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A new approach for variable rate fertilization based on direct read of soil map image

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Abstract

Aim of study: To develop a methodology for variable rate (VR) fertilization with less complexity in practice for variable rate fertilization.

Area of study: Northwest of Iran.

Materials and methods: A software was developed to read a soil map image pixel-by-pixel to provide the required information to tailor the fertilizer rate, regardless of which software was used for map generation. A total of 78 soil samples were collected and analyzed for soil potassium, and the results were used to generate an actual map including zones ranging from 70 to 190 kg/ha. The application rates were evaluated based on 50 deposition pans and compared with those calculated from the actual map. Based on the lag time in fertilization, three applied maps were also generated.

Main results: The correlation coefficients found between the application rates computed based on the original soil samples and posted the locations of the sample points on the applied maps were 0.95, 0.95, and 0.94, over the ravel speeds of 6, 7, and 8 km/h, respectively. The results showed there is a correlation coefficient of 0.96 with an RMSE of 1.88 kg/ha, where the application rates computed from deposition pans compared with the corresponding location on the actual map. All applied maps were identical to the actual map. The results showed that the VR fertilization based on a direct read of a map image operated as expected.

Research highlights: Fertilizer application was based on the direct read of map image. This study highlights also the need of new approaches in programing for simplicity of precision agriculture.

Additional key words: applicator; granular fertilizer; potassium; precision agriculture.

Abbreviations used: ACI (Applicator Controller Interface), CV (coefficient of variation), GPSCR (GPS Coordinate Recorder), IDW (Inverse Distance Weighing), LabVIEW (Laboratory Virtual Instrument Engineering Workbench), MAE (mean absolute error), MapReFA (Map Reader Software for Fertilizer Application), PA (precision agriculture), r (correlation coefficient), RMSE (root mean square error), ROI (Region of Interest), TLSF (Tractor Left Side Far), TLSN (Tractor Left Side Near), TRSF (Tractor Right Side Far), TRSN (Tractor Right Side Near), VR (variable rate).

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Introduction

The application of granular fertilizers is indispensable in modern agriculture. Each year farmers apply over 185 million tons of nitrogen (N), phosphorous (P), and potassium (K) fertilizers to their fields all around the world (Shannon *et al.*, 2019). Usually, conventional applicators spread a blanket of fertilizer over the whole field. Precision agriculture (PA) aims to apply the right amount of fertilizer in the right place, as determined through soil analysis and other influenced factors. This is the meaning of variable rate (VR) fertilizer application. In soil survey-based

VR fertilization, the applicator should tailor the discharge rate based on the soil nutrients availability. Identifying where needs more and where needs less fertilizer is the most crucial challenge in performing VR fertilization. The VR fertilization is classified as either passive or active. If a sensor collects the required information in real-time for varying fertilization rate, it will be active or sensor-based VR approach. Maleki *et al*. (2008a) implemented a soil sensor, which was evaluated beforehand by Mouazen *et al*. (2007), behind a shank's sole and collected soil spectra in real-time to predict soil P and utilize the results as the basis for phosphate application. An estimator model had to be also employed to convert the soil spectra into the soil P level (Mouazen *et al*., 2007). It is also required to take the other physical or chemical properties into consideration for more accurate site-specific application using sensor-based VR approach. In such a procedure, it is reported that the soil moisture masks the detection of other nutrients where soil spectra are collected for prediction of a given nutrient (Bogrekci & Lee, 2005). This means that for each soil property, an estimator model (*e.g*. moisture content), should also be developed and utilized to properly convert it into the soil's chemical and physical properties. Up to now, few studies have been conducted to carry out VR fertilizations across fields utilizing many soil properties estimator models (Guerrero & Mouazen, 2021). Hence, some believe the passive or map-based approach is more practical and efficient since it considers these parameters in advance using ordinary soil analysis and even makes a room for expert knowledge to finalize the application map. It is well known that there is remarkable spatial variability in a field scale, even for the same soil type (Oberthür *et al*., 1999). A detailed soil digital map should include the spatial variability of a given soil nutrient. Therefore, choosing a proper interpolation method for generating the soil map should be carefully taken into consideration. More explanation on that is beyond the scope of this study.

Today, applicators on the market can apply a variety of different fertilizer products across the field. Based on the soil test results, an application map is generated, which subsequently is loaded into a computer mounted in a VR fertilizer spreader (Ferguson & Rundquist, 2017). Regarding that, the application rate should be updated at specific zones based on the availability of soil nutrient contents. The tractor operator maintains a travel speed and the applicator prompts the operator to manually change the application rate where it is applicable. Although this technology has become a common practice implemented by most VR practitioners (Fulton *et al*., 2002), some agricultural producers refuse to accept it and still use the ordinary equipment. This is likely because they do not have enough investment for renewing farm equipment or they believe the use of those techniques seems to be somehow slowing down their routines. Moreover, the complexity of PA technology implies a greater degree of learning skills for their correct adoption and management (Pathak *et al*., 2019), which varies among every individual and can thus affect an appropriate implementation. Therefore, VR technology will be more common if the focus would be redirected to develop less complicated equipment with easy handling and adjustment. Note that, although combine harvesters equipped with crop monitoring instruments are rapidly being adopted in developed countries (Tiwari & Kumar Jaga, 2012), no considerable percentage is reported for technologies related to VR fertilizer applicators worldwide.

A thorough investigations through published articles, notes, software sharing forums, and industrial sectors revealed that no software is available for researchers who are interested in research studies on PA and also for growers who would rather complete and control the analysis themselves because they are concerned about data ownership. Since it has been reported by many experts that VR technology adds complexity to farm equipment (Fulton *et al*., 2005), particularly in control systems, it would be convenient less complexity in developing such equipment. The objective of this study was to employ VR applicator technology using a soil map image regardless of how it is generated so that every individual could perform VR implementation, avoiding present complexities.

Material and methods

Study area and soil sampling

A field of 9797.26 m^2 located in Iran, longitude of 47°19′7″ and latitude of 35°19′5″ with an 1865 m altitude, was allocated for field trials. Wheat (*Triticum aestivum* L.) had been cultivated in almost half of the field in the previous season, and the rest had been kept as fallow uncultivated. The initial soil moisture content was 17.5 % (dry basis). The soil texture type was clay loam according to the USDA soil classification system. A total of 78 soil samples were collected using a classical grid sampling scheme with a size of 125.6 m^2. Soil samples were taken in the late winter and early spring of 2018, from the 0-25 cm layer and subjected to chemical analyses for K content. The results of the soil analysis were then converted into fertilizer application rates based on the recommendation charts for corn (*Zea mays* L.). The minimum, maximum, mean, and standard deviation were 70, 190, 112.99, and 28.13 kg/ha, respectively. A coefficient of variation of 24.89 was found for this data set. Application rate was computed as potassium chloride (KCl) in kg/ha since it is widely applied annually by most local farmers for corn cultivation.

