Digital map-based site-specific granular fertilizer application system

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Variable rate application is the process of applying different rates of crop inputs according to the variability within an agricultural field. Variable rate fertilizer application is a technology that regulates the fertilizer application rate based on site-specific needs within a field. A GPS-based variable rate fertilizer application (VRFA) system was developed, which consisted of a differential global positioning system (DGPS), micro-processor, micro-controller, DC motor actuator, power supply, threaded screw arrangement and fluted roller metering mechanism. The digital soil nutrient availability and application maps for targeted yield were also developed. DGPS was used for real-time identification of grids. Based on the micro-controller algorithm, application rates were varied by changing the feed roller exposure length. The observed fertilizer application rate was 5 and 300 kg/ha for exposure length of 0 and 44 mm respectively. The results indicate that the fertilizer application rate changes according to the prescribed application rate at the identified grid with coefficient of variation (CV) of 11.7–15%. The values of root mean square error and relative difference of the system for different levels of application rates were 2.62 and 3.71 respectively. It can be concluded that the developed VRFA system closely meets the target fertilizer application rate at the selected grid point.

Keywords: Differential global positioning system, fertilizer applicator, interpolation, micro-controller, soil nutrient map.

MACRO-nutrients availability in the soil is not same throughout the field and varies from location to location. Recent research indicates that there is high variability of soil nutrients even in a small area of field[1]. The traditional method of application of fertilizer is to apply fertilizers uniformly throughout the field, according to average demand of the soil or crop. The constant rate of fertilizer application is inefficient and leads to over-fertilizing certain regions and under-fertilizing others, not meeting the actual nutrient demand. Increase in rate of fertilizer application in general increases crop yield up to an optimum level, but extra fertilizer is under-utilized or mobilized[2]. The application of fertilizers can be varied based on analysis of information collected from the field. Variable rate technology (VRT) is a method for improving input use efficiency by applying near-optimum rates based on soil conditions and crop requirements[3]. More the variability in yield within a field, it is more likely that site-specific input management will be needed. The use of site-specific VRT can help to improve input use efficiency as well as decrease the negative effect on environment due to over application of inputs[4]. The reduction of agro-chemicals input in sustainable crop production has been a major issue in modern agriculture. VRT has not been successfully introduced till date due to additional costs involved in replacing existing farm machinery and non-availability of low-cost VRT. Furthermore, excessive fertilizer application causes land degradation and pollution through leaching and volatilization[5,6]. The variable rate application of fertilizers is impractical and economically challenging to meet specific plant needs.

In precision agriculture (PA), three basic methods of implementing site-specific variable rate fertilizer application (VRFA) within a field include map-based systems along with GIS and global positioning system (GPS)[7,8], real-time on-the-go sensor-based systems[9,10], and a combination of sensor-based systems with map overlay[11]. All these methods use maximum yield–response decision rules in the form of implicit or explicit yield functions to determine input application rates. VRT used in conjunction with GPS is a common practice implemented by those using PA[12]. For development of VRFA, sensing of nutrients is the first step. This can be achieved by remote sensing, spectroscopy and real-time crop and soil sensing. NIR spectroscopy would be suitable to determine soil organic matter, soil organic carbon and soil moisture. Spectral reflectance-based on-the-go soil and crop nutrient sensing method is in the development stage, and hence is untested and expensive[13]. Limited research has been done with regard to on-the-go sensing of phosphorus (P) and potassium (K) nutrients in the soil. Maleki et al.[14] developed the spectral reflectance-based dataset and suitable calibration models using different data preprocessing methods for measurement of P. The models predicted available P in the soil with a coefficient of determination (R^2) of 0.73.

Several researchers conducted studies on the VRFA system. Kim et al.[6] developed a variable-rate granule applicator with a 10 m long boom. This system consisted of soil property map of 10×10 m grid size. The pneumatic applicator was equipped with simple blow heads and a metering system. The reported CV values regardless of the working speed ranged from 2.9% to 15.3% and 11.2% to 13.1% in the longitudinal and transverse directions respectively. Fulton et al.[12] conducted uniform-rate tests to assess the accuracy of variable-rate application of four granular applicators. They observed the potential application errors with VRT and also the need for proper calibration to maintain acceptable performance. Tola et al.[2]

modified a mechanical fertilizer application system for automatic setting of target fertilizer application rate. The system could maintain uniform application rate by performing real-time adjustments with on-the-go monitoring application. Chattha *et al.*[11] modified variable rate (VR) fertilizer spreader to control each pair of nozzles for spot-application of fertilizer in blueberry field. The system consisted of cameras, solenoid valves, pneumatic cylinders, VR controller and custom software. The modified system was capable of using prescription maps and automated sensing and control system simultaneously to detect foliage/bare spots in real time to avoid fertilization in bare spots/weed patches.

