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Optimum three-point linkage set up for improving the quality of soil spectra and the accuracy of soil phosphorus measured using an on-line visible and near infrared sensor

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On-line measurement of soil properties using the visible (Vis) and near infrared (NIR) spectroscopy is sensitive to soil-to-sensor distance (D) and angle (α) variations, which have prevented the successful development of on-line soil sensors so far. This study was undertaken to minimise these variations through optimising the three-point linkage of the tractor to improve the quality of soil spectra and the accuracy of plant available phosphorus (P-avl) measured with an on-line soil sensor. The sensor consisted of a tine, to the back of which an optical probe was attached to acquire soil spectra in diffuse reflectance mode from the bottom of the trench opened by the tine. A mobile, fibre-type, Vis–NIR spectrophotometer (Zeiss Corona 45 visnir fibre, Germany), with a measurement range of 306.5–1710.9 nm was used. Five lengths of the third point link (L) of the tractor of 545, 550, 555, 560 and 565 mm were selected to evaluate the quality of spectra collected on-line at 0.15 m tine depth. The on-line measured spectra were corrected to remove the effect of D and α. The correction was evaluated by estimating the accuracy of predicting P-avl using on-line measured spectra and a previously developed P-avl calibration model.

Results showed that the best quality of spectra measured on-line was obtained for L of 555 mm, at which D and α vanished. This finding was supported by the maximum value of average maximum reflectance (AMR) of 75.7% obtained and by 100% successfully collected spectra. The worst quality of spectra was obtained at L of 545 mm, with the largest D of 6 mm and the largest α of 0.6°. Values of L of 560 and 565 mm led to a decrease in the AMR (43.3 and 33.2%, respectively), while recording 100% successful spectra. Correction of on-line measured spectra led to clear improvements in the accuracy of on-line measured P-avl. A lower root mean square error (RMSE) of 1.07 mg 100 g^{-1} and higher ratio of prediction deviations (RPD) of 1.42 were obtained with corrected spectra as compared to uncorrected spectra (RMSE = 1.15 and RPD = 1.39). In addition, the correction of spectra resulted in an increase in the degree of similarity between laboratory and on-line measured P-avl maps by 29.6%. These results suggest the need for optimising the tractor hydraulic three-point linkage set up, and for spectra correction in order to improve the accuracy of on-line measured soil properties.

1. Introduction

Visible (Vis) and near infrared (NIR) diffuse reflectance spectroscopy is a promising measurement technique available to provide rapid information about soil physical and chemical properties, e.g. moisture, carbon, nitrogen, phosphorus and calcium content; and cation exchange capacity in an economical manner (Ben-Dor and Banin, 1995; Chang et al., 2001; Reeves and McCarty, 2001; Odlare et al., 2005; Cozzolino and Morón, 2006; Maleki et al., 2006a; Wetterlind et al., 2008). When light is illuminated towards the soil surface, the radiant energy is distributed through three different processes: reflection, absorbance and transmission (Dahm and

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Hahm, 2001). Since transmission for opaque materials such as soils equals zero, the balance between reflection and absorbance is governed by the influence of soil physical and chemical properties (Mouazen et al., 2005). The Vis–NIR spectroscopy was adopted by many research groups to measure soil properties. Although several researchers reported off-line non-mobile measurement, only few studies on on-line measurement of soil properties were reported (Shonk et al., 1991; Sudduth and Hummel, 1993; Shibusawa et al., 2003; Mouazen et al., 2005). This is attributed to difficulties in designing a sensor that can penetrate the soil and acquire spectra successfully (Mouazen et al., 2007). In addition, lower accuracy associated with providing general calibration models valid over a wide geographical area enhances limiting the attraction of researchers to develop a working on-line sensor. However, research is required to improve the performance of the few on-line Vis–NIR sensors exist, since on-line data acquisition about soil is useful input for sensor-based variable rate application of different inputs into agricultural soils (Maleki et al., 2007).

Based on laboratory measurement of soil spectra using a Vis–NIR spectrophotometer, we found the diffuse light reflected from the soil surface decreases with the increasing soil-to-sensor distance (D) and angle between the soil and sensor (α). These two parameters induce undesired changes in spectra, which requires a correction algorithm to retain the original spectral features. Other researchers encountered the same problem during the development of on-line measurement systems of soil properties (Sudduth and Hummel, 1993; Shibusawa et al., 2003). Generally, D affects the accuracy of prediction of soil properties e.g. carbon, nitrogen, etc. (Sudduth and Hummel, 1993). Mouazen et al. (2005) claimed that they were able to minimise D variation by introducing reasonably similar maps of moisture content developed by an on-line sensor and oven drying method. In fact, the highest light reflection from the soil surface can be recorded when direct contact between the soil and the sensor ($D = 0$ mm and $\alpha = 0^\circ$) is ensured. During on-line measurement the direct contact should be fulfilled, bearing in mind that vibration can always exist during measurement that might disturb the collection of spectra. However, the vibration induced noise can be eliminated from the spectra by spectra pre-processing such as smoothening, normalisation and/or multiplicative scatter correction (Mouazen et al., 2005).

In order to keep the sensor in continuous contact with the soil, two conditions have to be taken into consideration. Firstly, a proper mechanical design of the optical probe (the unit that penetrates the soil and collects soil spectra) has to be provided, which should ensure continuous penetration of the soil, preparation of a smooth soil surface and preservation of direct contact between the soil and the optical probe (Mouazen et al., 2005, 2007). The other condition is to ensure a proper calibration of the tractor three-point linkage, in order to attain transactional and longitudinal levelling of the optical probe. This has to be accompanied with manual adjustment of the tractor hydraulic system to locate the sensor to the required depth, while preserving levelling of the sensor.