Sampling points were geo-referenced using a GPS module (U-blox NEO 6M V2, Germany). This module had to be accommodated in the controlling hardware, which will be later discussed in detail. Finally, an Excel file was prepared with columns including longitude and latitude as well as a column for fertilizer application rate values. This

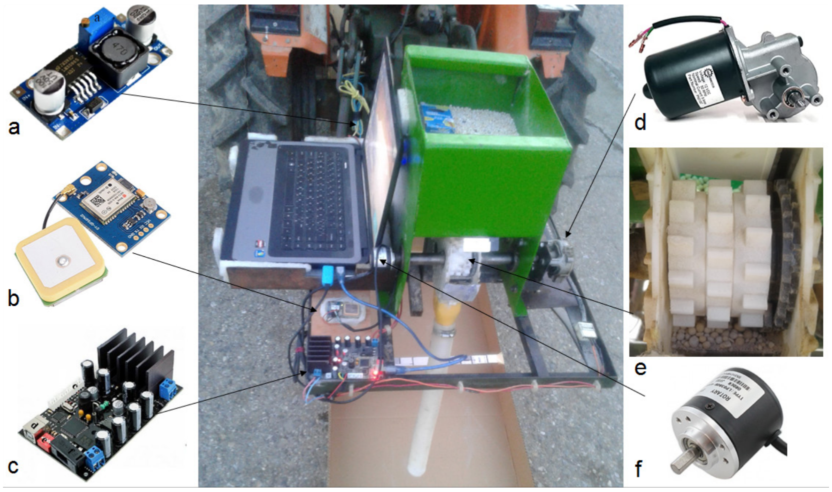

Figure 1. The implementation of a single-row VR applicator; a) voltage stabilizer, b) GPS module, c) encoder driver, d) DC electric motor and worm gear-type gearbox, e) studded–roller metering device, and f) encoder.

file was utilized to generate an application map designated as actual map.

In addition, a little portion of the soil was taken from each sample, mixed thoroughly, and sent to the soil laboratory for K content to see how much fertilizer was required if a uniform application rate is performed.

Fertilizer applicator

An applicator prototype was developed for VR granular fertilizer application. It consisted of a single-row unit assumed to have a 0.65 m width, since it is the common inter-row spacing for corn cultivation. This inter-row spacing was selected to be representative of an applicator with a 3 m width. A triple-rows-studded-roller was assembled as the applicator metering device (rotor). The rotational speed of the rotor was provided using an adjustable speed 12 V/8 Amp DC electrical motor (JY052, China). This motor could turn the rotor at 10-55 rpm through an internal worm-gear-type transmission system. The electrical power was supplied through the available tractor (Goldoni 998, 20 hp, Italy) socket property. However, a voltage stabilizer was required to prevent voltage and current fluctuations, preventing potential damage to the instruments. A DC to DC multi-turn converter (LM2596) with adjustable output voltage ranging from 1.2 to 37 V and 3 A was used to stabilize the power required for driving the electric motor. This instrumentation lets to have better control over the applicator, eliminating possible lags due to gauge wheel slippage if a routine chain and sprocket were used. The electrical motor was coupled to the rotor shaft, and an encoder (LPD3806-360BM-G5-24C, China) through a driver board MDC20 (Robot Makers Co., Iran) was coupled at the other end of the shaft to monitor the rotational speed (Fig. 1). A rubber-type gauge wheel was used to prevent potential fluctuation, particularly during field trials. A 750 mm, PVC falling pipe was sealed beneath the discharge gate of the rotor and a trapezium bottom box with a volume of 0.1 m^3 (12 kg) was installed at the top of the fertilizer metering unit to preserve fertilizer granules. A bag of potassium fertilizer was taken to the field to refill the box in due time.

The applicator was calibrated in a way to see how much fertilizer was delivered from the rotor while the rotor speed is changed. The rotor was initiated from 10 to 50 and 50 to 10 rpm in 2 rpm increments and then the discharge rate was measured while the fertilizer box was 100, 75, 50, and 25 % full. Each stage lasted one minute and tests were replicated three times. An interface was developed in the LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench, National Instruments, Austin, TX, USA, ver. 2015) programming environment to initiate the electrical motor in due time and at the same time to collect the signal sent by the feedback encoder to ensure the rotor is turning at a proper rotational speed. A digital scale with 0.01 g accuracy was used to measure the mass of each sample under laboratory conditions. This scale was used throughout the experiments unless stated otherwise.

It has been demonstrated that the application rate could not be changed instantaneously because of the delay in response that accumulates from computer processing speed, controlling software, electrical instruments, and mechanical devices (Maleki *et al.*, 2008b). Here, the time response or transition time is defined as the time difference between when a command is sent to the drive motor to change the speed of the rotor and when that command is thoroughly executed. Another software developed in the LabVIEW programming environment was employed to measure the whole process time. This time delay corresponds to the change in rate transition while the ascending or descending application rate is executed. The time response was cal-

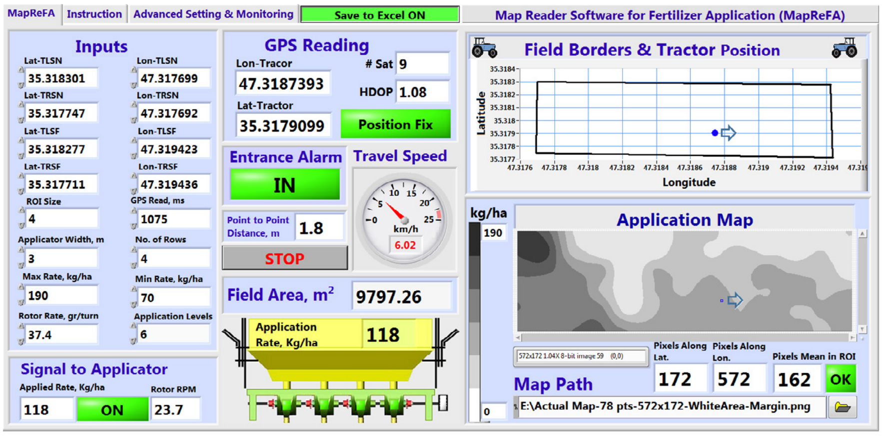

Figure 2. Screenshot of the MapReFA main panel. Lon-TLSN, longitude of tractor left side near. Lat-TLSN, latitude of tractor left side near. Lon-TLS, longitude of tractor left side far. Lat-TLSF, latitude of tractor left side far. Lon-TR, longitude of tractor right side near. Lat-TRSN, latitude of tractor right side near. Lon-TRSF, longitude of tractor right side far. Lat-TRSF, latitude of tractor right side far. ROI, region of intrest. HDOP, horizontal dilution of precision.

culated when the rotor speed was accelerated from 10 to 50 rpm and vice versa. Therefore, the transition distance could be measured using the transition time and the tractor speeds which were 6, 7, and 8 km/h.

An interface designated as ACI (Applicator Controller Interface) was also developed in the LabVIEW environment for communicating with the applicator to change the application rate in due time. Note that this interface was developed as separate software, not as a subprogram since different applicators have various electronics and need different controlling software.

Reposition of the applicator

Application changes as the applicator moves through the field according to the actual map. It was required to have a positioning system to monitor the tractor location in real-time. To locate the position of the applicator, a flexible and cost-effective GPS receiver module (U-blox NEO 6M V2, Germany) was employed. The multi-channel positioning engine available on this type of module could read the coordinates in about 1 s and its acquisition engine makes it capable of massive parallel time/frequency space searches and finding satellites instantly even in the most challenging environments. The U-blox module includes one configurable interface for USB serial communication. This positioning module uses NEMA (National Electrical Manufacturers Association) protocol for interchanging the signals and it had to be employed along with a controlling interface for receiving the satellite signals. A LabVIEW interface which was particularly developed by the National Instrument Company was used to receive the signal of this type of GPS device. This interface is available at the company forums through the net (https://forums.ni.com). This interface is designated here as GPSCR (GPS Coordinate Recorder). It was prepared for continuously transmitting the longitude and latitude values to the main program via the Global Variables Function, which is a data transportation function available in LabVIEW.