A geo-referenced application map along with GPS permits real-time operation of the VR system. VRFA with real-time location identification is the key for fertilizer management. Variable application rate with precise metering of granular fertilizer is the most important criterion for a fertilizer applicator[15]. In India, fixed-rate granular fertilizer applicators are most commonly used by the farmers. The conventional sowing and planting machinery cannot be used as such to address the variability in precision agriculture. Therefore, an effort was made to develop a digital map-based VRFA system which would be able to identify the soil zone by GPS and vary the application rate within a field according to the nutrient demand of the soil at a grid point.

A digital map-based VRFA system was developed to apply targeted amount of fertilizer at a specified field zone. Figure 1 shows the conceptual diagram of the developed digital map-based VRFA system. The tractor-mounted VRFA system consisted of a differential global positioning system (DGPS), micro-processor, micro-controller, DC motor, 12 V battery, threaded screw arrangement and fluted roller granular fertilizer applicator. The system was based on prescription map of soil nitrogen (N), which was a digital data file containing specific information of latitude and longitude along with input rates to be applied.
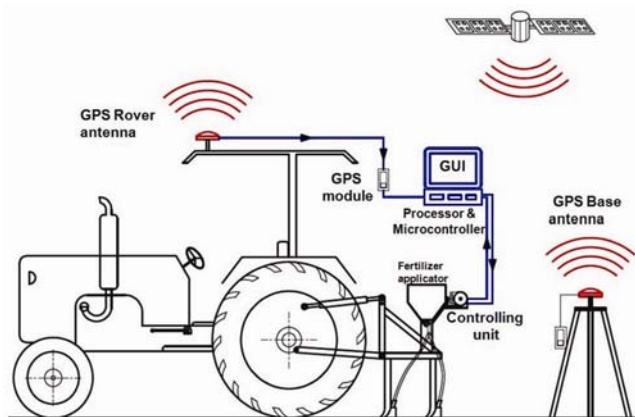

Figure 1. Conceptual diagram of digital map-based variable rate fertilizer application (VRFA) system.

Soil nutrient variability assessment and its mapping is the first step for development of the VRFA system. A systematic grid sampling approach was used in which the field was divided into equal size of 30×30 m. Totally 10 soil samples were collected in 0.85 ha area at a depth of 150 mm geo-referenced using GPS (Garmin Oragon 450 t) device and were analysed in the laboratory for soil N status. Nutrient levels at different intermediate points in field were calculated using IDW interpolation technique[16]. IDW interpolation program was developed in MATLAB® for determination of N level at different intermediate points. Digital soil nutrient availability map with corresponding coordinates of the selected field was generated using developed code in MATLAB® (Figure 2). After development of N availability map, fishnet of size $(8 \times 8$ m) was created on the map using Arc-GIS software. The coordinates of each centroid of the fishnet along with nitrogen status were extracted from the digital map. The application rate for each coordinate point was calculated based on the target nutrient requirement. N availability and soil test crop response (STCR)-based target yield-based application map with corresponding latitude and longitude of the selected field was generated with the help of MATLAB®-based program through micro-processor. The digital N application map was developed (Figure 3) and uploaded in the interfacing program.

The DGPS unit costing around Rs 300,000 was used for locating coordinates of grid points in the field. The unit consisted of two hand-held GPS receivers. One was fixed at a location near the test field as base receiver and the other one as rover receiver mounted on tractor cabin and moved into the field to transmit coordinates of system location. A micro-controller (AtMega-328P) was used and interfaced with the graphic user interface (GUI) software through COM port for serial communication, signal processing and controlling the operation of the actuator. Four relay switches (SPDT, 12 VDC, 12A) were connected to the micro-controller to control the actuation time and direction of DC motor. Two of them were assigned for clockwise and the other two for counter-clockwise rotation of the motor. The clockwise rotation resulted in an increase in exposure length of the feed roller and vice versa. The signal wires of two sets were connected to digital pins (D12, D13) of the micro-controller and output wires were connected to the DC motor. A position sensor was also installed to communicate information about current exposure length (CEL) of the fluted roller. The required exposure length (REL) was calculated by the GUI according to the prescription map.

