

Article

Precision for Smallholder Farmers: A Small-Scale-Tailored Variable Rate Fertilizer Application Kit

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Abstract: Precision agriculture technology at the hands of smallholder farmers in the developing world is often deemed far-fetched. Low-resource farmers, however, are the most susceptible to negative changes in the environment. Providing these farmers with the right tools to mitigate adversity and to gain greater control of the production process could unlock their potential and support rural communities to meet the increasing global food demand. In this study, a real-time variable rate fertilizer application system was developed and tested as an add-on kit to conventional farm machinery. In the context of low investment costs for smallholder farmers, high user-friendliness and easy installment were the main concerns for the system to be viable. The system used nitrogen (N)-sensors to assess the plant nutrient status on the spot and subsequently adjust the amount of fertilizer deposited according to the plant's needs. Test bench trials showed that the add-on kit performed well with basic operations, but more precision is required. Variability between N-sensors and metering systems, combined with power fluctuations, created inaccuracies in the resulting application rate. Nevertheless, this work is a stepping stone towards catalyzing the elaboration of more cutting-edge precision solutions to support small-scale farmers to become successful, high producing agro-entrepreneurs.

Keywords: precision agriculture; variable rate fertilizer application system; sustainable agriculture; NDVI; mechanization

1. Introduction

Hundreds of millions of smallholder farmers feed one-third of humankind; an impressive feat considering that this happens mostly in non-mechanized systems with little to no access to information and practical solutions for optimized farming while facing new challenges to production. Climate change negatively affects yields through heat waves, droughts, and other extreme weather events [1]. Soils are being depleted, experiencing degradation and erosion, arable land and labor for farming is being lost to urban expansion [2], and ground and surface waters are drying up [3]. Exhausting fossil fuels means less energy for farm operations and increasing fertilizer prices [4]. These challenges pose significant threats not only to global food security, but to rural livelihoods in general. Indeed, smallholder farmers are struggling to meet the demand and produce enough yields to support their families' basic needs, barely keeping up with their counterparts in the developed world who have access to high quality agricultural supplies, state-of-the-art precision equipment, and a full range of financial services.

To address this growing global food demand and its pressure on natural resources, there exist several options to promote sustainable intensification, i.e., increasing food production in an area of

land already in use in order to reduce environmental impacts. For instance, precision agriculture uses technologies to apply nutrients, pesticides, and water in an exact location and time to reduce waste and optimize all resources [5]. In precision agriculture, variable rate fertilizer application (VRA) refers to the application of fertilizer compounds, i.e., the rate of application is based on the quality of the field to which fertilizer is applied, as opposed to traditional farming, where a constant fertilizer rate is usually applied to the whole cultivated area. In crop production, knowing the quality of the field means that site-specific soil nutrient availability or plant nutrient requirements are understood. While there are many methods to determine a field's quality, sensor-based VRA requires no map or positioning system since the sensors measure a continuous stream of nutrient status data on-the-go, inferred by the crop characteristics of the plants right below the sensor [6]. Based on this information, the resulting variable amount of fertilizer applied aims to reduce intra-field crop growth differences and negative environmental impacts caused by leaching of excessive N use [7]. As such, sensor-based methods provide a real-time and practical solution to recognize and respond quickly to the lack of nutrients during crop growth and by doing so, reduce production losses in general [8]. In large scale operations, VRA fertilizer application for in-season nutrient administration as site-specific management has often proven successful in terms of increasing nitrogen use efficiency [9] and crop profitability [10]. As nitrogen (N) is often the most common limiting nutrient for optimal plant growth and in particular for grain yield [11,12], N-sensors can recommend the quantity of fertilizer to be applied for a plant to continue to grow under optimum conditions, i.e., the output indicates the plants' direct need for N. Subsequently, the recommended output can be used to enable a VRA system to respond immediately and only apply the amount of fertilizer required by the plant under the sensors' reading area.