Originality

A positioning system, a prescription map, a VR applicator, and a controlling software are essential elements in performing map-based VR fertilization. The latter is restricted by companies and is not available for public use (Robert, 2002; Albornoz *et al.*, 2017). Usually, the map required for a map-based VR fertilization is a digital data file that specifies the input amounts for application at different locations throughout the field. As elucidated before, the main objective of the present study is to show an easy approach to perform VR fertilization using a new user-friendly software. MapReFA (Map Reader Software for Fertilizer Application) was developed entirely in LabVIEW programming environment to directly read a soil map image pixel-by-pixel for providing the required information to tailor the fertilizer rate, regardless of which software (*e.g.* Surfer or ArcGIS) has been used for map generation. The screenshot of the main panel of the MapReFA is illustrated in Fig. 2 and the its diagrams are available in Annex [suppl] to those interested in developing the software in version 15 or higher. The program implemented in front panel offers five main blocks; the *Inputs* block for entering the required information, the *GPS Reading* block for receiving latitude and longitude coordinates of the tractor/applicator (shortly called tractor hereafter), the *Field Borders & Tractor Position* block for displaying the field borders and location of the tractor, the *Application Map*

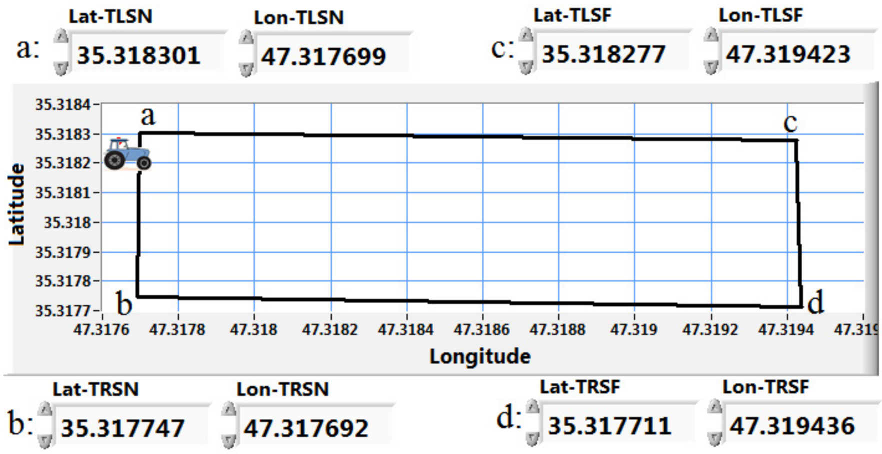

Figure 3. Instruction of entering coordinates of field corners.

block for displaying the soil map, and finally, the *Signal to Applicator* block for sending the signal to the VR fertilizer applicator. In addition, there are some indicators to show field area, tractor speed, and distance of two successive coordinate points while tractor traveling across the field for further considerations. Having recalled the soil map, it appears in the *Application Map* block. The intensity level in the map's image is ranged from lighter to darker depending on how many application rates for fertilization exist inside the map area. Next, the number of application levels should be entered in *Input* blocks according to the number of intensity available on the map. The MapReFA user can optionally consider the number of application rates less or more than those available in the map.

The shape of the field can be a polygon, but it is better to have a quadrilateral field shape. In any case, the coordinates of a quadrangle in which the field is enclosed are entered in *Inputs* block. Upon executing MapReFA, the borders around the field are plotted as thick black lines based on the four corner coordinates. These corners have been entered before. Note that no conversion for field coordinates is required and one can insert directly the coordinates in degrees, minutes and seconds. It is necessary to designate the corner where the tractor is initially entering the field. It is known that some agricultural operations should be carried out in the longitudinal direction and some in the transverse direction of the field according to land conditions such as surface slope and plowing direction. Having identified the direction of movement, the entrance corner for entering the tractor into the field is recognized. The coordinate of the field corners are designated as; TLSN (Tractor Left Side Near), TRSN (Tractor Right Side Near), TLSF (Tractor Left Side Far), and TRSF (Tractor Right Side Far) (Fig. 3). The benchmark for the right and left sides is the hand of the tractor driver. Such a naming creates a unique criterion which let other designations be established accordingly. The tractor position is located by a blue circle in *Field Borders & Tractor Position* block provided that the GPSCR has been executed before. The movement of the blue circle is proportional to the tractor speed and the frequency of the GPSCR data flow. When the tractor starts moving, the blue circle approaches the field. As soon as the blue circle crosses the field border, a LED (light-emitting diode) named Entrance Alarm notifies that. Note that the field border is always the TLSN-TRSN line in entering the field and the TLSF-TRSF line in exiting the field. As the tractor crosses the field border, a blue square whose motion is adjusted to the blue circle begins to move on the surface of the map image. The size of this square (in pixels) is already entered in the *Inputs* block in ROI (Region of Interest)-Size. An ROI equal to one means that only one pixel of the map image is the basis for determining the application rate whereas an ROI equal to two means the average values of 4 pixels inside the ROI is calculated to determine the application rate, and so on. If the ROI is located on a region of the map that has the lowest gray intensity (not white) the minimum fertilization rate is determined for application and vice versa.

The perpendicular distance of the tractor to the TLSN-TRSN line and the TLSF-TRSF line must be continuously calculated to see where the tractor is located. The perpendicular distance of the tractor to these borderlines is calculated because the field may not be a sharp rectangular. The difference of these two values is always a constant value before the tractor enters the field. In fact, this difference is the length of the field along the tractor's traveling direction. Once the tractor enters the field, the difference starts diminishing and eventually closes to zero while the tractor approaches the TLSF-TRSF line. As long as this difference is less than the field length, it means that the tractor is still inside the field. Therefore, this calculation can be utilized as an alarm for the tractor entering and leaving the field. The alarm returns true and false to Entrance LED as a trigger to start and stop fertilizing, respectively.

The orientation of the field may be oblique to latitude and longitude direction. In addition, the field may not necessarily have a right-angled shape. Therefore, a continuous calculation has to be also carried out to see whether

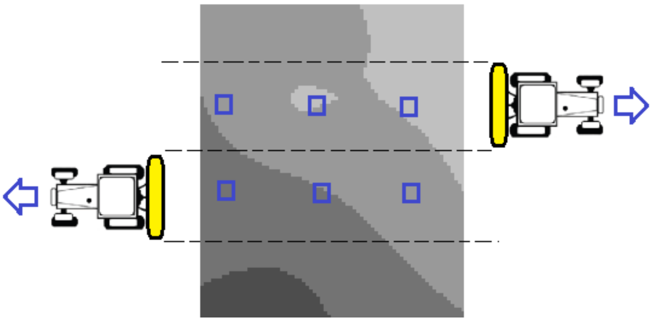

Figure 4. How the variable rate fertilizer applicator utilizes the average of color pixels within the ROI.

the field is getting tapered or expanded while the tractor is moving back-and-forth across the field. The next tractor round can be calculated according to the slope of the TLSF-TRSF and TLSN-TRSN. In addition to controlling the start and stop fertilization, calculating the next tractor round allows MapReFA to determine the number of steps along the travel direction to synchronize the ROI in entering and leaving the field. The number of steps is related to two successive coordinate points read by the GPS module where the application rate is done updating accordingly. As the tractor is being traveled across the field, the oldest coordinate is dropped, and the new one takes part in next calculation. This calculation is crucial because the travel length in the field should be proportional to the number of pixels on the map. Thus, the ROI has a movement equivalent to the tractor movement in entering and leaving the field, no matter whether the new round trips are being shortened or lengthened.