The main objective of this study was to develop a methodology to optimise the tractor three-point linkage system set up, aiming at minimising D and α and improving the quality of on-line collected soil spectra. The second aim of this study was to evaluate the effect of correction of on-line measured spectra on the accuracy of prediction of plant available phosphorus in soil (P-avl).

2. Materials and methods

2.1. Portable, fibre-type visible and near infrared spectrophotometer

The spectrophotometer was a fibre-type Vis–NIR instrument developed by Zeiss Company (Zeiss Corona 45 visnir fibre, Germany). It is fast (1 soil scan per 0.4 s) and of small size, has no moving parts, and has been successfully used on mobile machines, e.g. to measure grain quality on combines (Reyns et al., 2001; Maertens et al., 2004), soil moisture content (Mouazen et al., 2005) and extractable P, P-avl, total carbon, organic carbon and pH (Mouazen et al., 2007). It was also used to optimise an on-line variable rate applicator of triple super phosphate (P_2O_5) during maize planting based on on-line measurement of soil extractable phosphorus using the on-line Vis–NIR sensor of this study, shown in Fig. 1 (Maleki et al., 2006b, 2007). The instrument has, in addition to the Si-array available for the measurement in the Vis and short infrared wavelength region (306.5–1135.5 nm), an InGaAs diode-array for the measurement in the NIR region (944.5–1710.9 nm). The light source is a 20 W tungsten halogen lamp illuminating the targeted soil surface with a spot of 2–3 mm light through an optic fibre. The illumination and reflectance fibres were positioned at a 45° angle in an optical probe used to carry out reflectance measurement from the soil surface prepared by the tine (Fig. 2). Standard white (75% reflectance) and black (7% reflectance) references were used.

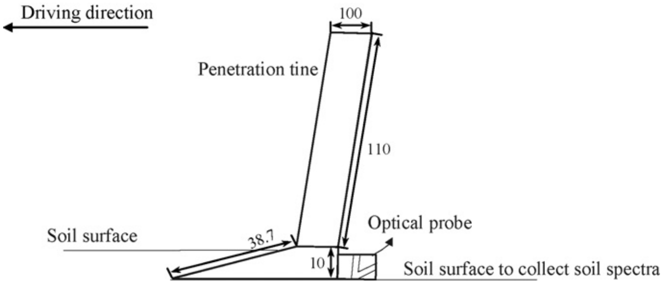

Fig. 1. The optical probe attached to the backside of the penetration tine.

2.2. On-line visible and near infrared soil sensor

The on-line measurement system consisted of a penetration tine (subsoiler), to which the optical probe is attached (Fig. 1). The tine and optical probe were set on a frame, which was mounted onto the three-point linkage of the tractor. It is a simple frame, which has a metal wheel on each side to regulate the subsoiler depth. However, depth control is only done in the downwards direction by the two wheels. In this way, the upwards movement of the tine due to tractor driving over a higher spot than that of the sensor driven behind can not be controlled. The depth (draught based) control system linked to the hydraulic system of the tractor had to be set at minimum response to draught variation during the field test to reduce vibration and variation in D and α. The tine penetrates the soil to any required depth between 5 and 40 cm, making a trench, whose bottom is smoothened due to the downwards force acting on the tine. This downwards force increases friction between the flat bottom of the tine and its retrofitted probe with the soil, which improves smoothening of the bottom of the trench and maximises light reflectance.

2.3. Laboratory calibration of the measurement system

A preliminary test was undertaken under laboratory conditions to set the three-point linkage and the hydraulic system of the tractor in a proper position that would ensure the tine penetration to a depth of 15 cm, while preserving the optical probe in a horizontal position (angle α and $D = 0$ in Fig. 2a) parallel to the bottom of the trench opened by the subsoiler. The horizontal probe levelling included longitudinal and transactional adjustments of the upper third point link and lower two-point links, respectively. The experiment showed

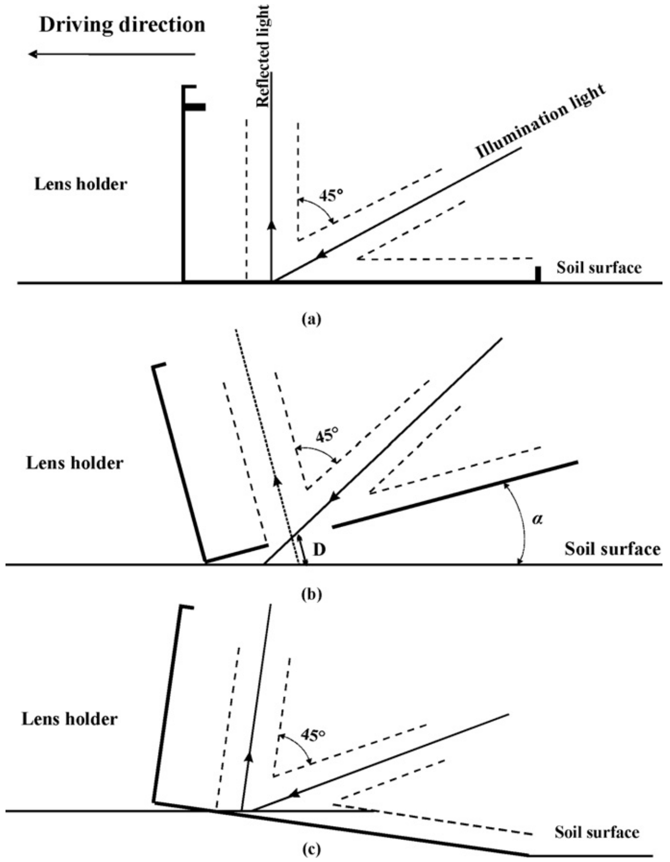

Fig. 2. Optical path throughout the optical probe for (a) tine at optimal position, (b) tine inclined backward, and (c) tine inclined forward.

that the optimal L is 555 mm, for which a longitudinal (parallel to the direction of travel) levelling of the optical probe was achieved. In order to insure this position of the optical probe, the hydraulic system of the tractor was manually adjusted to a given level. This optimal calibration set up obtained under laboratory conditions, including the three-point linkage and hydraulic system, was adopted during the on-line field measurement.