N-sensors do not directly detect the N present in the plant, but rather use vegetation indices (VIs) based on an amount of reflected light to infer a plant's actual N status at a given time. As such, a VI is measured as a ratio of reflectance measurements of different spectral bands, specifically for different VIs. Subsequently, the value of the ratio is related to the colour of the plant (i.e., how green the plant is). The colour or greenness of a plant is relevant, since a plant's active component for photosynthesis and consequently growth (or production) is chlorophyll. Nitrogen is a building stone for chlorophyll (i.e., $C_{55}H_{72}O_5N_4Mg$), and since the majority of the functional N in a plant is allocated to chlorophyll [13], a lack of greenness can be seen as a deficit in a plant's nutrition, therefore indicating the need for a certain amount of N fertilization [14]. More specifically, N-sensors using the normalized difference vegetation index (NDVI) assume that plants with no nutritional restriction growing to their full potential in the environment at hand present a deeper green colour or higher NDVI. Algorithms are then developed that allow the calculation of a fertilizer dose for plants that give a lower NDVI compared to the index received from ad-libitum fertilized plants [15]. As such, by measuring plants during their growth phase, it can be determined how much N the plant needs at the time of measurement to achieve the same nutrient state as the plant under richly fertilized conditions, or rich strip (RS) plants [16]. Since the growth curve of a plant and its potential yield are very dependent on its environment, individual agro-ecological zone algorithms have to be developed, such as those calculated for different regions in Mexico [17,18]. A more thorough overview can be found in [19] and [20].

An N-sensor can be either passive or active. Passive sensors do not have a power source and can only perform when an auxiliary source provides the stimulus. Factors such as light intensity, solar position, or sky turbidity can significantly affect the sensor's output, making it difficult to provide a reliable recommendation when used outdoors. In contrast, active sensors generate a signal (e.g., laser, ultrasound, etc.) that will "bounce" off the object and the difference between the emitted and received signals is used to provide the desired data. These sensors have the advantage of being entirely independent and provide reliable readings regardless of environmental conditions [21].

While remote-sensing, such as the MasAgro GreenSat system [22], which uses satellite images or image analysis from airborne multispectral cameras, can generate information on crop N status over large areas at once with high precision, so measurements from ground-based N sensors for site-specific

crop management decisions are far more user-friendly and relatively inexpensive. Above all, they can be easily integrated into handheld tools or farm machinery. Indeed, obtaining high-resolution multispectral images might not be economically feasible for smaller areas [23] and timely access to information derived from satellite images can be quite troublesome for farmers in the developing world. Progress has been made to lower the image acquisition cost (as for example presented by [24], where integrated wireless webcams monitor crop growth to automate chemical pest control and to reduce image processing time [25]). However, due to the high mechatronic nature of the design, application is limited for use in controlled environments or demands extensive calibration and user-training for broad application. In contrast, while ground-based sensors do not have the ability to analyze large areas at once, they are very flexible, independent, and can generate very local data on specific plant N status.

Although many studies have indicated the advantages of VRA fertilizer application, the high equipment investment cost could weigh out these benefits [26], suggesting that the technology at this stage would only be viable for large-scale farm operations. Others have confirmed this, but indicate that the high costs can be lowered by adapting existing uniform N fertilizer applicators to VRA N fertilizer applicators [11]. VRA can also play an important role in mitigating the risk of high nitrate leaching [27], especially in nitrate vulnerable zones where environmental stewardship is warranted [7]. Thus, in the present study, a granular, on-the-go VRA system was developed, focusing mainly on reducing the initial investment costs for the equipment and adapting the system to existing constant rate machinery. As such, the proposed system was designed as an add-on kit that can be installed onto conventional fertilizer equipment with fluted roller metering systems. This prototype was developed with the following objectives: (1) to offer VRA-precision technology using active N sensors tailored to small and medium-scale farmers; and (2) to improve these farmers' crop production potential by increasing their ability to apply precise amounts of expensive inorganic fertilizer, thus reducing their losses. With the targeted user group being smallholder farmers in the developing world, the main criteria in the design of the add-on kit were a low investment cost, high user-friendliness (i.e., simple structure, few electronics, and easy to clean or replace), and simple installation onto existing farm machinery.

2. Materials and Methods

2.1. Selection of N-Sensor

Comparing the properties of different N-sensors currently available on the market (Table 1), the GreenSeeker[®] Handheld sensor (Trimble Inc., Sunnyvale, CA, USA) was chosen as the N-sensor for our prototype. Handheld sensors lack some precision in comparison to others, but their low cost compensates for this (Table 1). Furthermore, the efficiency of the handheld GreenSeeker[®] has been proven equal to the more expensive version (i.e., GreenSeeker[®] RT100), in particular for maize and wheat varieties, and its lightness and compactness make it easy to attach to any kind of machine by simply using a holding frame [28]. The GreenSeeker[®] N-sensor infers a plant's nutritional state depending on the NDVI [29] it generates. As such, the only output that the N-sensor generates when activated is NDVI readings.