Each pixel inside the ROI has an intensity ranging from 0 to 255. Accordingly, the average of these pixels has a value ranging from 0 to 255 too. Typically, zero is taken for black, and 255 is taken for white. The values between 0 and 255 are associated with different intensities of gray. When the map image is copied directly from the map generator software environment (*i.e.* Surfaer or ArcView), there is a possibility that a small white margin is copied around it. But this will not make trouble for the MapReFA because a sophisticated algorithm excludes the white margin where no information related to the application rate exists. It is even recommended to copy a slight white margin to ensure all the colored surface of the map containing the field information is taken. Thus, the upper limit of 255 is reserved for the map margin which MapReFA excludes from the calculation. Therefore, the application rate is set on 0 kg/ha as default so that no fertilizer could be discharged from the applicator when tractor is out of the field. A mathematical identity determines the fertilizer rate based on the minimum and maximum fertilizer rates calibrated with lower and upper limits available in the map image. Here the minimum and maximum fertilizer rates were 70 and 190 kg/ha, corresponding to the minimum and maximum pixel values of 230 to 38, respectively. If the user selects 6 rates of fertilization, the change in fertilizer rates will be 24 kg/ha for every 38.4 decrease or increase in ROI pixel average. The application rate is instantly changed to zero when the entrance LED alarm becomes off. This is where the tractor passes the field border of the line of TLSF-TRSF. No process is executing at this stage, but the coordinate's data are still received through GPSCR, and it is monitored on the panel.

Note that, if the ROI size is 1 pixel, the map width would be directly divided by the number of ROI round trips to determine how many back and forths have been taking place. Therefore, for the ROI of 1, only the information of a map strip with a 1-pixel width is used as the basis for fertilization. It means the ROI will jump to the new pixel and leave many pixels without using their information. Furthermore, the ROI will jump laterally to the middle of the next pass in each return (Fig. 4), and the large area of the application map would be also left useless. Thus, it is recommended to have an ROI size greater than 1 pixel to let a larger area of the map participate in varying the fertilizing rate. This helps to avoid sudden rate change during fertilization.

MapReFA has to properly function, regardless of how the field coordinates are located. The field shape may be horizontal, vertical, or incline compared to the latitude and longitude directions. Once entering the field corner coordinates, the shape of the field borderlines appears in the *Farm Borders and Tractor Position* block and at the same time the soil map appears in *Application Map* block. Note that the application map is still displayed horizontally (Fig. 5a). By receiving the coordinates of the tractor, the blue circle will start moving towards the field. Upon the blue circle passes over the field border, the ROI appears on the map and starts horizontally moving, proportional to the tractor speed. Therefore, the MapReFA algorithm will adjust itself to the angle of the field borders and read the required information of the relevant points from the application map. This feature lets the MapReFA user prepare the application map image without concerning about the field inclination.

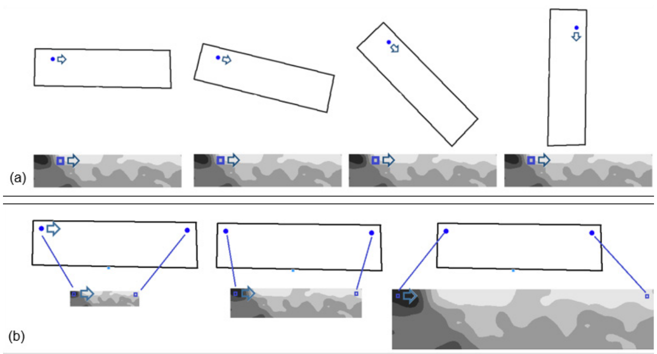

Figure 5. The MapReFa behavior for different farm inclinations (a), and the synchronization of the ROI movement when using different map sizes.

In addition, different situations may occur when copying and pasting the soil map for creating a png image file. The immediate question is that, which size of the map should be copied and pasted to make a png file? Almost all software has screens for image displaying that can be customized to small, large, or full-scaled size. It makes sense that most users would copy 100% of the bandwidth, but what if when it does not happen. To present an appropriate answer, suppose three MapReFA users try to copy and paste a given map in three sizes; small, medium (100%), and large (Fig. 5b). It will be stated hereafter to show how the MapReFA algorithm adopts itself when uses these three map sizes. The distance between the coordinates points read through GPSCR determines how many times the application rate is changed (Fig. 5b). On the other hand, the number of pixels in latitude and longitude direction is calculated and divided by the ROI dimensions to find the number of intervals within the soil map that ROI requires to jump. This calculation lets ROI adjust itself regardless of the map size. Thus, if the map size is smaller than the full-scale size, the intervals would become smaller and let ROI approaches the other side of the map slower than the blue circle within the field boundaries. On the other hand, for a large map, the ROI moves faster and reaches the end of the map at the same time the blue circle approaches the other side of the field.

Application maps

Among the interpolation methods, the Kriging was used for map generation since it is frequently used for mapping soil properties in the analysis and interpretation of spatial variation of soil (Stein *et al*., 1988; Boucneau *et al*., 1998). Furthermore, the Kriging interpolation method is recommended when the number of samples per area is large (Warrick, 1998). Surfer (Golden Software, vers. 14) was used to generate a prescription map based on the application rates instead of nutrient levels. Therefore, the darker and the lighter map zones were attributed to the higher and lower application rates, respectively. According to the soil samples analysis for the examined field and based on the recommendations, 70 and 190 kg/ha were used as lowest and highest rates, respectively. The prescription map designated as actual map was converted into grayscale with 6 intensity levels corresponding to 70, 94, 118, 142, 166, and 190 kg/ha. The map image was copied directly from the Surfer screen and pasted into Paint which is an accessory software available in all versions of Windows (Fig. 6a). Any other basic image-editing program can be also used providing that the outcome file is in a compatible form of BMP, TIFF, JPEG, JPEG2000, PNG, and AIPD. The coordinates of the four corners of the field have to be also noted down for inserting into the MapReFA software.

A virtual map was also generated to evaluate the accuracy of the applicator in changing the application rate while traveling across the field (Fig. 6b). This virtual map was utilized to confirm the methodology described in the present study. The function of MapReFA could be checked using this virtual map to ensure whether the application rate is changed based on the corresponding pixels read from the map image. The virtual map could be also utilized to estimate the transition distance, where an appli-

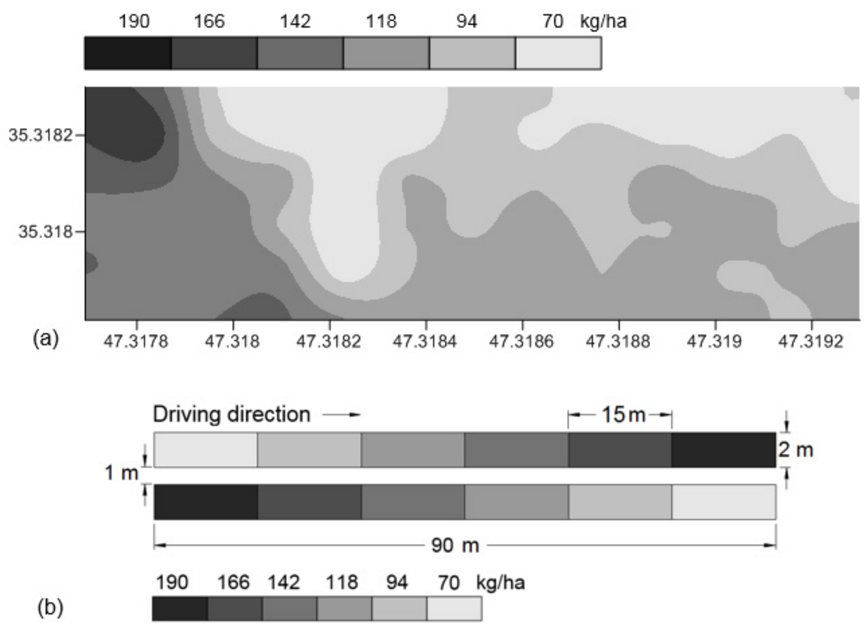

Figure 6. The actual map for potassium chloride fertilization (a) and a virtual map developed to determine the applicator performance while fertilization rate changes as ascending and descending (b).

cation rate switched to another one. For this purpose, an area of 90×5 m was allocated for the field trial, similar to the virtual map size. The coordinates of the field corners were recorded and entered later into the MapReFA during the field trial. The area was divided into two strips of 90×2 m where each strip was also divided into six 15×2 m plots, adapting the procedure used by Dusadeerungsikul *et al*. (2019). The strips were laterally spaced 1 m for tractor wheels. Six application rates of 70, 94, 118, 142, 166, and 190 kg/ha were assigned over the 1st to 2nd strips, similar to the application rates assigned in the actual map. The application rates within each strip were arranged as ascending and descending scheme.