2.4. Field measurement

2.4.1. Evaluation of the effect of different third point link lengths on quality of spectra

To verify the laboratory calibration of the three-point linkage and hydraulic system, on-line measurement of soil spectra was carried out on a Haplic Luvisol (FAO classification) field in Heverlee, 30 km east of Brussels (Belgium). The field soil texture determined by wet sieving and a hydrometer test was a silt loam (Table 1), according to the United Stated Department of Agriculture (USDA) system of texture classification. The experiment was carried out in the autumn of 2005 after harvesting sugar beet. The field was even, particularly the plot where the test was carried out.

Table 1
Soil texture fraction of the experimental field topsoil (0–20 cm) according to the USDA soil texture classification.

Particle size	Heverlee field	Lovenjoel field
	Silt loam	Silt loam
Sand (>50 μm) (g kg^{-1})	90	202
Silt (2–50 μm) (g kg^{-1})	778	697
Clay (<2 μm) (g kg^{-1})	132	101

Table 2
Soil moisture content measured at 15 cm depth and calculated soil-to-sensor distance and angle α in both experimental fields.

	Third point link length (L) (mm)	Soil-to-sensor distance (D) (mm)	Soil-to-angle angle (α) (deg)	Average soil moisture content (kg kg^{-1})
Heverlee field				
Line A	545	6	0.6	20.1
Line B	550	3	0.3	19.4
Line C	555	0.0	0.0	19.2
Line D	560	0.0	−0.2	18.7
Line E	565	0.0	−0.6	19.4
Lovenjoel field				
All field lines	562	0.0	−0.42	16.1

The optical sensor was pulled through 5 parallel lines, 5 m apart along a 15 m distance parallel with the direction of the tramlines. Carrying out the measurement within a relatively small area of the field minimised the effect of variable soil conditions and field topography, which allowed information about the effect of L on the quality of spectra to be extracted.

The system was driven at a travel speed of 1.5–2.0 km h^{-1}, setting the tine tip at a depth of 0.15 m. Each collected spectrum was an average of 5 successive spectra collected along a distance of 1–1.50 m, depending on tractor speed. The averaged gravimetric moisture content (d.b.) for all lines was at the field capacity (Table 2), ranging between 18.7 and 20.1 kg kg^{-1}. Five different L of 545, 550, 555, 560 and 565 mm were adopted. Each length was used for measurement of one individual line. After measurement of an individual line, L was changed for the next measurement line. This variation in L provided different positions of the optical probe as shown in Fig. 2. Since the variation of α and D are very small (scale of few degrees and millimetres for α and D, respectively), it was not possible to measure them precisely during on-line measurement. Therefore, they were calculated theoretically under laboratory conditions and reported in Table 2.

2.4.2. Correction of on-line collected soil spectra

Due to a technical issue associated with the Vis–NIR spectrophotometer from Zeiss company used in this study, spectral shifts towards the upper or the lower directions were recorded during on-line measurement with most of measured spectra at all L (Fig. 3). The shift occurred at 970 nm, which might be attributed to vibration and/or different D and α between the background (reference) measurement and soil measurement. Furthermore, this spectral shift could also be due to a differential response between the two detectors used (400–969 nm and 970–1700 nm). A simple test under non-mobile laboratory conditions confirmed that vibration has no effect on the creation of this shift. In fact, vibration induced noise in spectra along the entire wavelength range. Examining the effect of different D and α between white reference measurement ($D = 0$ mm and $\alpha = 0^\circ$) and real soil measurement ($D > 0$ mm and $\alpha \neq 0^\circ$) proved that the presence of shift in spectra is due to variable D and α. The size of this shift depends on the magnitude of D and α.

Spectra correction was done by a custom built program developed using the LabView programming language. This program was based on the assumption of shifting the lower spectra segment (at 306–968 nm or 972–1700 nm) to match the higher part. This was done as follows:

1. The difference in reflectance in % between 968 and 972 nm wavelengths was calculated.
2. If the reflectance at wavelength 968 nm was higher than that at 972 nm, the reflectance difference was added to all wavelengths

