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# Variable Rate Application of Herbicides for Weed Management in Pre- and Postemergence

*Alessandro da Costa Lima and Kassio Ferreira Mendes*

## Abstract

With the advent of precision agriculture, it was possible to integrate several technologies to develop the variable rate application (VRA). The use of VRA allows savings in the use of herbicides, better weed control, lower environmental impact and, indirectly, increased crop productivity. There are VRA techniques based on maps and sensors for herbicide application in preemergence (PRE) and postemergence (POST). The adoption of the type of system will depend on the investment capacity of the producer, skilled workforce available, and the modality of application. Although it still has some limitations, VRA has been widespread and has been occupying more and more space in chemical management, the tendency in the medium- and long term is that there is a gradual replacement of the conventional method of application. Given the benefits provided by VRA along with the engagement of companies and researchers, there will be constant evolution and improvement of this technology, cheapening the costs of implementation and providing its adoption by an increasing number of producers. Thus, the objective of this chapter was to address an overview of the use of herbicides in VRA for weed management in PRE and POST.

**Keywords:** VRA, precision agriculture, chemical control, automation

## 1. Introduction

The growing demand for food and the limitation of territorial expansion of agricultural areas direct agriculture toward an increasing intensification with the rational use of resources and maximization of production [1]. For 2050, the world population is estimated at 9 billion people; this represents a need for an increase in food production around 70 to 100% that can be achieved if more efficient cultivation techniques are adopted with fewer impacts on the environment [2]. For this to be possible, it is necessary to have knowledge and control of the variables that interfere in the costs of production and productivity of crops. In this sense, precision agriculture is a tool that makes it possible to meet these needs.

Precision agriculture comprises a set of technologies that combines sensors, information systems, improved machinery, and informed management to optimize production, considering variability and uncertainties in agricultural systems [3].

This modern agriculture starts from the concept that an area of production is not homogeneous, that is, it has great variation. Thus, it is not appropriate to use agricultural inputs and management techniques equally for areas that have different characteristics. The aggregated knowledge throughout history helps to scientifically explain the variability observed and offers paths to localized management with more technique and rigor [4].

This new approach mainly benefits from the emergence and convergence of various technologies, including the global positioning system (GPS), geographic information system (GIS), microcomputers, control automation, remote sensing, mobile computing, advanced information processing, and telecommunications [5]. With these technologies, it is possible to analyze spatial variability, through data collection, information management, application of inputs at varying rate, and, finally, the economic and environmental evaluation of the results [6].

Precision agriculture allowed to perform not only the mapping of the physicochemical properties of the soil, application of fertilizers in a localized way, pest monitoring, harvesting and post-harvest operations, among others [3] but also the mapping and control of weeds, with localized sprays through mapping equipment or real-time systems and thus rationalize the use of pesticides and also minimize damage to the environment. Thus, the objective of this chapter was to address an overview of the use of herbicides in variable rate application (VRA) for weed management in PRE and POST.