Validation of the actual map

Validation is the process of verifying whether the mathematical results calculating relationships between variables are acceptable as descriptions of the data. In this part of the experiments, the validation of the actual map was carried out using two approaches. The first was cross-validation method which is the most commonly used method of assessing the accuracy of interpolation methods (*e.g*. Kriging) and uses all sampled points to develop and compare interpolation models (Betzek *et al*., 2019). Out of the other methods, the leave-one-out technique is the most common form of cross-evaluation, excluding each individual soil sample from the prediction and iteratively repeating the procedure for the number of input soil samples (Thorp *et al*., 2007). Note that the main goal of the present study was focused on describing a new methodology for VR fertilization rather than soil map validation. Accordingly, another approach was carried out using the grid values of the application rate estimated by the Kriging interpolation model for soil sample locations. The locations of grid values on the actual map were exported from the Surfer and put against the original 78 data points. Then, a correlation approach concerned with the association of these two application rates was established to see how accurate the interpolation method is in the actual map. The goodness of fit of gridded data was assessed through statistical measures of prediction performance which were correlation coefficient (r), root mean square error (RMSE), and mean absolute error (MAE).

Evaluation of VR fertilization using the virtual map

Apart from the calibration procedure for measuring the discharge rate according to the rotor speed, a test was also carried out to demonstrate whether applicator functions properly. The main aim was to see while the ROI is moving over the map image, the corresponding rate is properly adjusted by both MapReFa and applicator or not. To do that, a deposition test was required since accurate metering is independent of the accurate distribution of material delivered from an applicator. A deposition test for the VR applicator is defined as the collection of fertilizer particles on a pan with a specific pan layout and then converting the result into kg/ha. There is a standard deposition test including recommended size for collection pans mostly utilized for evaluating VR spinner-type broadcast spreader (S341.2, ASAE Standards, 2000). Here, the pan should be placed aligned in the travel direction for collecting granules. The preliminary test revealed that if the standard pan layout is utilized the beginning of the area in which the delay time has to be determined will be missed. Some limitations of the standard pans were also reported by Fulton *et al*. (2005) who modified the standard pans for their study. Consequently, some modifications were made to the size of the pan to ensure that the total material distribution length was captured. Dimensions of the collection pan were modified to 40 cm wide, 300 cm long, and 10 cm sidewalls. Similar pans were also prepared with 15 cardboard dividers with 20 cm spans. The collection pans without dividers were placed at the middle of each plot, particularly for computing the target application rate assigned for each plot. In addition, pans with dividers were placed on the ground at the beginning of the plots of the virtual map where the rate transition started changing. The test was conducted at three travel speeds of 6, 7, and 8 km/h over both stripes of ascending and descending schemes. Initially, the GPSCR and ACI interfaces were launched. The GPS tracker antenna was installed close to the fertilizer discharge tube. Then the tractor started moving toward the field strips, and the applicator started applying fertilizers according to the pattern as illustrated in Fig. 6b. Note that the application rate was automatically changed at the end of each 15 m plot by the MapReFA. Upon completion of each run, the tractor was moved to the beginning of the second strip, and then the granules on the collection pan were collected and kept in individual plastic bags, sealed, and labeled according to the location. The test was carried out in six replications over each strip. Then the amount of fertilizer was separately collected in the pans and compartments, converted into kg/ha for analysis. The number of the divider was counted when the application rate was exceeded the target rate assigned for the plot. It could determine the delay distance with 20 cm intervals.

Evaluation of VR fertilization using the actual map

Fifty grid points with a grid size of 20 by 20 m were assigned in the field and marked with plastic piles. The piles were geo-referenced to have an identical location for comparing the final results. A collection pan of 0.65

cm wide, 100 cm long, and 10 cm sidewalls was placed close to these piles to collect the amount of fertilizer spread down from the applicator. The field trials should be carried out in back-and-forth tractor runs as it is a usual approach in field operations. Test runs were carried out at three travel speeds of 6, 7, and 8 km/h and replicated three times to ensure no error masks the results. Then the actual map was recalled into the MapReFA and the coordinates of the field corners and other required inputs were entered into the MapReFA panel (Fig. 2). Again, GPSCR and ACI interfaces were launched. Upon completion of each test run, the fertilizers fallen on the collection pan were collected and placed in individual plastic bags, sealed, and labeled according to location until the time of weighing. Finally, fertilizers in the individual collection pans were compared with the corresponding ones on the actual map.

Comparison of the actual map and applied map

The MapReFA can collect all the exchanged data in an Excel file for further analysis. It mainly includes longitude and latitude coordinates as well as the rate of fertilization for sequential points on the field whose distances are proportional to the frequency of the coordinates transmitted via GPSCR. The output files could be utilized for developing the applied maps to also visually compare them with the actual map. The resulting data points are various when different travel speeds are utilized during the field trails. Descriptive statistics could be easily computed over the data set recorded during the field trials. However, identical data size was required to have a proper comparison between the actual map and applied maps which were generated using the data collected at travel speeds of 6, 7, and 8 km/h. To achieve that, the 78 data point's coordinates of the actual map were posted on the applied maps to note down the corresponding points available on the actual map. Then a correlation associated with the application rates in data sets was computed.

Results and discussion

Calibration of the applicator metering device

A strong positive linear correlation was found between the rotational speed of the feeding rotor and application rate. When the fertilizer box was 100, 75, 50, and 25 % full, the r values (and RMSEs) were 0.99 (0.75 g), 0.99 (0.47 g), 0.99 (0.29 g), and 0.99 (0.78 g), respectively. The overall discharge rate of 37.4 g/rev was calculated over these box condition that was employed later in MapReFA. Therefore, it was just required to adjust the rotor speed to acquire a target rate. That when the rotor speed reaches the commanded speed depends on the delay in software and hardware specification, which will be discussed later.

Evaluation of VR applicator using the virtual map

The fertilizer granules collected from the collection pan at the middle of each experimental plot were compared with the target application rate computed by the MapReFA. The results showed that there is a perfect match between the amount of fertilizer discharged from the applicator and the corresponding application rates read from the virtual maps using the conversion of the intensity of the pixels in the ROI into the application rates. The correlation coefficients of 0.99, with RMSE of 0.46 kg/ha, and 0.99 with RMSE of 0.66 kg/ha were found over ascending and descending schemes, respectively.

Validation of the actual map

The results showed that the prediction accuracy of the Kriging model for the examined field had the validity measures of r= 0.83, RMSE=20.78 kg/ha, and MAE=13.73 kg/ha when a cross-validation method was employed. The values of the validity measures found between the original data set of 78 grid-points and the application rates estimated by the Kriging model for those corresponding points were r=0.97, RMSE=4.87 kg/ha, and MAE=4.19 kg/ha. It can be concluded that the Kriging interpolation method was a good estimator for the application rates in the examined field. Also, this validation procedure could justify the reliability of the soil tests analysis since there is always an inherent error associated with soil sampling, soil analysis, and interpretation (Gallagher & Herlihy, 1963; Faber *et al*., 2007).