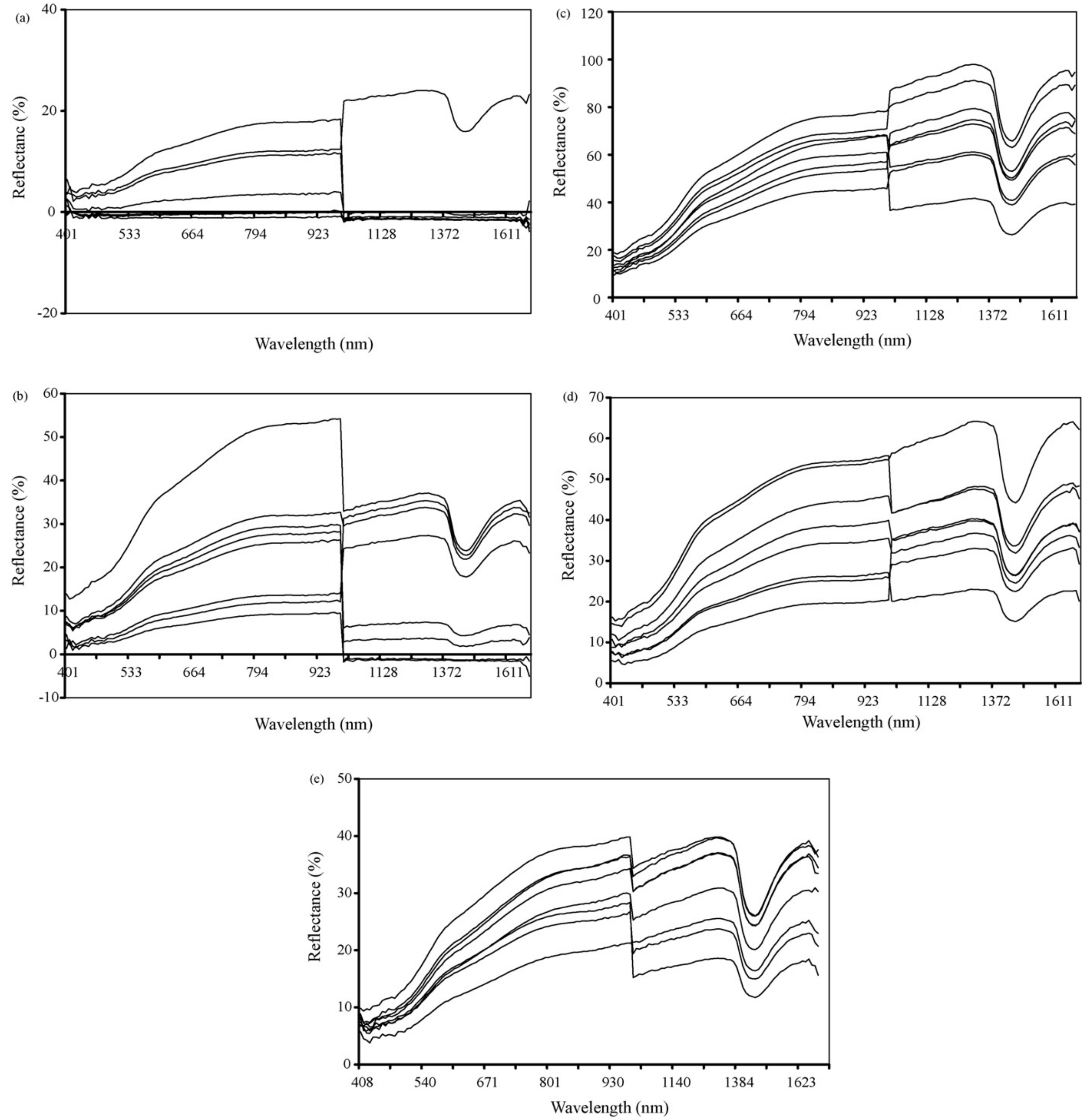

Fig. 3. Recorded soil spectra at different probe inclination angle (α) resulted from different lengths of the tractor third-point link (L); (a) $\alpha = 0.6^\circ$ at $L = 545$ mm; (b) $\alpha = 0.3^\circ$ at $L = 550$ mm; (c) $\alpha = 0.0^\circ$ at $L = 555$ mm; (d) $\alpha = -0.2^\circ$ at $L = 558$ mm; (e) $\alpha = -0.6^\circ$ at $L = 565$ mm.

over the range of 972–1700 nm. While, if the reflectance at wavelength 968 nm was lower than that at 972 nm, the reflectance difference was added to all wavelengths over the range of 306–968 nm.

2.4.3. Evaluation of the effect of soil-to-sensor distance and angle variations on the prediction accuracy of plant available phosphorus in soil

Previous on-line measurement data from 2004 was recalled to test the effect of spectra correction on improving the accuracy of prediction of P-avl, as an example. Availability of chemical and spectral data from the previous year (2004) allowed the correction approach proposed during Heverlee field measurement in 2005 (see Section 2.4.2) to be tested. The measurement in Heverlee field in 2005 concerned about mechanical calibration only, where no chemical data were available. The correction approach will be tested by comparing the prediction accuracy of P-avl before and after removing the shift in spectra.

The experimental field in 2004 was a Haplic Luvisol (FAO classification) grass field of 2 ha area and was situated in Lovenjoel near Leuven east of Brussels, and had silt loam texture according to the USDA soil classification (Table 1). The field had a slight slope

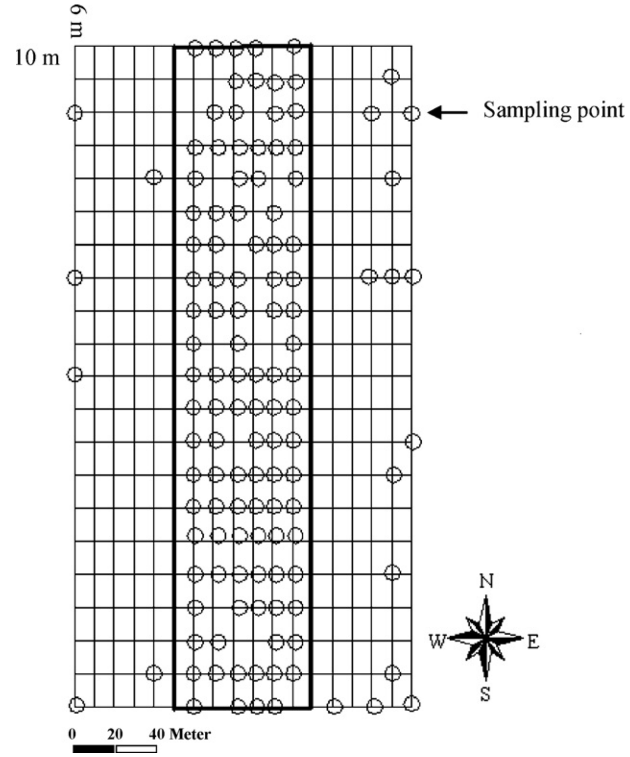

Fig. 4. Soil sampling locations in a grid of 6 m × 10 m in a 100 m × 200 m Lovenjoel field.

and was free of tram lines. The field was divided into a 6 m × 10 m grid, as shown in Fig. 4. The optical sensor was pulled along the longest directions of the field through 18 parallel lines each 6 m apart at a forward speed of 2–3 km h^{-1}, setting the tip at a 0.15 m depth. A total of 126 soil samples were collected mostly from the 6 middle lines (Fig. 4) after sensor passed. Each sample was collected at the bottom of the trench opened by the tine over a distance of 1–1.5 m. The samples were dried and sieved with a 2 mm sieve, before P-avl was measured using the Olsen method (Olsen et al., 1954). A sufficient amount of wet samples was used to estimate the moisture content by drying in an oven at 105° for 24 h. The average field moisture content was at the field capacity. The results of soil moisture content and P-avl of these samples are presented in Tables 2 and 3, respectively.