Table 1. Overview of a series of currently available site-specific crop management (SSCM) N sensors.

Sensor	VI Used	Installation	Estimated Price for Complete System in USD †	Manufacturer/Reference
GreenSeeker [®] Handheld	NDVI	Handheld—1 sensor	550	Trimble Inc., Sunnyvale, CA, USA
GreenSeeker [®] RT100	NDVI	Handheld or mounted on tractor—1 sensor/1 display	5500	Trimble Inc., Sunnyvale, CA, USA
SPAD 502	NDVI	Handheld—1 sensor/1 display	5662	Konica Minolta; [30]
OptRx [®] Crop Sensor	REIP	Anywhere on tractor—2 sensors + command kit	11,000	AgLeader Technology, Ames, IA, USA

Table 1. Cont.

CROP SPEC	NDVI	Anywhere on tractor—2 sensors and display, mapping and application system	18,000	Topcon Positioning Systems, Inc., Livermore, CA, USA
Crop Circle™	NDVI	Handheld or mounted—3 sensors and display, mapping and application system	17,500	Holland Scientific, Lincoln, NE, USA
Yara N Sensor®	NDVI	Top of tractor—2 sensors and display, mapping and application system	25,000	Yara UK Limited, Lincolnshire, UK
ISARIA	REIP	Boom system on tractor—2 sensor system, with display mapping and application system	30,000	Fritzmeier Umwelttechnik, Großhelfendorf, Germany
Multiplex®	NBI	Anywhere on tractor—2 sensor system	33,000	Force A, Orsay, France

‡ Prices in United States Dollar (USD) are based on personal communication with providers and website information; <https://www.futurefarming.com/Tools-data/Articles/2017/6/Round-up-of-tractor-mounted-crop-biomass-sensors-1576WP/>. NDVI = normalized difference vegetation index, REIP = Red-Edge Inflection Point Index, NBI = Nitrogen Balance Index.

2.2. Prototype Add-On Kit Set-Up

From reading the plant nutrient status to applying the correct amount of fertilizer, the kit consists of the following essential components: N-sensor, microcontroller with datalogger, and VRA-fertilizer meter. In essence, a mechanical fluted roller fertilizer meter was adapted to respond in an automated fashion to an optical N sensor. The VRA-fertilizer meter was made from a standard sliding fluted roller, frequently found in conventional farm machinery. A linear movement parallel to the axis of rotation can reduce or increase the amount of groove volume (i.e., flute) available to capture and dispense the fertilizer. By linking the roller with an independent piston-like electric actuator (i.e., FA-PO-35-12-6, Fircelli Automations, Ferndale, WA, USA), the volume of the fluted roller can be adjusted during operation in order to change the distributed fertilizer volume (Figure 1). The actuator piston works as an auxiliary system for increased control and operability, while the standard fertilizer meter is driven by the wheel traction. In this case, the revolution speed of the fertilizer meter axle requires a synchronized relation with the operation speed. The electric cylinder or actuator with a small 12 V battery was chosen over hydraulic pistons (requiring hydraulic valves and cables) or secondary motors (heavy and expensive) in order to reduce installation costs. An additional benefit of using an electric actuator is that its position at any time can be registered by a potentiometer and consequently can be monitored and controlled by a microprocessor.

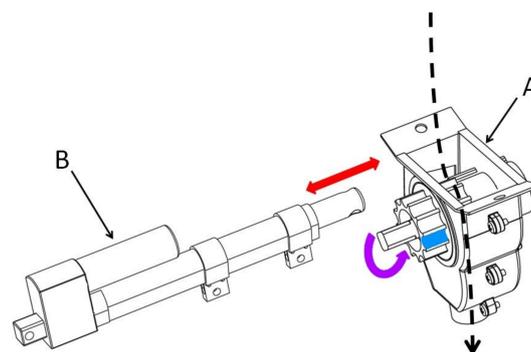


Figure 1. The proposed VRA dispenser with its components: (A) fluted roller box, and (B) electric actuator. The red arrow represents the linear movement performed in real time by B, while the purple arrow is the movement of the roller generated by the operation traction. The striped black arrow represents the trajectory of the fertilizer passing through the fluted roller box. Finally, the blue marked area indicates one of the grooves in the fluted roller where the fertilizer is caught (adapted from [31,32]).