Time response and transition distance

It was required to evaluate the efficiency of the applicator to properly evaluate the method described in this study. As mentioned earlier, from the moment that a string message is sent to change the application rate until the moment the fertilizer is delivered from the applicator is considered as the response time (Maleki *et al*., 2008b). Calculating this latency was important because it is used to calculate the transition distance. The delay times were 108 and 77 ms/rev when the application rate increased and decreased over an interval of 24 kg/ha, respectively. The transition distance could then be calculated based on the travel speed. Consequently, transition distance is the distance traveled by the applicator to complete the change action from one application rate to another.

Referring to the time delay measured by the LabVIEW interface, the delay times were 0.45, 0.53, and

0.60 s for a 24 kg/ha increase in application rate at travel speeds of 6, 7, and 8 km/h, respectively. In the descending scheme, the delay times were 0.32, 0.38, and 0.43 s for a 24 kg/ha decrease in application rate at travel speeds of 6, 7, and 8 km/h, respectively. Consequently, the transition distances were 0.75, 1.02, and 1.33 m for a 24 kg/ha increase in application rate over travel speeds of 6, 7, and 8 km/h, respectively. For the descending scheme, the transition distances were 0.54, 0.73, and 0.96 m for a 24 kg/ha decrease in application rate over travel speeds of 6, 7, and 8 km/h, respectively. As can be seen, the transition distances in the ascending scheme were longer compared to those in descending scheme. It may associate with the torque required to change the speed, which is larger during speeding up. It should not be misinterpreted that it is incorrect fertilization within these transition areas. Since the application rate is changed, for example, from 70 and 94 kg/ha in a 1.33 m transition distance at 8 km/h speed, there is only a 24 kg/ha difference that starts being increased from 70 kg/ha until it approaches 94 kg/ha. Therefore, this difference would be negligible.

According to the virtual map, where the ascending scheme was utilized, the transition distances were 1.04, 1.36, and 1.64 m, for a 24 kg/ha increase in application rate at travel speeds of 6, 7, and 8 km/h, respectively. The transition distance was 0.92, 1.08, and 1.32 m, for a 24 kg/ha decrease in application rate at travel speeds of 6, 7, and 8 km/h, respectively. This result shows longer transition distances compared to those computed using the LabVIEW interface. The reason might be due to the 75 cm elevation of the metering device to the ground, which caused longer transition distances due to the delay in free fall of the granules. It is concluded that the delay in rate response in the applicator developed in the present study also exists similar to other VR applicators reported in the literature (Fulton *et al*., 2005).

Although it has been reported that in a very small area, there is always the potential for a dramatic change in soil nutrients levels (Raun *et al*., 1998), it should be noted that in a map-based approach, such a drastic change rarely occurs. This is because, in map-generating process due to the use of interpolation procedure between sampled points, the levels of nutrients moderate neighbor points almost in all map gridding methods such as IDW (Inverse Distance Weighing), Kriging, nearest neighbor, etc. Therefore, the application rate changes when it ascends or descends, and the possibility of placing two zones on the map with a notable difference is impossible or with some reservations rarely happens. Of course, this is observed in the sensor-based approach, where the sensor detects the level of the soil nutrients with sometimes a notable difference and accordingly the application rate is calculated regardless of the requirement of the adjacent zones. That is why an attempt was made in the sensor-based approach to prevent a sharp fluctuation of the fertilization rate by calculating a certain number of consecutive scanned points for adapting fertilization (Maleki *et al*., 2007). In the present study, a tool was provided in case such a fluctuating pattern occurs. As elucidated before, the aptness of the ROI size depends on how the intensity values are distributed over the map area. The ROI size can be selected smaller if the application zones are conveniently separated from each other. On the other hand, the dimension of the ROI can be selected larger if the applicator's reaction is not fast enough in rate changing.

Evaluation of VR fertilization using the actual map

The results from the deposition procedure using 50 pans were used to demonstrate the overall performance of the applicator as well as the MapReFA accuracy in fertilization. According to the coordinates of the pans, corresponding 50 points were picked up from the actual

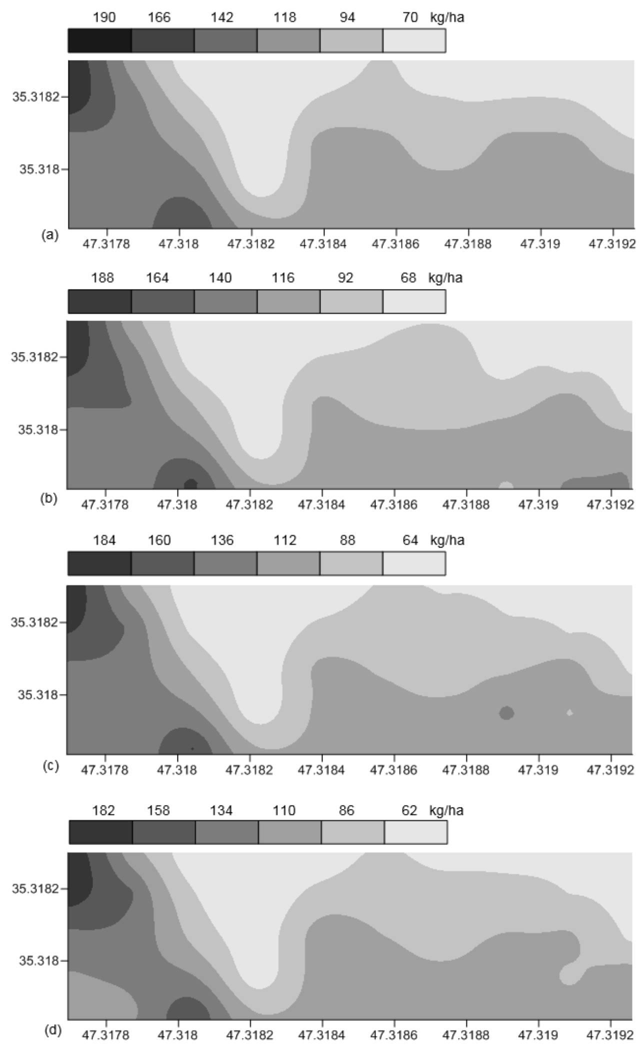

Figure 7. The maps using 50 posted points picked up from the actual map (a) compared to corresponding pans collected at travel speeds of 6 km/h (b), 7 km/h (c), and 8 km/h (d).

map for generating a map (Fig. 7a). Fertilizers collected from the deposition pans in three replications at three travel speeds of 6, 7, and 8 km/h are also illustrated in Fig. 7b,c,d. Similar zones are observed in the majority of map zones meaning that the applicator applied the right amount of fertilizers according to the actual map on deposition test points. However, the left-down corner of the map generated from the data from deposition pans at the travel speed of 8 km/h had a different pattern in fertilizer distribution. Having rechecked the results revealed that the application rates computed from the pans situated at that corner were 132.15, 134.77, and 128.62 kg/ha over travel speeds of 6, 7, and 8 km/h, respectively. The latest belongs to the field trials at 8 km/h and apparently could not have been strong enough to lift the map intensity similar to others.

The correlation coefficients associated with the application rates computed from deposition pans of field trials conducted at travel speeds of 6, 7, and 8 km/h were compared with the application rates recommended by the actual map (see Fig. 8). The little deviation from the perfection is attributed to the time delay as well as the fertilizer granules free-falling from the discharge pipe. Therefore, it should not interfere with the overall performance of the methodology described in this study. As was expected higher slope in the calibration equation was found for lower rotational speed. However, higher correlation coefficients in application rates were found for higher travel speeds. Having looked at the rotor speeds for lower application rates such as 70 kg/ha revealed that the rotor speed of the studded roller at a travel speed of 6 and 8 km/h was 14 and 18.7 rpm, respectively. It means the uniformity in application rate was higher at a travel speed of 8 km/h. Because, the best rotational speed for such a metering device is 15 to 40 rpm (Bernacki *et al.*, 1972). Therefore, to have a better conclusion of this part of the study, the average application rates overall travel speeds were compared to that recommended by the actual map. The results showed an r of 0.96 with an RMSE of 1.88 kg/ha.