A digital global positioning system, Trimble® AgDGPS 132 was used to locate the position of soil spectra. The 126 on-line collected spectra with a location matching the location of the 126 soil samples collected for laboratory analysis of P-avl were later separated from the data set and used to predict P-avl using the model described in a previous study (Maleki et al., 2006a). This model was established using the Partial Least Squares (PLS) analysis with a full cross validation technique on 204 independent spectra of fresh soil samples collected from many fields in Belgium having these texture classes of loamy sand, sandy loam and silt loam. Measurement of spectra used for developing P-avl model was done under laboratory non-mobile measurement conditions. The results of the calibration model and the prediction of P-avl of 126 off-line recorded spectra under laboratory condition of soil samples collected in Lovenjoel field is illustrated in Table 4 (Maleki et al., 2006a). This model was used in this study to predict P-avl using spectra collected on-line in Lovenjoel field. Maps of laboratory Olsen measured and on-line predicted P-avl using on-line recorded spectra were developed using geostatistical software (GSLIB). The algorithm used was ordinary kriging (Goovaerts, 1997), which requires the determination of a variogram model. The experimental variogram was obtained through:

Table 3
Chemical analysis results of plant available phosphorus (Olson method) in soil for 126 samples of Lovenjoel field.

	No.	Maximum	Minimum	Mean	Standard deviation
Available phosphorus (mg 100 g^{-1})	126	11.0	2.9	4.8	1.7

Table 4
Statistics results of Partial Least Squares (PLS) model of plant available phosphorus in soil (P-avl) resulted from samples collected from many fields of Belgium having texture classes of loamy sand, sandy loam and silt loam (Maleki et al., 2006a).

Statistics	Sub-set samples		
	Calibration	Full cross validation	Laboratory validation on off-line spectra
R^2	0.83	0.73	0.68
Slope	0.83	0.76	1.007
Offset	1.219	1.71	−0.709
RMSE (mg 100 g^{-1})	0.943	1.202	1.08
Bias (mg 100 g^{-1})	-6.3×10^{-7}	0.01157	0.67
RPD	–	1.92	1.76
RER	–	7.22	7.72

RMSE, root mean square error.
R^2, coefficient of determination.
RPD, ratio of prediction deviations.
RER, ratio error range.

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})}\sum_{\alpha=1}^{N(\mathbf{h})}\{z(\mathbf{x}_\alpha + \mathbf{h}) - z(\mathbf{x}_\alpha)\}^2 \qquad (1)$$

where $\gamma(\mathbf{h})$ is the variogram for a distance vector (lag) **h** between observations $z(\mathbf{x}_\alpha)$ and $z(\mathbf{x}_\alpha + \mathbf{h})$, and $N(\mathbf{h})$ is the number of pairs separated by **h**. The experimental variogram data were modelled by considering the indicative goodness of fit provided by Variowin (Pannatier, 1996). In all cases a spherical model was found to be best:

$$\gamma(h) = C_0 + C_1 \cdot \left(\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right) \quad \text{if } 0 < h \le a \qquad (2)$$

$$\gamma(h) = C_0 + C_1 \quad \text{if } h > a \qquad (3)$$

where C_0 is the nugget effect (Y-intercept), $C_0 + C_1$ is the sill and a is the range. The interpolated map cell size was 1 m^2 with 200 rows and 80 columns.

To compare variogram models, they were standardised by: $\gamma(h)/(C_0 + C_1)$. In this way all variograms received a sill of one.

3. Results and discussion

3.1. Evaluation of soil spectra collected on-line at different third point link length

Fig. 3 shows soil spectra collected on-line for 5 different experimental lines carried out with 5 different L, reflecting 5 values of angle α and D (Table 2). A total of 8 spectra for each measurement line collected along 15 m travel distance are shown in Fig. 3.

With L equals to 545 mm (line A), the quality of spectra is extremely bad. Apart from 8 spectra only one spectrum is a soil spectrum. However, two other spectra are successfully measured by the first detector (306–945 nm), while no reflection features are captured in the near infrared region of (946–1700 nm). This poor quality of spectra is attributed to the fact that the sensor focal point falls above the soil surface due to the large *D* (Fig. 2). In this case the incidence of the path of illuminated light and the path of reflected light does not occur at the bottom of trench soil. But, in order to have a maximum collection of electromagnetic energy from the soil surface, the focal point should fall directly on the soil surface, at which *D* and α vanish. This means that the incidence of the illuminated and reflected light should strictly occur on the soil surface following the passage of the tine and optical probe coming closely behind. The shift in spectra between the two detectors increases in size with increasing *D* and α, until no signal is collected at the NIR range, similar to Fig. 3a. This case can be represented by the position of the measurement system illustrated in Fig. 2b, where the tine inclines towards the forward direction forming an angle α with the horizontal. At this position of the tine-optical probe system *D* and α are too large (Table 2), for which only a very small amount of diffuse reflected light from the trench bottom could be captured by the probe and reached the detector. Capturing this small amount of light takes place only when the path of illumination light partially met with the path of the reflected light on the soil illuminated spot at the bottom of the trench.

