA

Franzen, D.W. and T.R. Peek, 1995. Field soil sampling density for variable rate fertilisation. *J. Prod. Agric.*, 8: 568–574

Geodenken, M.W., G.V. Johnson, W.R. Raun and S.B. Pholops, 1998. Soil test phosphorus crop response projections to variable rate application in witer wheat. *Commun. Soil Sci. Plant Anal.*, 29: 1731–1738

Hammond, M.W., 1993. Cost analysis of variable fertility management of phosphorus and potassium for potato production in central Washington. *In*: Robert, P.C. (ed.), *Soil Specific Crop Management*, pp: 213–228. ASA, CSSA, SSSA, Madison, WI

Hanotiaux, G. and M. Vanoverstraeten, 1990. *Study of the Utilisation of Mineral Phosphorus Fertiliser in Western Europe*. Study sponsored by IMOHOS, World Phosphorus Institute, Casablanca, Morocoo

Jafari, A., S.S. Mohtasebi, H.E. Jahromi and M. Omid, 2006. Weed detection in suger beet fields using machine vision. *Int. J. Agric. Biol.*, 8: 602–605

Klatt, J.G., A.P. Mallarino, J.A. Dowing, J.A. Kopaska and D.J. Wittry, 2003. Soil phosphorus, management practices and their relationship to phosphorus delivery in the Iowa Clear Lake agricultural watershed. *J. Environ. Quality*, 32: 2140–21489

Koch, B. and R. Khosla, 2003. The role of precision agriculture in cropping systems. *J. Crop Prod.*, 8: 361–381

Lowenberg-DeBoer, J. and A. Aghib, 1999. Average return and risk characteristics of site specific P and K management: Eastern Corn Belt on-farm trial results. *J. Prod. Agric.*, 12: 276–282

Maleki, M.R., A.M. Mouazen, B. De Ketelaere, H. Ramon and J. De Baerdemaeker, 2008a. On-the-go variable rate phosphorus fertilisation based on a visible and near infrared soil sensor. *Biosyst. Eng.*, 99: 35–46

Maleki, M.R., H. Ramon, J.De Baerdemaeker and A.M. Mouazen, 2008b. A study on the time response of a soil sensor-based variable rate granular fertiliser applicator. *Biosyst. Eng.*, 100: 160–166

Maleki, M.R., A.M. Mouazen, H. Ramon and J. De Baerdemaeker, 2007. Optimisation of soil VIS-NIR sensor-based variable rate application system of soil phosphorus. *Soil Till. Res.*, 94: 239–250

Mallarino, A.P., 1996. Spatial variability patterns of phosphorus and potassium in no-tilled soils for two sampling scales. *Soil Sci. Soc. America J.*, 60: 1473–1481

Mallarino, A.P. and J.S. Schepers, 2005. Role of precision agriculture in phosphorus management practices. *In*: *Phosphorus Agriculture and the Environment*, pp: 881–908. Agronomy Monograph No. 46. ASA, CSSA and SSSA, Madison, WI

Mallarino, A.P. and D.J. Wittry, 2000. Identifying cost-effective soil sampling schemes for variable-rate fertilisation and liming. *In*: Robert, P.C., R.H. Rust and W.E. Larson (eds.), *Precision Agriculture [Cd-ROM], Proc. Int. Conf. 5th, Mineapolis, MN. 16-19 July, 2000*. ASA, CSSA and SSSA, Madison, WI

McIntyre, G.A., 1967. Soil sampling for soil testing. *J. Australian Institute Agric. Sci.*, 18: 309–318

Mohammadzamani, D., S. Minaei, R. Alimardani, M. Almassi, M. Rashidi and H. Norouzpour, 2009. Variable rate herbicide application using the global positioning system for generating digital management map. *Int. J. Agric. Biol.*, 11: 178–182

Mouazen, A.M., J. De Baerdemaeker and H. Ramon, 2005. Towards development of on-the-go soil moisture content sensor using a fibre-type NIR spectrophotometer. *Soil Till. Res.*, 80: 171–183

Mouazen, A.M., M.R. Maleki, J. De Baerdemaeker and H. Ramon, 2007. On-line measurement of some selected soil properties using a VIS-NIR Sensor. *Soil Till. Res.*, 93: 13–27

Mulla, D.J. and J.S. Schepers, 1997. Key processes and properties for site-specific soil and crop management. *In*: Piers, F. and E.J. Sadler (eds.), *The State of Site-Specific Management for Agriculture*, pp: 1–18. ASA, CSSA, SSSA, Madison, WI

Nielsen, D.R. and J. Bouma, 1995. Soil spatial variability. *Proc. Workshop ISSI and SSSA, Las Vegas, NV. 30th November-1st December, 1984*. Pudoc., Wageningen, The Netherlands

Raun, W.R., J.B. Soile, G.V. Johnson, M.L. Stone, R.W. Whitney, H.L. Lees, H. Sembiring and S.B. Philips, 1998. Microvariability in soil test, plant nutrient and yield parameters in Bermudagras. *Soil Sci. Soc. America J.*, 62: 683–690

Sawyer, J.E. and A.P. Mallarino, 2002. *General Guide for Crop Nutrient Recommendation.* In Iowa Publication Pm-1688 (Rev.) Iowa State University, Extensions

Sawyer, J.E. and A.P. Mallarino, 1999. *Interpreting P and K Soil Test Results.* Integrated Crop Management, Iowa State University Publication, available at: http://www.ipm.iastate.edu/ipm/icm/1999/1-18-1999/interpretpk.html

Thrikawala, S., A. Weersink, G. Kachanoski and G. Fox, 1999. Eccnomic feasibility of variable-rate technology for nitrogen on corn. *American J. Agric. Econ.*, 81: 914–927

Vanden Auweele, W., W. Boon, J. Bries, G. Coppens, S. Deckers, F. Elsen, J. Mertens, H. Vandendriessche, P. Ver Elst and N. Vogels, 2000. *De Chemische Bodemvruchtbaarheid Van Het Belgishe Akkerbouwen Weilandareaal, the Chemistry of Soil Fertility of Belgium Arable and Grass Lands*. Belgium Soil Service Department, Heverlee, Belgium, Available at: www.bdb.be

Yang, C., J.H. Everitt and J.M. Bradford, 1999. *Comparison of Uniform and Variable Rate Fertiliser Application Using a Variable Rate Liquid Applicator*. ASAE, No. 99-1145 Joeseph, Mich., ASAE

Yang, C., J.H. Everitt and J.M. Bradford, 2001. Comparison of uniform and variable rate nitrogen and phosphorus fertilizer application for grain sorghum. *Trans. ASAE*, 44: 201–209

Wibawa, W.D., D.L. Dludlu, L.J. Swenson, D.G. Hopkins and W.C. Dahnke, 1993. Variable fertiliser application based on yield goal, soil fertility and soil map unit. *J. Prod. Agric.*, 6: 255–261

Wittry, D.J. and A.P. Mallarino, 2004. Comparison of uniform and variable rate phosphorus fertilization for corn-soybean rotations. *American Soc. Agron. J.*, 96: 26–33

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