The final complete kit consisted of two N-sensors, coupled with a modular built circuit board housing the microcontroller and datalogger (control box), two magnetic calibration sensors, a Bluetooth transmitter to read out the data, the 12V battery, and finally two electric pistons, installed onto the fertilizer meters of the farm machine (Figure 2). The cost of the parts and programming for the present prototype add-on kit (including microcontrollers, pistons, wiring, and cell-modem and a Graphic User Interface (GUI)-module) was approximately 3000 USD for the 1-1 kit (one piston, one sensor) and 5000 USD for the 2-2 kit (two pistons, two sensors). These prices include the GreenSeekers®; without GreenSeekers®, the costs lower to 2500 USD for the 1-1 kit and 4000 USD for the 2-2 kit.

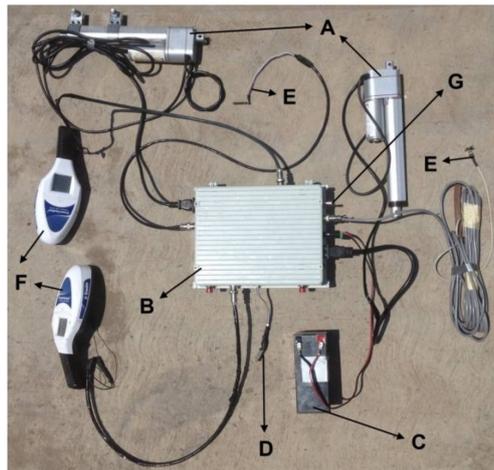


Figure 2. Overview of the external components of the developed VRA-fertilizer kit, including (A) electric actuator piston; (B) control box; (C) 12V Battery; (D) Bluetooth transmitter; (E) magnetic calibration sensor, (F) N-sensor; (G) ON/OFF-switch.

2.3. Test Bench Trials

Testing of the prototype was carried out at CIMMYT's experimental station in El Batán, Texcoco, Mexico (19.532397, -98.845846). On a conveyer-belt test bench, two fertilizer hoppers were mounted, each with a pair of fluted roller meters from which the granular fertilizer was to be distributed. The fertilizer hoppers were built specifically for the experiment, made out of a stainless steel sheet (thickness of 1.9 mm) able to contain approximately 40 kg of granular urea. The mounted fluted rollers are commercially available (John Deere, Original Equipment Feed Cup #AN280009). One piston per fertilizer hopper was connected to its respective pair of fluted rollers. At the front, two identical N-sensors were positioned at a reading height of 80 cm above the conveyer belt (Figure 3). This reading height was chosen to be well within the manufacturer's optimal reading range and was based on previous work done by [33] comparing crop sensor systems for informed fertilizer placement. Following both this work and [28], the projected surface should cover an area of 280-300 cm², which was ideal for the presented testing purposes. If the vegetation is lower or higher, the arm that holds the sensor can be moved upwards to obtain the ideal height above the canopy level. Intra-field variation on individual plant height was not taken into account. Figure 3 shows the experimental setup on the test bench, but in the field, a single sensor is placed directly above a plant row. As such, in the two-sensor kit, inter-row distance would range between 75 and 90 cm. The projection width of the handheld GreenSeeker® at an 80 cm height is about 33.3 cm, thus no interference should occur.



Figure 3. Setup of the test bench with two N-sensors up front connected through the control box with the VRA fertilizer meters (left); close-up view of the fluted rollers connected with the electric actuator piston (right).

Next, colour panels were used to trigger a response of the N-sensor, aiming to test the subsequent reaction of the actuator based on the colour. A set of colours was chosen to cover a broad spectrum, including NDVI values from 0.12 up to 0.81. Even though these indices can be unrealistic for actual plants in their growing phase, this allowed the system to be tested for extreme situations. By changing colour panels, abrupt reactions can be provoked, similar to gaps in the plant row or when turning of the tractor occurs. To avoid application on bare soil, NDVI values equal or below 0.2 trigger a reaction to close the system. General NDVI values of viable plant vegetation range between 0.2 and 0.9, thus values lower than 0.2 are considered barren soil or sparse vegetation [34]. There is no need to differentiate between the two, as the plant is either not the desired crop or is already lost (i.e., no recovery is expected by applying more fertilizer). As such, the lowest value of 0.12 should always make the piston close the fertilizer meter completely. For the upper limit, one should use the value of the reference ad-libitum-fed plants in the rich strip and set the VRA-system to top-off at this value. As the colour panels' NDVIs are known, it is possible to compare the theoretical response value with the actual value and as such determine the VRA-kit's precision. The colour panel information, including average NDVIs, is summarized in Table 2.