To evaluate the successful capturing of the reflected light, the maximum reflectance (in percentage) measured for each spectrum was considered. The average maximum reflectance (AMR) of all 8 spectra is adopted and reported in Table 5. Indeed, a very small value of AMR of 7.8% is found during the measurement through line A. This also proves that a very small percentage of diffuse reflected light from the soil surface could be captured.

Increasing *L* to 550 mm (line B) decreases *D* and α (Table 2), and subsequently the quality of collected soil spectra improved (Fig. 3b). This is reflected by the number of successfully collected soil spectra and by AMR (Table 5). However, the values of these two indicators are still too small to declare a well-levelled position of the optical probe on the bottom of the opened trench. This means that α and *D* during line B measurement are still relatively big (Table 2), and the probe position is still similar to the case illustrated in Fig. 2b.

The best soil spectra are collected with *L* of 555 mm (line C in Fig. 3c). This observation is justified by the fact that AMR obtained for line C is the highest among the 5 experimental setups (Table 5). This case can be illustrated by Fig. 2a, where the tine is at the optimal position allowing the bottom of the optical probe to be in continuous contact with the trench bottom opened by the penetration tine (α and $D = 0$). This position should result in a smoother soil surface at the bottom of the opened trench, and thus maximum light is reflected. The maximum captured reflection is attributed to the incidence of the illumination light and reflected light baths on the soil surface prepared by the system (Fig. 2a). The maximum value of AMR obtained here indicates that the signal-to-noise ratio is high, and is higher than the other 5 experimental lines. The percentage of successfully measured spectra is 100%, and all measured spectra can be used for predictions of soil chemical and physical properties.

Table 5
Statistics about on-line collected soil spectra (8 spectra) in Heverlee field at different length of the tractor third point link (*L*).

Line	Length of third point link (*L*) (mm)	Number of successful spectra	Percentage of successful spectra (%)	Average maximum reflectance (AMR) (%)
A	545	1	12.5	7.79
B	550	4	50.0	30.60
C	555	8	100.0	75.68
D	560	8	100.0	43.28
E	565	8	100.0	33.15

With further increase in *L* to 560 (line D) and 565 mm (line E), the quality of soil spectra acquired degrades. In this case the incidence of the illuminated light and reflected light falls below the reflection surface of the soil (Fig. 2c) leading to light collection from only the edge of the illuminated soil spot. This is reflected by the decrease in AMR values for both lines (Table 5). However, the number of successfully collected spectra does not change (100% successful spectra). The decrease in the AMR for these two lines means a decrease of the signal-to-noise ratio, and eventually the prediction accuracy of soil properties might be influenced. Comparing the spectra collected for each measurement line, it can be concluded that the best quality of spectra is obtained with 555 mm *L* (zero values of *D* and α), as illustrated in Fig. 3.

3.2. Correction of on-line measured spectra

Although *L* of 555 mm was found to be the optimal length, at which *D* and α theoretically vanish, shift still occurs at a wavelength of 970 nm for most measured spectra, which emphasises the need for spectra correction at any selected *L*. The disturbed and hollowed soil structure that resulted after sugar beet extraction in Heverlee field could introduce significant variation in *D* and α, which would explain this shift (Fig. 3). However, in grass or after harvest of cereal crops, the authors found less occurrence of this shift in spectra. In fact, variation in *D* and α can only be minimised, but not be avoided. The correction of soil spectra adopted in this study to eliminate this shift results in smooth spectra without a shift up or down. Figure 5 shows corrected spectra of those measured at *L* of 555 mm (Fig. 3c). These spectra have to be subjected to further pre-processing (normalisation, derivation, smoothing, etc.) before it can be used for the final prediction of soil properties. The type of spectra pre-processing depends on the type of element to be quantified (Mouazen et al., 2006).

In order to evaluate the usefulness of the correction made on spectra to remove the shift that occurred at 969–970 nm wavelength, the on-line measured spectra (126 spectra) in Lovenjoel field were used to predict P-avl using spectra with and without shift (corrected spectra). The predicted P-avl values of 126 spectra were compared with the corresponding laboratory reference measurement of soil samples collected from the same locations. There is a difference in the prediction accuracy of P-avl values between on-line measured soil spectra collected from field without spectra correction (root mean square error (RMSE) = 1.15 mg 100 g^{-1} and ratio of

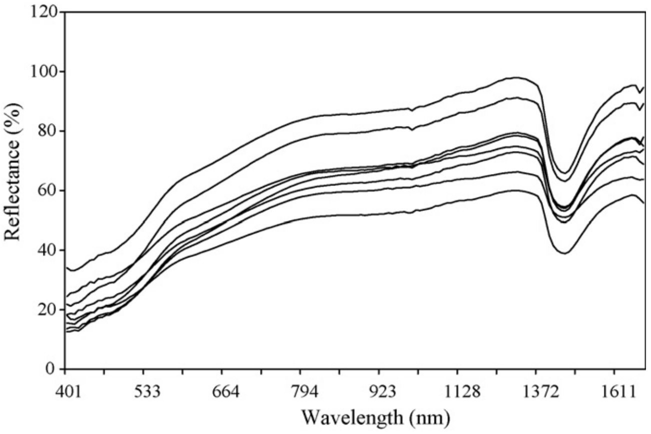

Fig. 5. Corrected spectra measured for line C in Heverlee field with 555 mm long third point link (*L*).

Table 6
Statistics results of plant available phosphorus in soil (P-avl) prediction using on-line measured spectra in Lovenjoel field.