An existing commercially available nine-row fertilizer applicator was modified for variable rate application with the help of mechactronic system. The overall length, width and height of the fertilizer applicator unit were 2.15, 0.84 and 1.34 m respectively. The ground wheel-powered fertilizer applicator had fluted rollers for metering
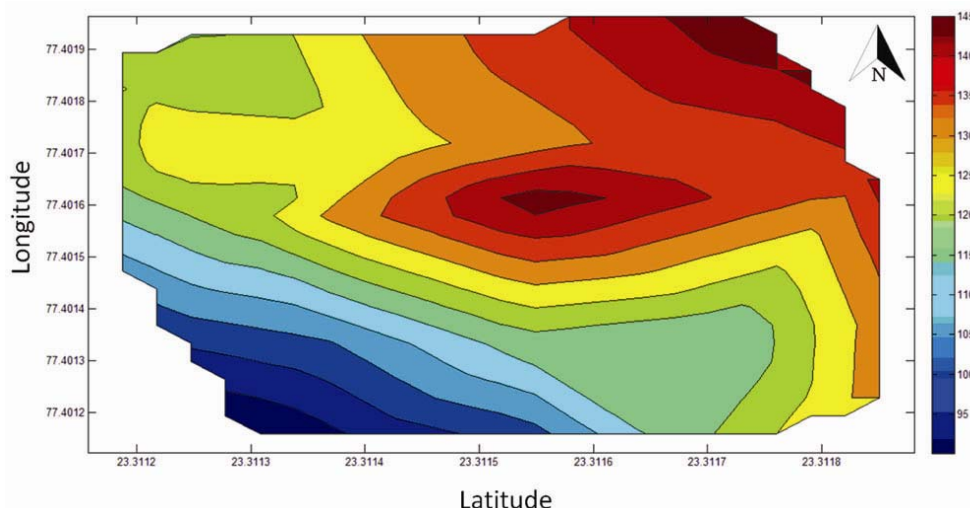
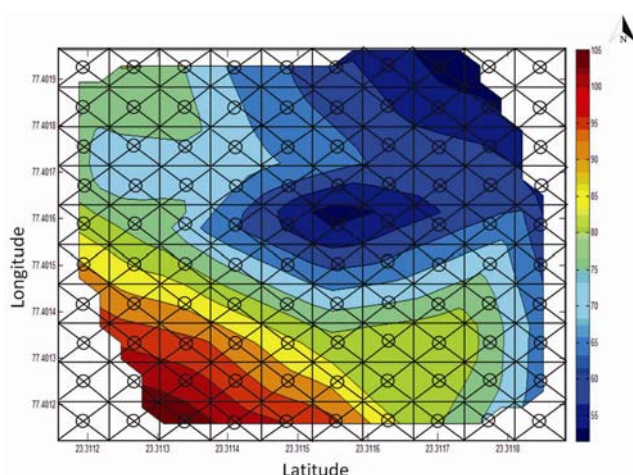**Figure 2.** Soil nutrient (nitrogen) availability map developed using MATLAB®.

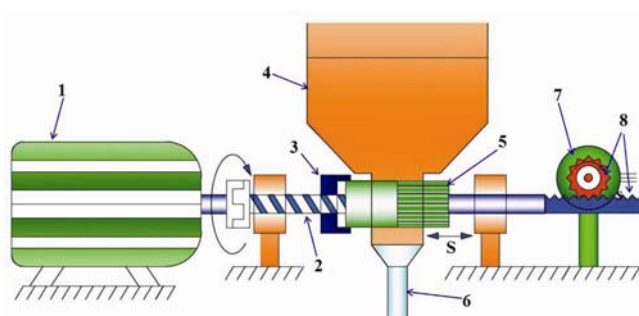**Figure 3.** Nutrient application map for VRFA along with fishnet feature.

Figure 4. CAD view of arrangement of DC motor and position sensor of VRFA system. 1, DC motor; 2, Threaded screw; 3, Threaded nut; 4, Fertilizer box; 5, Fluted roller; 6, Delivery tube; 7, Potentiometer; 8, Rack and pinion set; S, Lateral displacement of flute (0–44 mm).

of granular fertilizer. The variable rate of fertilizer application was achieved by regulating exposure length of fluted roller. The variable rate was obtained by changing the length of active feed roll of metering drive shaft through an actuator. The metering unit was independent of the forward speed of the tractor ranging from 1.8 to 4.5 km/h.