The MapReFA makes a possibility to post-survey the field trials after performing the VR approach. It answers the question: how much the field performance is similar to the pattern in the actual map? Some error sources such as GPS horizontal accuracy, GPS sampling frequency, and applicator delay time were identified in several studies (Chan *et al.*, 2004; Fulton *et al.*, 2005). However, the results were limited to reporting the values of the error rather than overall outcome maps including all error sources (Chan *et al.*, 2004; Fulton *et al.*, 2005). As it was mentioned before, the application of fertilizer based on the actual map is always accompanied by a delay in performance. Hence, it affects the borders of the map zones where they do not receive the right amount of fertilizer based on the recommendation map. When the application rate is changed, there is a transition distance where one application rate is switched to another. Therefore, when the applicator is adjusted according to the new coming signal, the application rate is being increased or decreased until the transition distance is terminated. Consequently, the resulting map (let's call it applied map) would not have a similar pattern compared with the actual map.

Fig. 9 depicts the applied maps when the applicator traveled at 6, 7, and 8 km/h. All applied maps were identical to the actual map. Note that the applicator receives the signal to change the application rate right on the border of the actual map. Thus, the applicator does not react instantaneously, and the rate does not change immediately as well. Therefore, the map pattern dissolves into the next zone. This disorder is expected to be more when the applicator travels faster. However, these three applied maps are so identical because the most difference in transition distance is 0.6 m which is attributed to 1.04 and 1.64 m transition distances at travel speeds of 6 and 8 km/h, respectively. The legends for these three applied maps and the actual map are the same; therefore, the appearance of a point illustrates deviation from the actual application. Borders of the zones in all applied maps show noticeable deviation from the actual map for VR application

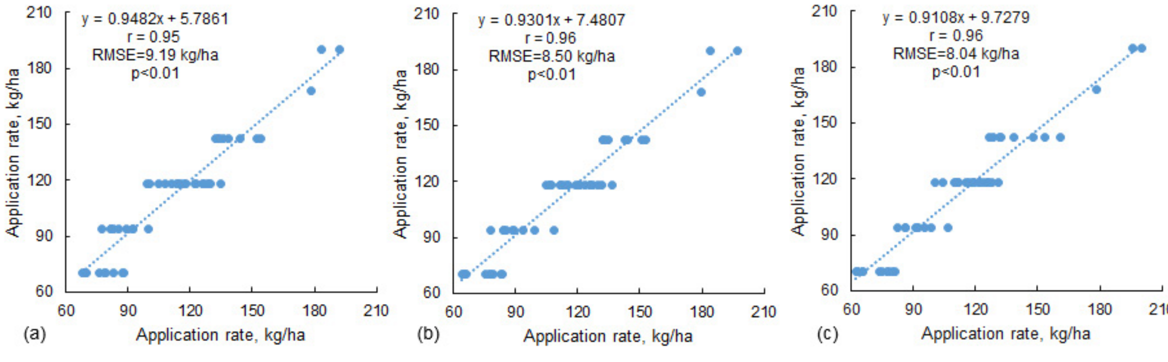

Figure 8. Correlation coefficient comparing the direct collection of the fertilizer in 50 pans to the application values of corresponding locations on the maps generated using field trials at travel speeds of 6 km/h (a), 7 km/h (b), and 8 km/h (c).

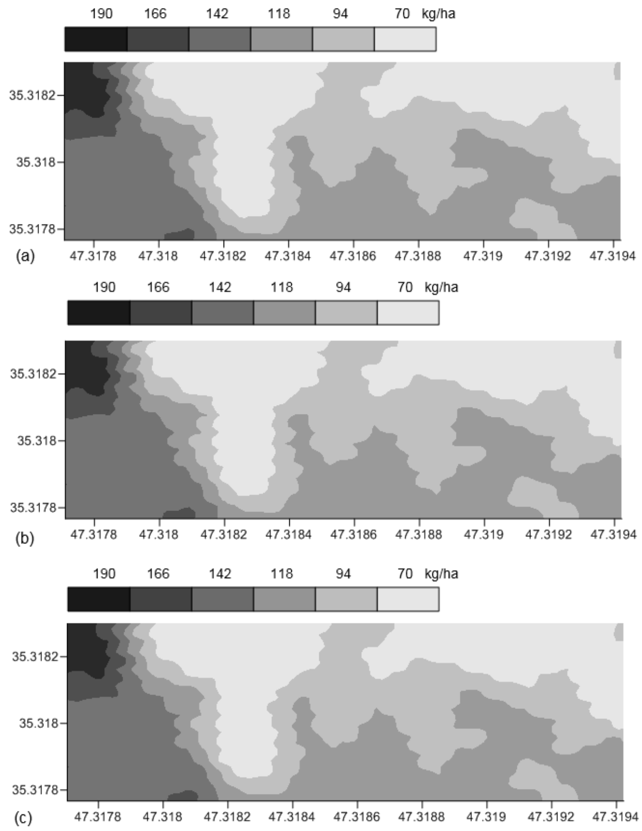

Figure 9. Applied maps resulting from travel speed of 6 km/h (a), 7 km/h (b), and 8 km/h (c).

of potassium chloride. This is due to the fact that when the travel speed is faster the data point shifted more to the next zones. Therefore, it makes more data points for interpolation during computational processing by the software (*i.e.* Surfer). Fig. 10 shows it in more detail and reveals how color intensity is dissolved into the next zones according to the direction of the travel and the delay of the applicator in changing the application rate. Deviations from the actual application rate may be attributed to another factor. The control system was incapable of performing instantaneous rate changes at zone boundaries, thereby creating a situation in which the prescribed rate at zone boundaries was not achieved. In other words, the MapReFA software used in this study starts changing a new rate when received a new signal exactly on the zone boundaries. Note that in controlling a VR sprayer, activating the nozzle before reaching the desired point can partially compensate for the rate change delay. Because start and stop location of spraying on the desired point crucially matters. However, this is not the case in VR fertilization because the look-ahead feature means changing the rate in the zone that we have already succeeded in its adjustment for proper application. As has been stated before, the application rate was mainly changed from two adjacent rates (*e.g.* from 70 to 94 kg/ha) in a maximum transition distance of 1.64 m at travel speed of 8 km/h, which is negligible.

Switching from white to dark gray zone happens only when the applicator enters the field (not exiting the field) where the closest zone is dark gray. Such a situation was considered during the MapReFA development. It is a simple argument in programming. When the applicator exits the field the intensity of the last zone is kept in memory. According to that and the time delay calculated for the applicator, the applicator starts fertilizing before entering the field.

A comparison was made between the fertilizer recommendation using the original soil samples and the applied maps generated using field trials at travel speeds of 6, 7, and 8 km/h (Fig. 11). The application rates recommended by the original soil samples were significantly ($p<0.01$) associated with those in applied maps. The travel speed has no significant effect on the application rates for the examined speeds. A comparison was also made between the actual map and three applied maps that were generated using the data collected at travel speeds of 6, 7, and 8 km/h (Fig. 12). As can be observed, most data points were coincident while the applied maps were compared with the actual map. The difference in the correlation coefficients computed and illustrated in Fig. 9 compared to Fig. 12 is the influence of the classified application rates from 70 to 190 kg in the actual map. Compared with the application rates computed from the actual map, the variations in application rates in applied maps were slightly decreased when travel speed increased. Fulton *et al.* (2003), who reported an extensive study on VR applicators, found a very poor correlation for the application where an actual map and applied map were compared ($r<0.67$). The travel speed caused slightly some deviations in application rates which might be attributed to the delay time and transition distances in field trials. The CV of the application rates calculated for applied maps of 6, 7, and 8 km/h were 28.5%, 28.6%, and 28.7%, respectively. This variation was slightly higher than that computed for the original samples set used to generate the actual map (*i.e.* 24.89 for the original data set).