Statistics	Sub-set samples	
	Raw uncorrected spectra	Corrected spectra
R^2	0.56	0.62
Slope	0.7231	0.7079
Offset	1.4822	1.5134
RMSE (mg 100 g^{-1})	1.15	1.07
Bias (mg 100 g^{-1})	−0.139	−0.128
RPD	1.39	1.42
RER	6.47	6.71

RMSE, root mean square error.
R^2, coefficient of determination.
RPD, ratio of prediction deviations.
RER, ratio error range.

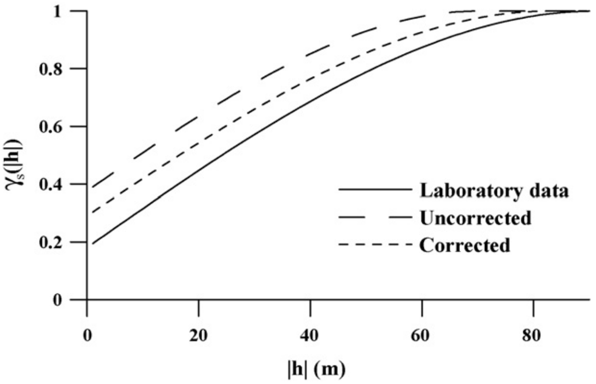

Fig. 6. Standardised variograms of plant available phosphorus in soil (P-avl) based on laboratory chemical analysis, uncorrected and corrected on-line measured soil spectra in Lovenjoel field.

prediction deviations (RPD) = 1.39) compared to those predicted with corrected spectra (RMSE = 1.07 mg 100 g^{-1} and RPD = 1.42). This difference indicates only small improvement in the prediction accuracy obtained after correction of spectra, as shown in Table 6. This point-by-point statistics however does not take the spatial structure of the data into account. Therefore, standardised variograms were calculated and modelled by a spherical model of the 126 laboratory measurements, the uncorrected and the corrected P-avl values (Fig. 6). It can clearly be observed that the variogram of the corrected P-avl approaches more the variogram of the laboratory values compared to the uncorrected values, with both the nugget effect and the range closer to the values of the variogram of the laboratory data. This indicates that the spatial structure variation of P-avl is better captured by the corrected predictions compared to the uncorrected.

The improvement of using corrected spectra to predict P-avl can also be shown as a map basis. By visually comparing Fig. 7a–c, similarities in the spatial patterns of P-avl are obvious. Similarity between categorical maps is usually quantified through a statistical kappa (κ) value (Cohen, 1960), expressing proportionally how much better the results are compared to a purely random classification. The larger κ, the more accurate the classification. To obtain categorical maps of P-avl, all maps were classified into five classes based on the 0.2, 0.4, 0.6 and 0.8 quantiles of the interpolated laboratory measurements. The resulting maps are shown in Fig. 8a–c. The κ value of comparing the laboratory classification with the uncorrected P-avl is 0.428, whereas for the comparison with the corrected P-avl classification κ is 0.555. According to Landis and Koch (1977), the strength of agreement between the laboratory classification and both the classification of the corrected and the uncorrected P-avl was considered to be moderate. Nevertheless, the improvement of using corrected spectra for P-avl prediction results in an increase in map similarity of 29.6% (based on the κ values).

The accuracy of P-avl map developed in this study is much improved compared to that introduced by Mouazen et al. (2007). This improvement can be attributed to the more accurate model used in this study (Maleki et al., 2006a) compared to that used by Mouazen et al. (2007). The model of Maleki et al. (2006a) was built for only three soil textures, namely, loamy sand, sandy loam and silt loam, whereas the model of Mouazen et al. (2007) was built for

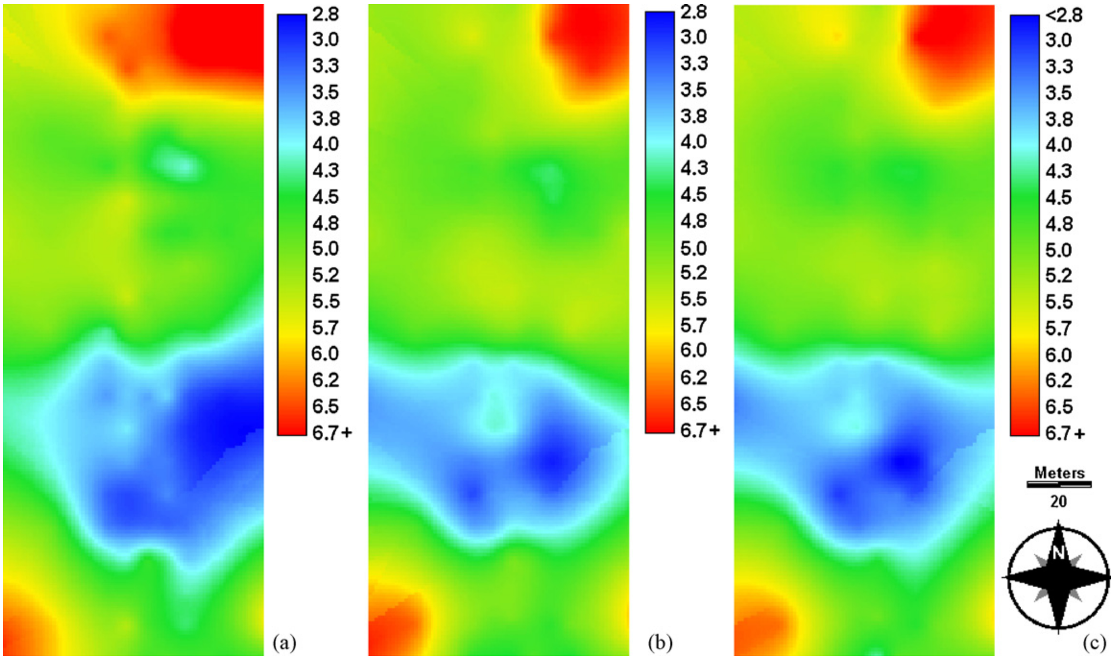

Fig. 7. A 1 m × 1 m grid obtained by ordinary kriging of plant available phosphorus in soil (P-avl) based on: (a) laboratory chemical analysis, (b) uncorrected, and (c) corrected on-line measured soil spectra in Lovenjoel field.