From the preliminary experiments, it was found that 5.8 Nm (maximum) torque was required to vary exposure length of the flutes. Frequent to-and-fro motion of flutes was observed at high speed of motor (beyond 120 rpm). Therefore, a 12 V DC motor (60 W, 120 rpm) was used as an actuator, which controlled the movement of the metering mechanism of fertilizer applicator through threaded screw arrangement (Figure 4). Based on the selected fertilizer application rate, four relay switches actuated the DC motor clockwise and anticlockwise, which shifted the fluted roller exposure length according to fertilizer requirement at a grid point. A low-cost potentiometer (10 k)-based linear gauge arrangement was used to fix current exposure length of the fluted roller (Figure 4). It was also used to determine the present distance and direction of the fluted roller to be shifted according to the target fertilizer application rate.

A GUI program was developed to receive the GPS data and control the fertilizer application rate according to the requirement of specific soil zone. It was programed in Microsoft Visual Studio platform. The developed GUI had four functions, viz. parsing of latitude and longitude from National Marine Electronics Association (NMEA) string, grid identification, display calculated fertilizer application rate along with grid code and signal communication with the micro-controller. The application map (coordinates of grids and application rate) in digital form was incorporated in the developed GUI and integrated with a micro-controller and DC motor to control fertilizer amount according to the instruction of GUI program.

The rover receiver was connected to the microprocessor, which received the NMEA string sent by the receiver from the serial port using specific C# functions.

RS-232 port was used for interfacing the receiver with the computer. Text boxes and push buttons were provided to feed the information about com port and baud rate of GPS and to upload calibration equation of fertilizer applicator. Some text boxes were provided to display latitude and longitude of current location, identified grid code, speed of operation and exposure length of fluted roller.

Figure 5 shows a flow diagram of the VRFA system. The developed VRFA system was synchronized with DGPS, micro-processor, micro-controller, actuator and

Figure 5. Flow diagram of VRFA system.

Figure 6. Process flow diagram of VRFA system with different components.

metering mechanism using visual studio platform (Figure 6). The approximate cost of fertilizer applicator with controller was Rs 60,000. The system judged the location of the variable rate fertilizer applicator by GPS signals. This system controlled fertilizer delivery rate through a combination of exposure length of fertilizer applicator metering mechanism and prescription data which were given by the pre-defined program. Once the grid was identified, GUI software sent a signal in the form of digital value to the micro-controller via serial port.

The VRFA was calibrated in the laboratory to find out the relation between the exposure length of fluted roller and fertilizer application rate. The granular fertilizer was filled up to full level in the fertilizer box to avoid variation in uniformly of discharge rate. Urea granules of 730–780 kg/m^3 bulk density were used in the study, which had a N-P-K composition of 46-0-0. The fertilizer applicator was calibrated at 12 levels of exposure length. A calibration curve was plotted between the exposure length and fertilizer discharge rate.

The developed VRFA system was evaluated for different target fertilizer application rates. Granular urea was filled in the hopper and outlets of the applicator were covered with poly bags to collect and measure the applied fertilizer (Figure 7). The tractor was operated at each grid point and the fertilizer collected in poly bags was weighted to measure the actual application rates at the corresponding grid point.