Table 2. Colour panel information including NDVI.

Colour	HEX-Value	HSV-Value	Average NDVI
Red	#CA021C	352°,99,79	0.12
Pink	#D0ABB6	342°,18,82	0.23
Cyan	#008D4	179°,100,85	0.43
Violet	#97A2E1	231°,33,88	0.57
Emerald	#46D582	145°,67,79	0.60
Green	#00C87F	158°,100,78	0.81

During the trial, the system was loaded with two different sets of parameters, derived from calibration experiments on maize performed in Valles Altos, Mexico, in 2014. Parameter selection was made to coincide with a realistic fertilization timeframe. Since second fertilization for maize usually takes place around 40 days after planting, the first parameter set consisted of data from 38 days after planting. This fixed time gave a growing degree-day sum (GDDsum) of 304 and rich strip NDVI measurement of 0.85. The second parameter set was based on data from 57 days after planting. Waiting longer to apply fertilizer would make it difficult to enter the field with most standard equipment since maize plants would have grown quite high by then. GDDsum at that time was 432.5 with a rich strip NDVI measurement of 0.90 on average. Potential yield for the area was set at 10 t/ha. Based on these numbers, the recommended application rate for all possible NDVIs was calculated using the nitrogen

fertilization optimization algorithm as published by [35] and validated for the handheld GreenSeeker sensor by [28]. The results for both times are presented in Figure 4.

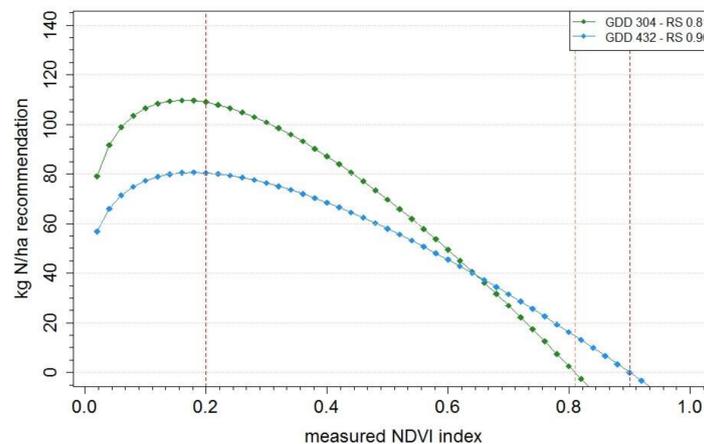


Figure 4. Results of the Valles Altos maize calculation of the NDVI algorithm for growing degree-day sum (GDDsum) 304 and rich strip (RS) NDVI 0.81 from data taken 38 days after planting, and for GDDsum 432 and RS 0.90 from data taken 57 days after planting. Note the cut-off for NDVI values below 0.2 as this is assumed to be bare soil, as well as the RS cut-off when no extra fertilizer addition is needed.

Once the measured NDVI value has been converted into a recommended N application rate, it is necessary to relate this to the amount of fertilizer that is to be applied by the fluted roller fertilizer meter. Both the internal opening of the fluted roller and the axle's rotation speed influence this amount. However, the actuator piston connected to the fluted roller can only change the internal opening. Therefore, under all circumstances, it is necessary to operate the system at a pre-established rotation speed (RPM). In the present case, the RPM was set at 38.5. Using the calibration sprockets of the planter/fertilizer, this RPM can be achieved independently of the tractor operation speed.

The selected fertilizer meter has a maximum opening of 50 mm. In order to determine the relationship between the fertilizer application rate and the actuators' position (and therefore the opening of the fluted roller), the amount of fertilizer leaving the fluted roller on 10 different stances was measured. At each position, 10 samples were collected and weighted and subsequently converted into kg N/ha. Linear regression showed a close relationship between the fertilizer meter application rate and the opening position of the connected actuator (Figure 5). Granular urea (46-0-0) was used as fertilizer formula. With this information, the expected response of the VRA-kit depending on the colour panel used was calculated for both situations and the response compared to the measured response of the VRA-system. The experiment was repeated three times for the whole set of colour panels.