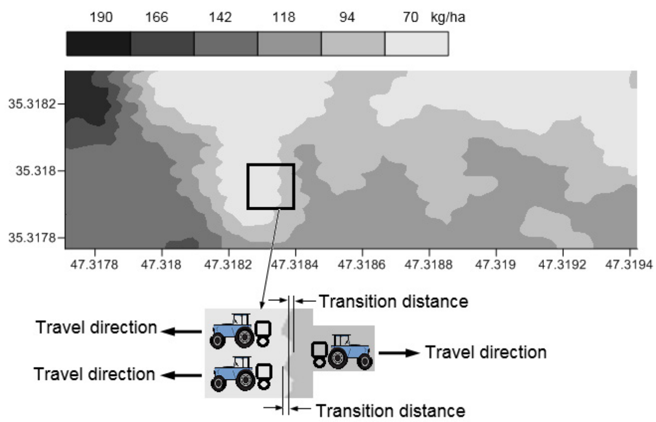

Figure 10. Showing how the delay time causes transition distance during fertilizer application.

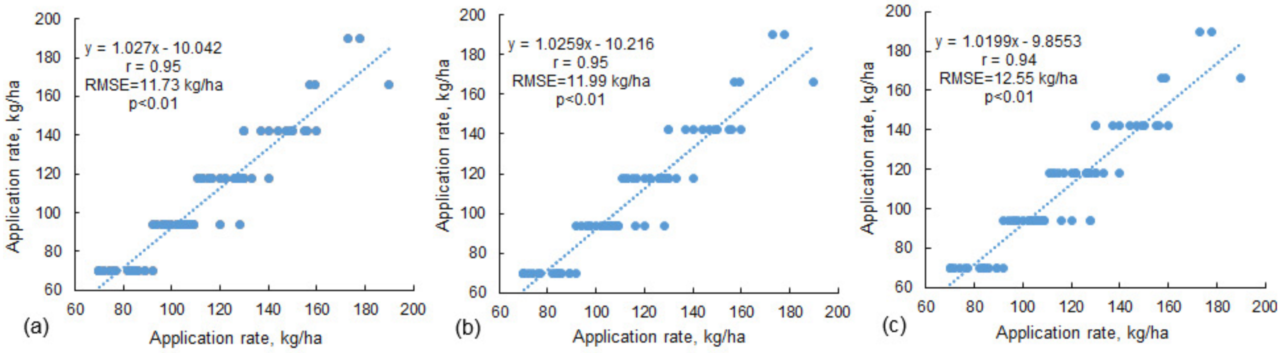

Figure 11. Correlation coefficients comparing the fertilizer recommendation using the original soil samples to the applied maps generated using field trials at travel speeds of 6 km/h (a), 7 km/h (b), and 8 km/h (c).

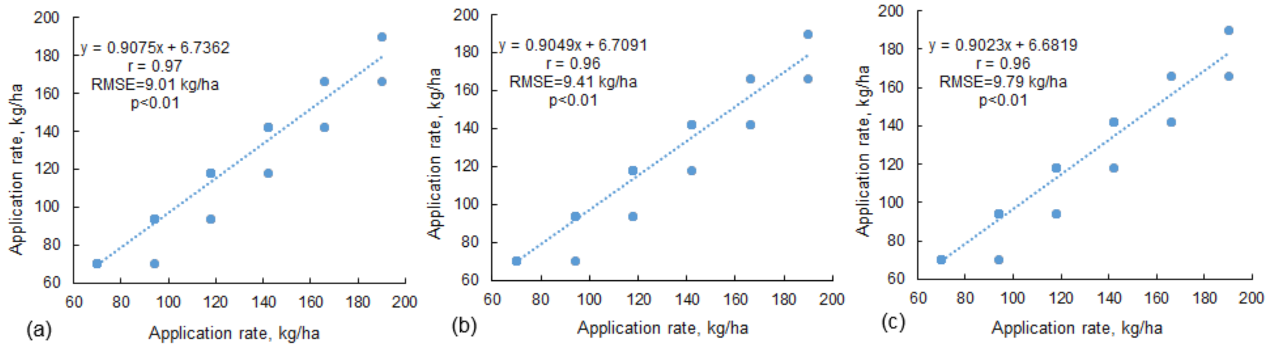

Figure 12. Correlation coefficients comparing the fertilizer recommendation using the actual map to the applied maps generated using field trials at travel speeds of 6 km/h (a), 7 km/h (b), and 8 km/h (c).

Comparison of variable rate and uniform rate fertilization

A uniform rate of 115 kg/ha potassium chloride was recommended entire the field when a routine soil sampling and fertilizer advice was utilized. According to the output files, 1722, 1467, and 1287 sample points were recorded during the field trials at travel speeds of 6, 7, and 8 km/h, respectively. This means the application rates were updated while the 3-m-width-applicator passing over the areas of 5.34, 6.27, and 7.17 m^2 at travel speeds of 6, 7, and 8 km/h, respectively. The average of application rates computed for the actual map and applied maps of 6, 7, and 8 km/h were 109.38, 106.06, 106.05, and 106.17 kg/ha, respectively. As can be seen, the average of the fertilization rates calculated using the actual map was close to those calculated for applied maps at three examined travel speeds. According to the calculation made, 54.7 % of the field would receive under-application if a VR application were carried out over the entire field based on the actual map. Only 1.3% of the area received the right amount of fertilizer when the actual map was compared with the uniform rate of 115 kg/ha. Note that the actual map cannot be utilized without traveling across a field. Therefore, the maps which should be taken into consideration are the applied maps. According to the applied maps about 54, 55, and 55 % of the field received under application with the CVs of 0.33, 0.34, and 0.34 % for examined tractor traveling speeds of 6, 7, and 8 km/h, respectively.

Conclusion

In this paper, it has been shown the ability of a new approach in VR field study. The difference of the method compared with previous studies was the use of the map image instead of the arrays hidden behind the map. Copying the map image and saving it as an image help the users to get rid of potential complications available in commercial equipment. No matter which software is employed for map generation is primary advantage of the software compared to the previous approaches used in VR implementation. Adapting the amount of fertilizer based on an actual map was successfully examined. The fertilizer rate change was based on the average of the pixels in the application map while the applicator passed across the field. This experiment and the results outcome showed that the control system based on direct read of the map image operates as expected. The approach can be employed by VR practitioners, who are unable to use the commercial software, which is restricted by companies, and also by growers who are concerned about data ownership. Furthermore, its ability to collect a data set after performing VR application lets us seek how the VR equipment can apply fertilizers compared to those recommended by the initial map.

Authors' contributions

Conceptualization: Maleki M.R.
Data curation: Maleki M.R., Mahmoodpour M.
Formal analysis: Maleki M.R.
Funding acquisition: Not applicable
Investigation: Mahmoodpour M.
Methodology: Maleki M.R.
Project administration: Maleki M.R.
Resources: Mahmoodpour M.
Software: Maleki M.R.
Supervision: Maleki M.R., Mollazade K.
Validation: Maleki M.R.
Visualization: Maleki M.R., Mollazade K.
Writing – original draft: Maleki M.R.
Writing – review & editing: Maleki M.R., Mollazade K.

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