$$E = \frac{\left| F_a - F_p \right|}{F_p} * 100,$$

where E is the overall implementation error (%), F_p the prescribed fertilizer rate (kg ha^{-1}) and F_a is the average recommended fertilizer rate (kg ha^{-1}). The following statistical indices of fit measure were used to determine the
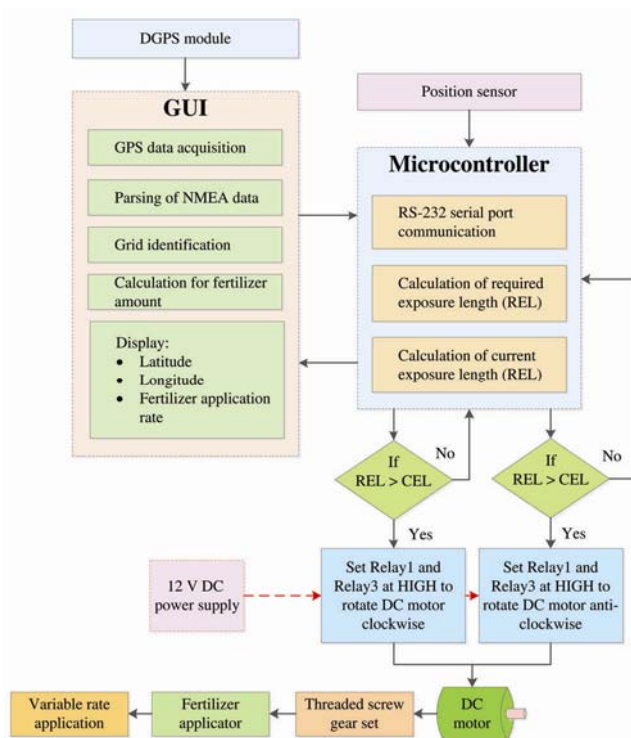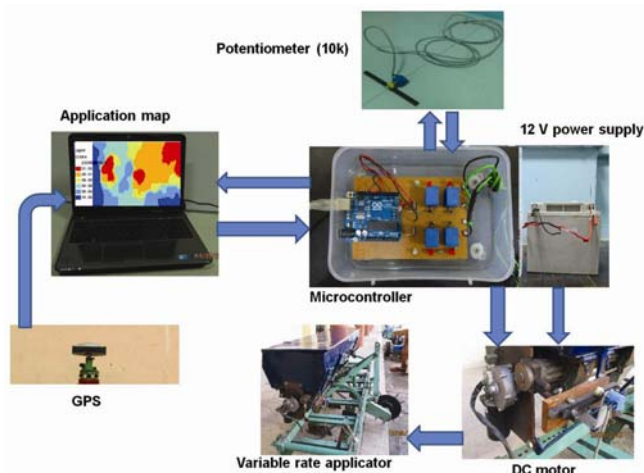

Figure 7. Field testing of digital map-based VRFA system.

accuracy of fertilizer distribution at different grid points, where the variability between replicates was determined for each treatment and level of precision[4]

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(F_a - F_p)^2},$$

$$RD = 100 \times \frac{RMSE}{F_{aav}},$$

where RMSE is the root mean square error (kg ha^{-1}), RD the relative difference (%), F_{aav} the average of the observed values (kg ha^{-1}) and N is the number of comparisons. To ensure validity of the results, the variability between replicates was determined for each treatment and level of accuracy. The coefficient of variation was calculated using the expression[4]

$$CV = 100 \times \frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(RD_{av} - RD_i)^2}}{RD_{av}},$$

where CV is coefficient of variation (%), RD_{av} the average relative difference (%), RD_i the relative difference for each repetition (%) and N is the number of repetitions.

The VRFA system was calibrated by varying the exposure length of fluted roller metering mechanism from 0 to 44 mm at an interval of 4 mm. The fertilizer application rate was 5 and 300 kg/ha for exposure length of 0 and 44 mm respectively. From the calibration curve, it was observed that there was a linear relationship ($r^2 = 0.996$) between fluted roller exposure length and fertilizer application rate (Figure 8). The equation was programmed in the VRFA controller to actuate the DC motor to achieve the desired application rate by changing the exposure length.
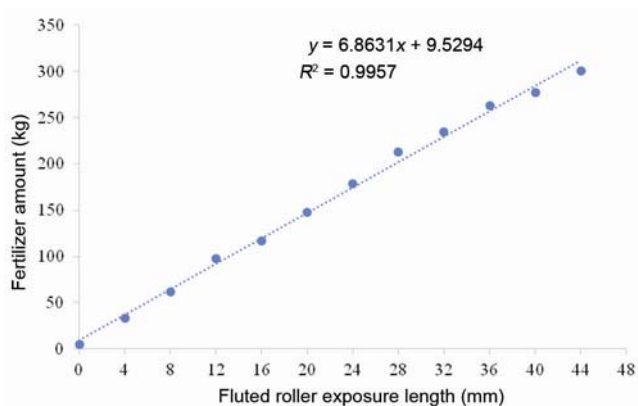
The GPS was installed on top of the tractor so that it can receive data without any interruptions. A time lag of 80–550 ms was observed, with an average of 300 ms for grid identification. In order to synchronize time lag with forward speed of travel, the distance (d) between GPS receiver and fertilizer applicator was maintained such that the tractor can travel the same distance (d) in the average time lag. The distance (d) can be adjusted for a specified range of travelling speeds from 1.8 to 4.5 km/h. The grid identification accuracy depends on the forward speed of travel. It was found that the value of accuracy increased with increase in operating speed. As the tractor travelled from one grid to another, each was identified with an average accuracy of ±340 mm in longitudinal as well as lateral direction.