In order to simulate at an operating speed of 3.4 km/h, the test bench was run for intervals of 52.94 s to cover a 50 m distance per colour panel. This fixed maximum speed is imposed due to a 6 s response lag in which the N-sensor signal is processed and translated to piston movement (including movement from fully open to fully closed position or vice versa of the fluted roller). At this speed, when mounted on a four wheel tractor, the system's response lag matches the distance covered between plant N status measurement and adjusted fertilizer deposition. If the machine is to perform faster in the field, the sensor position relative to the fertilizer meter can be increased. Future work will include faster calculation procedures to reduce lag.

In the field, one would expect faster changing colour responses while passing over the individual plants in a row, but less abrupt changes (unless a missing plant occurred). For this reason, the swift reaction of the piston to changing of the colour panels is more important, as well as its ability to respond correctly in extreme situations (e.g., barren soil due to plant gaps).

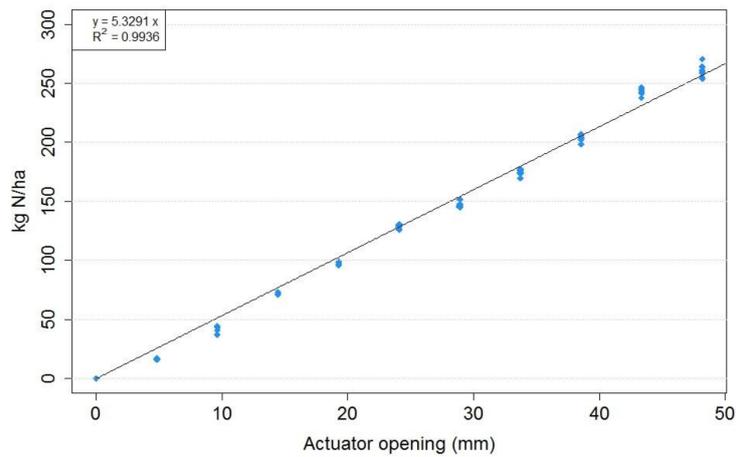


Figure 5. Relationship between amount of fertilizer released by the fluted roller and the actuator opening position.

As previously mentioned, the RPM of the fluted roller was maintained at 38.5 RPM by selecting the correct drive sprocket combination. The distributed fertilizer was collected for 52.94 s in plastic bags from the moment the pistons moved into position. Subsequently, the colour panel was changed and a new bag placed under each dispenser. Afterwards, all bags were weighed and the values converted to kg N/ha distributed per fluted roller. Since each piston moves simultaneously with the fertilizer dispenser, half of the corresponding recommended amounts were theoretically deposited in each bag. The experiment was repeated for each GDDsum/RS combination. Fresh fertilizer was used for colour panel series and repetitions, and no fertilizer was recycled.

3. Results

3.1. N-Sensors Capture Continuous NDVI Data

A preliminary test to validate the N-sensors' behavior under continuous data capturing appeared to be satisfactory, but significant differences in the output between the used N-sensors could be found. Nevertheless, the NDVI output as captured by each N-sensor for the different colour panels was within range to be used as such. Table 3 sums up these values for each colour panel.

Table 3. Averaged NDVI measurements from the two N-sensors \pm 1 standard error for each sensor with an asterisk indicating significant differences between Sensors 1 and 2 (two sample *t*-test, * $p < 0.05$). PRE = predetermined NDVI index.

Colour	PRE	AVG Sensor 1	AVG Sensor 2
Cyan	0.43	0.44 \pm 0.01	0.42 \pm 0.02
Red	0.12	0.11 \pm 0.00	0.13 \pm 0.00 *
Green	0.81	0.80 \pm 0.01	0.82 \pm 0.00 *
Violet	0.57	0.57 \pm 0.00	0.57 \pm 0.00
Emerald	0.60	0.60 \pm 0.00	0.59 \pm 0.00 *
Pink	0.23	0.22 \pm 0.00	0.23 \pm 0.00

3.2. Data Processing: Linking N-Sensor Output to Actuator Piston Trigger

Once the N-sensors are scanning the colour panels, information is sent continuously to the microprocessor in the control box. Data is accepted and processed, and subsequently a signal for each respective electric actuator piston is produced. The actuator receives this signal which orders it to activate or not, for how long, and in what direction. Logically, this movement of the fluted roller

opening is directly related to the difference between the RS-value and the NDVI read by the N-sensors; a large difference means a severe N shortage in the plant and demands a high fertilizer dressing, while a small difference indicates a plant at an optimal nutritional state and only minimal N addition is required. Figure 6 shows an overview of the data received and produced by the microprocessor during the trial. The data shown were collected from test runs with GDDsum 432.5 and RS 0.90 as parameter values. Similar results were obtained during the other trials.