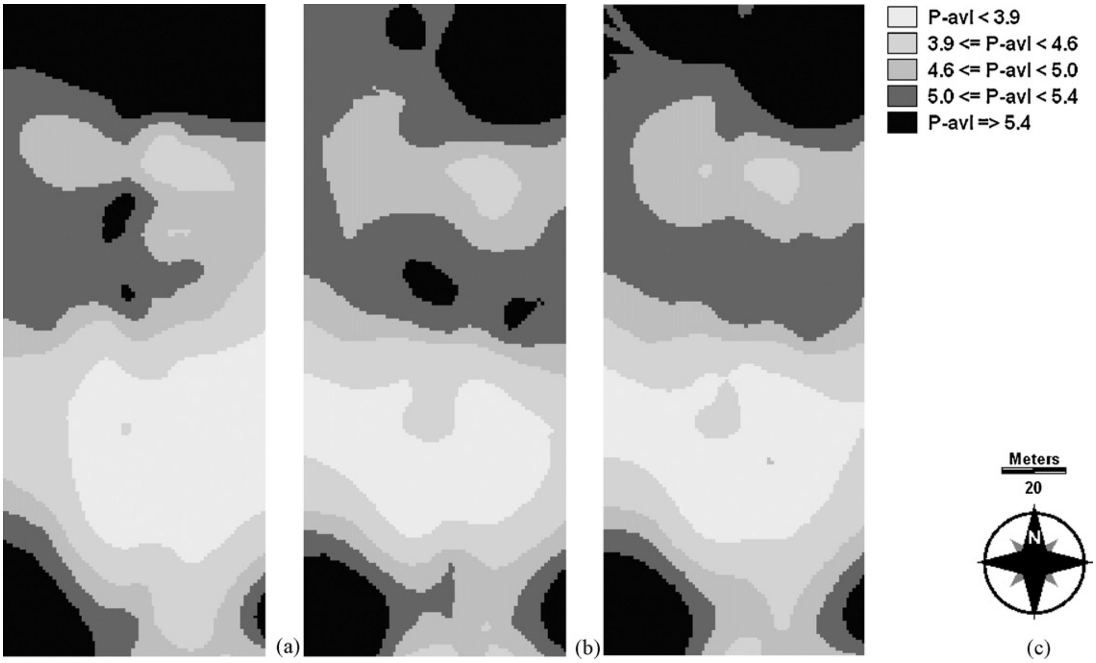

Fig. 8. Categorical maps of plant available phosphorus in soil (P-avl) based on (a) laboratory chemical analysis, (b) uncorrected, and (c) corrected on-line measured soil spectra in Lovenjoel field.

all texture classes encountered in Flanders, the Northern part of Belgium. Furthermore, the model of Maleki et al. (2006a) used more samples (204) for a smaller number of texture classes (3) as compared to the smaller number of samples (175 samples) for a larger number of texture classes used for the model of Mouazen et al. (2007). This makes the model developed by Maleki et al. (2006a) more accurate than that developed by Mouazen et al. (2007) for prediction of P-avl for these three texture classes. Since the texture of the Lovenjoel field (silt loam) is one of the three textures valid for Maleki et al. (2006a) model, it is logical that more accurate prediction has to be achieved using this model (compared to that of Mouazen et al., 2007).

Comparing results given in Table 4 with those of Table 6, one can conclude that the accuracy of on-line measurement of P-avl (a smaller R^2 of 0.62, almost equal RMSE of 1.07 and a smaller RPD of 1.42) is rather less than the off-line, non-mobile measurement (a larger R^2 of 0.68, almost equal RMSE of 1.08 and a higher RPD of 1.76). The reason of such degradation in the accuracy of P-avl prediction during on-line measurement is the deviation between the starting point of a spectrum measurement as compared to that of corresponding soil sample collected for laboratory chemical analysis. With the most accurate digital global positioning system, a deviation in position of 0.5–1 m is expected. This deviation might introduce a source of error, since the variability in soil is even smaller than this tolerance (1–0.5 m). Another reason that might introduce a source of error is the larger surface (1.25 m) scanned by the spectrophotometer compared to the amount of soil considered for the chemical analysis.

4. Conclusions

An approach to calibrate the tractor hydraulic system for successful on-line measurement of soil spectra using visible and near infrared spectroscopy was introduced and tested. The calibration included the determination of the optimal length of the tractor third point link (L) and the manual adjustment of the hydraulic system to position the sensor at a specified depth, while preserving a horizontal levelling of the sensor for maximum light reflection detection from the bottom of the opened trench.

For successful on-line measurement, the soil-to-sensor distance (D) and angle (α) should be minimised so that maximum electromagnetic energy reflected from the soil surface can be collected. This also requires a successful mechanical design of the on-line sensor that ensures continuous sliding of the optical probe over the measured soil surface, when it is set to the required depth after the proper calibration of the tractor three-point linkage and hydraulic system is achieved. However, each measurement depth requires a different calibration, which has to be carried out separately.

Modifying and correction of soil spectra is essential to improve the accuracy of on-line measured soil properties. This becomes a critical step when on-line measurement is to be carried out after root crops harvest (sugar beet or potato), since the soil layer penetrated by the sensor is disturbed or even contains hollowed space. Therefore, the effect of correction of spectra would have been greater if the crop had been a root crop instead of grass, since smaller variation in D and α is experienced after grain crop harvest.

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