Time lag in this system depends on electronic delay, mechanical delay and delay in fertilizer delivery. An experiment was conducted in the laboratory to determine response time of the system to get desired exposure length of the metering mechanism. Different values of exposure length were fed into the system and the corresponding time was recorded in the processor to achieve the desired application rate. The minimum and maximum time lag were observed to be 910 and 2280 ms, for varying fertilizer application rates of 5–100 and 5–300 kg/ha respectively (Figure 9). The observed delay time was more for higher difference in two successive application rates. The lag time was synchronized with the forward speed of travel using adjustable mounting of DGPS unit.

Testing of the VRFA system in field indicated that fertilizer application rate changed according to the prescribed application rate for the identified grid. CV or variability for nine outlets of granular fertilizer was in the range 11.7–15.0%. It was observed that higher value of CV was associated with the higher application rate and vice versa. The variation in application rate with longitudinal distance was more uniform for lower (5 kg/ha) compared to higher (300 kg/ha) application rates. Fertilizer uniformity and application accuracy were directly affected by several factors such as calibration of machine,
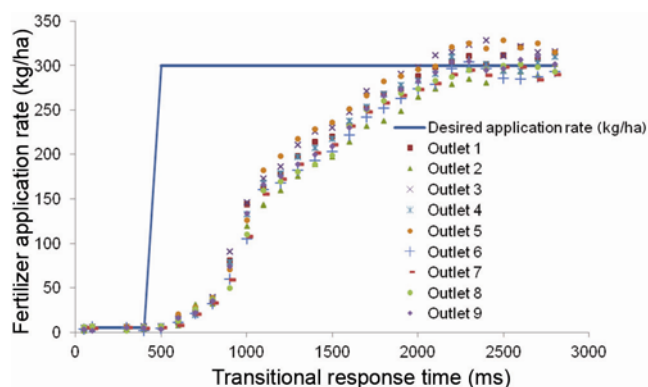

Figure 8. Relationship between fluted roller exposure length and discharge rate of urea fertilizer.

Figure 9. Relationship between transitional response time and fertilizer application rate at nine outlets of seed-cum-fertilizer drill.
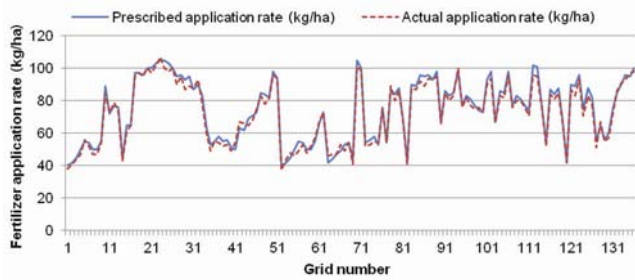
Figure 10. Prescribed and actual fertilizer application rates for 8 × 8 m grid resolution in random order.

GPS tracking and actuator response. The turning radius of the tractor with fertilizer applicator was 3.3 m with brake. RMSE and RD at different levels of application rate ranged from 1.3 to 4.6 and from 1.75 to 6.56 respectively (Figure 10). The forward speed of the tractor had no significant effect on application rate using the VRFA system. The system accuracy was up to 15% of the recommended rate for grid resolution of 8 × 8 m. It was observed that the applicator closely met the target fertilizer application rate for the tested grid size.

A map-based VRFA system was developed and evaluated for site-specific application of fertilizers. The fertilizer application accuracy ranged from 89.3% to 98.1% at various discharge rates. RMSE and RD at different levels of application ranged from 1.3 to 4.6 and 1.75 to 6.56 respectively. The developed VRFA system was effective and accurate to respond to target application rates with small time lag. The VRFA system was able to closely meet the target fertilizer application rate with a variation up to 15% for a grid resolution of 8 × 8 m. The developed VRFA system, micro-controller and actuator could be integrated with row-crop seed-cum-fertilizer drills for use on prescription maps.

There are some limitations with regard to the developed system. The cost of the DGPS is high. The cost of the developed system can be reduced by replacing DGPS unit with local positioning system or real-time soil nutrient sensor. The developed system was evaluated with only one type of granular fertilizer, viz. urea. However, other types of granular fertilizer (micro-nutrients) could be applied simultaneously using three different fertilizer boxes with variable rate-controlling units and some modifications in the micro-controller programming. The prescription map-based VRFA system can also be developed for liquid fertilizer application using variable-rate liquid applicator with an analog signal-based flow control valve. The same GUI can be used with some modifications in micro-controller programming and control unit.

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