Looking at Figure 6, the system seems to respond correctly, at least in terms of direction and timely response. Maximum response time equaled the predetermined lag; when the NDVI reaches the RS value (i.e., 0.90), the piston moves towards complete closure of the fluted roller during the following 6 s. When an invalid NDVI signal is received (i.e., NDVI < 0.20), the piston also finds itself in a fully closed position. At intermediate NDVI-levels, the pistons open to an intermediate position. The noise visible in the sensor signals was due to small voltage fluctuations from the power supply. On closer examination of the processed data, it becomes clear that the system is operating in the right direction, but in most situations, the actuator moved much further open than necessary, resulting in an unnecessarily high fertilizer application (Table 4).

Table 4. Comparison of the expected amount of fertilizer to be released per fluted roller pair to the actual released amounts.

Colour Panel	Expected Value	kg N/ha Released	
		Measured Pair 1	Measured Pair 2
Cyan	82.2	136.4	95.4
		113.9	89.1
		113	92.6
Green	0	−0.02	−6.6
		10.4	−4.8
		14.2	3.1
Violet	55.6	89.3	87.7
		101.2	86.8
		107.5	99.4
Emerald	49.4	89.2	88
		91.4	86.3
		107	95
Pink	107.2	87.6	87.3
		88.9	85.3
		109.4	93.6

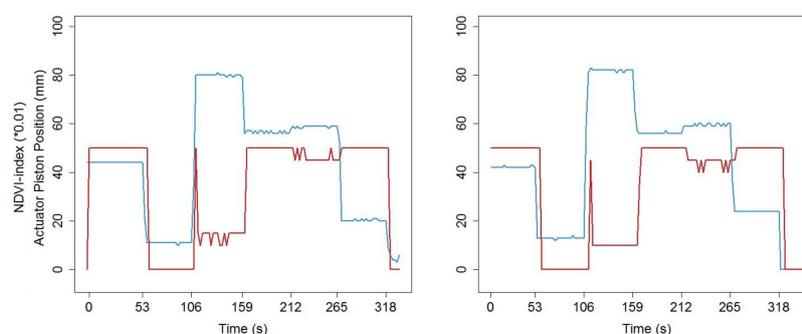


Figure 6. Link between N-sensor 1 (left) and N-sensor 2 (right) and corresponding actuator movements during the test for GDD 432-RS 0.90. N-sensor processed data are represented in blue and the reaction of the actuator piston in red, measured in mm.

3.3. Real-Time Adjustment to Achieve a Variable Rate Application

As mentioned, each actuator piston is connected to two fluted rollers, forming a pair. The total amount of fertilizer passing through each pair was retained during each test run repeated three times. In order to smooth out slight variations, the average amounts of fertilizer distributed by each pair were compared with the calculated recommended outcomes. The results of the trials, using the parameter set of 40 days after planting (i.e., GDDsum 304 and RS NDVI 0.81), are presented in Table 4. It is clear that the mechanism lacks accuracy, especially so in intermediate situations where large deviations up to almost double the needed amount are registered. On average, for the violet panel, 71% too much fertilizer was released and a surplus of 88% was found for the emerald panel. For extreme situations, however, the deviations are less pronounced and resulted in a surplus deposition of 29% and 14% shortage for the cyan and pink panels, respectively.

Subsequently, it must be said that the overall precision has to be greatly improved for the kit to be useful in the field, but this is a matter of calibration and fine-tuning of the piston movement (i.e., reduce lag and adjust meter filling rate at the used RPM). Nonetheless, an overall R^2 of 0.63 was found when fitting the observational data to the expected outcomes. The amount of fertilizer collected when the red colour panel is presented to the N-sensors was used as a tare weight for the others, since the soil in the study area is reddish. This resulted in negative values in some situations while using the green colour, meaning no material was coming out, as would be expected (Table 4).

4. Discussion

4.1. VRA-Kit Prototype Performance

Within a small-farm enterprise, improved control and precision is of particular importance in terms of nutrient management during the crop cycle, as inorganic fertilizers are expensive and the application regimen greatly determines the final yield. In fact, inadequate use of fertilizers, e.g., indiscriminate broadcast applications and bad timing, can cause N losses of up to 70%, not taking into account intra-field nutrient variances [36]. This can be resolved to a certain extent by using recommendation strategies that split fertilizer applications during the growth cycle, but for precise in-situ fertilizer applications, specific equipment and/or machines are needed.

In this study, precision agriculture concepts were integrated with a fertilizer application method more commonly used in medium to small-scale farming. Overall, the add-on VRA-kit responded adequately, although the system lacked some operational efficiency. There is room to improve the accuracy of the reactions, especially for interpretation of the analyzed NDVI data by the electric actuators. In particular, the N-sensor output data that was sent through to the actuators should be interpreted independently for more precise results. During the trials, it was observed that the system was rather sensitive to power outage differences. As such, the deviation from one actuator set to another was most likely caused by an unequal power distribution, making the second actuator move slower, and subsequently its fluted roller movements were less pronounced. To avoid these kinds of problems, an internal power feed for the whole system, including the N-sensor, could be installed.

In the case of our prototype, it was clear that the system in general was applying too much fertilizer, even with the amount averaged out over the repetitions (Table 4). In addition, a different quantitative N-sensor/actuator-unit response was noted, but the proportional reaction pattern was roughly identical: both systems responded well at extreme NDVI-values when the fluted rollers were either in fully closed or fully opened positions. However, for intermediate to above-average NDVI values, the desired precision was not achieved. Moreover, due to the design of the fluted rollers, even in the closed position, some fertilizer still made its way through if the system kept turning. Nevertheless, the results of the test bench trials are promising.

4.2. Fertilizer Selection for Precision Agriculture

Considering the different physical forms in which inorganic fertilizer compounds are commercially available, the most common are liquid and solid fertilizer formulas, usually generically described by an N-phosphorus (P)-potassium (K) ratio description. Both liquid and solid (granular) formulas can be mixed to obtain the desired amount of N, P, and K to be applied. Liquid fertilizers have the advantage of easier, more uniform mixing and therefore are usually more precise when applying, especially at variable rates. In order to do so, however, a sophisticated sprayer system (generally known as a flow-based system [6]) is required with many components including flow meters, pumps, and pressure gauges, as well as a solid sealing system for all tubing, plugs, and nozzles. Apart from the high initial investment costs (from 30,000 up to 120,000 USD depending on the brand, provider, sensor, and size), the complexity of the system requires an advanced knowledge and specific maintenance care, two aspects that might be serious obstacles for the low-resource farmer.

Dry or granular fertilizer, as used in this trial, in contrast, is far more accessible and used worldwide, mainly because of its ease of transport, storage, and lower cost [37–39]. In addition, granular fertilizer formulas are more practical to handle in the field, even more so now that bulk recipe mixtures are readily available on the market [38]. The ease of application, however, has to be balanced with the loss of precision. Broadcast spreading usually generates a far from uniform distribution and leads to losses due to a lack of incorporation in the soil. Granular VRA systems have been developed for both broadcasting [40] and high-precision pneumatic band/row fertilizers [41–43], exchanging economy for efficiency. All these systems, however, have been developed for prescription map-based VRA and none offer a real-time sensor based solution. Our proposed model thus addresses this gap by offering an elegant solution to the need for high precise granular fertilizer application, in addition to taking into account intra-field variances. The further development of this prototype could highly increase the control of small farm enterprises on their fertilizer inputs and give them the ability to become more productive, particularly more cost-effective despite a reduced cultivated area [6,11].

5. Conclusions

The challenge of this study was to present an initial prototype that would make VRA-fertilizer application economically feasible for smallholder farmers, and clear a path for precision agriculture tools and principles that can be applied and integrated into poor rural farm communities of the world. This goal was achieved with the production costs of the prototype less than 5000 USD compared to commercial systems, which can easily cost ten times as much. Furthermore, the VRA-kit presented here was conceived as a low investment add-on kit to existing agricultural equipment, enabling it to be used by trained precision service providers assisting farmers at different levels of operation. The test bench trials highlighted its potential as an innovative and efficient farm equipment application tailored to the small and medium-scale farmer. It combines traditional farm machinery with a modern tool that can enable smallholder farmers to gain better control and precision required in their daily operations. As of yet, more attention should be given to fine-tuning the mechanical components in order to minimize precision losses due to assembling irregularities. Future experiments will test the efficiency of the prototype in the field, including additional agronomic parameters. Investing and fine-tuning equipment such as this will allow low productive farmers anywhere to transform themselves into precise high output agro-entrepreneurs.

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