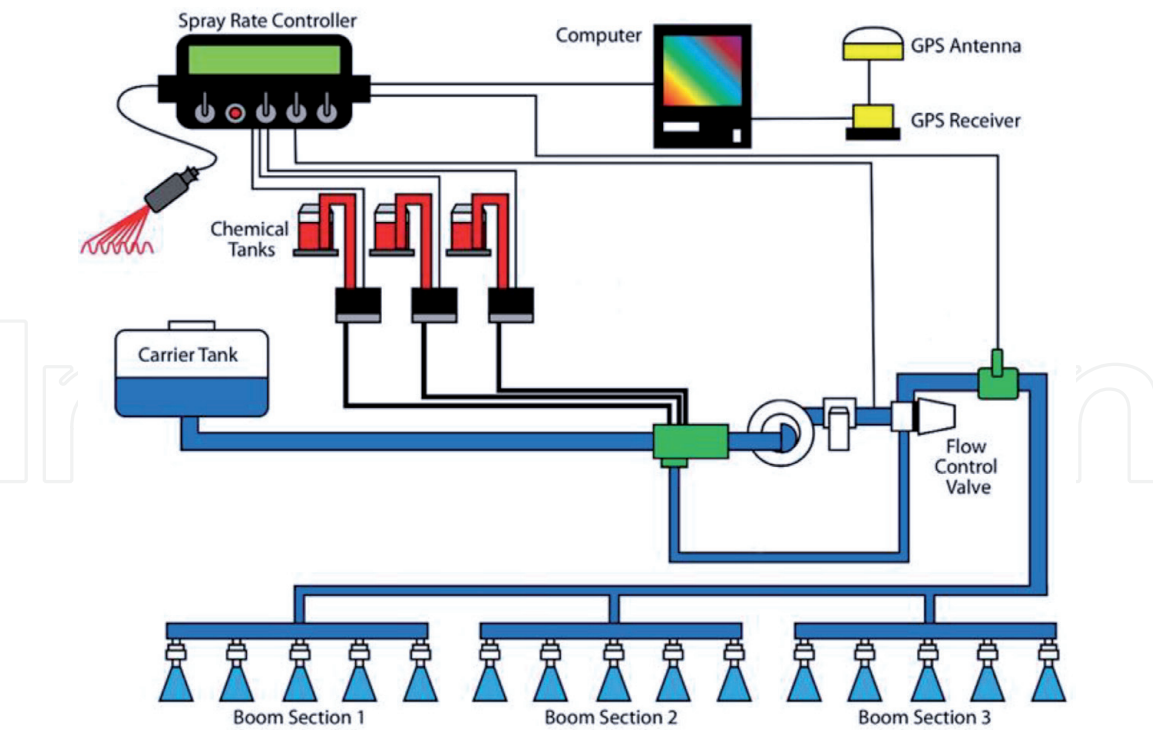
## **2. Variable rate application (VRA) of herbicides**

Weed control with herbicides makes up much of the production costs of a crop. In conventional agriculture, herbicide doses are recommended for large areas, without considering many aspects of spatial and temporal variation. When the use of herbicides is made at a fixed rate, economic losses occur directly and indirectly, both due to the above—what is necessary for herbicides and for possible control failures that decrease productivity. In addition, environmental contamination may occur by leaching herbicides into groundwater and rivers. To fix these problems, it is necessary to use the precision agriculture tools and implement a VRA system [7].

VRA refers to the application of herbicides based on area, location, and soil conditions, among other characteristics. Important characteristics such as the variation in infestation and weed density in the application of herbicides in POST and in the sorption capacity that the soil exerts in the application of herbicides in PRE are considered in this system. This allows us to control weeds more efficiently and reduce environmental risks, as there are no applications of underdoses or overdoses. This technology works by integrating a variable rate control system with the sprayer for herbicide application [8, 9].

VRA systems can be different in many ways, but have components in common; the basic system deployment consists of five components that are represented in **Figure 1**: GPS receiver for location and orientation of the machinery at the time of application, a computer that will perform the data processing, a software capable of relating the data collected in the area and determine the dose to be applied, in addition to controllers that will be responsible for changing the flow and pressure of the spray syrup [7].

The application at a varied rate can be fundamentally based on maps or sensors (**Table 1**). Such methodologies require specific resources that differ greatly from each other.



**Figure 1.** Main components of a variable rate spraying system (spray rate controller, computer and software, GPS receiver, and control valve). Source: adapted from Grisso et al. [7].

Parameter	Map based	Sensor based
Methodology	Grid sampling—lab analyses—site-specific maps and the use of variable rate applicator	Real-time sensors—feedback control measures and the use of variable rate applicator
GPS/DGPS	Very much required	Not necessary
Laboratory analysis (plant and soil)	Required	Not required
Mapping	Required	May not required
Time consumption	More	Less
Limitations	Cost of soil testis and analysis limit the usage	Lack of sufficient sensors for getting crop and soil information
Operation	Difficult	Easy
Skills	Required	Required
Sampling unit	2 to 3 acres	Individual spot
Relevance	Popular in developing countries	Popular in developed countries

Source: Ahmad and Mahdi [10].

**Table 1.** Comparison of the application in varied rate based on maps and sensors.

2.1 Map-based variable rate application (VRA)

Application maps of specific areas are generated by analyzing previous georeferenced samples of soil or plants of the area to be managed. Due to the need to collect many samples to create a representative map of the area, the costs of analysis tend to increase with this method and need more time to get ready. The map-based system is highly dependent on GPS and differential global positioning system (DGPS), as it is necessary to cross-reference the coordinates of the samples collected with the

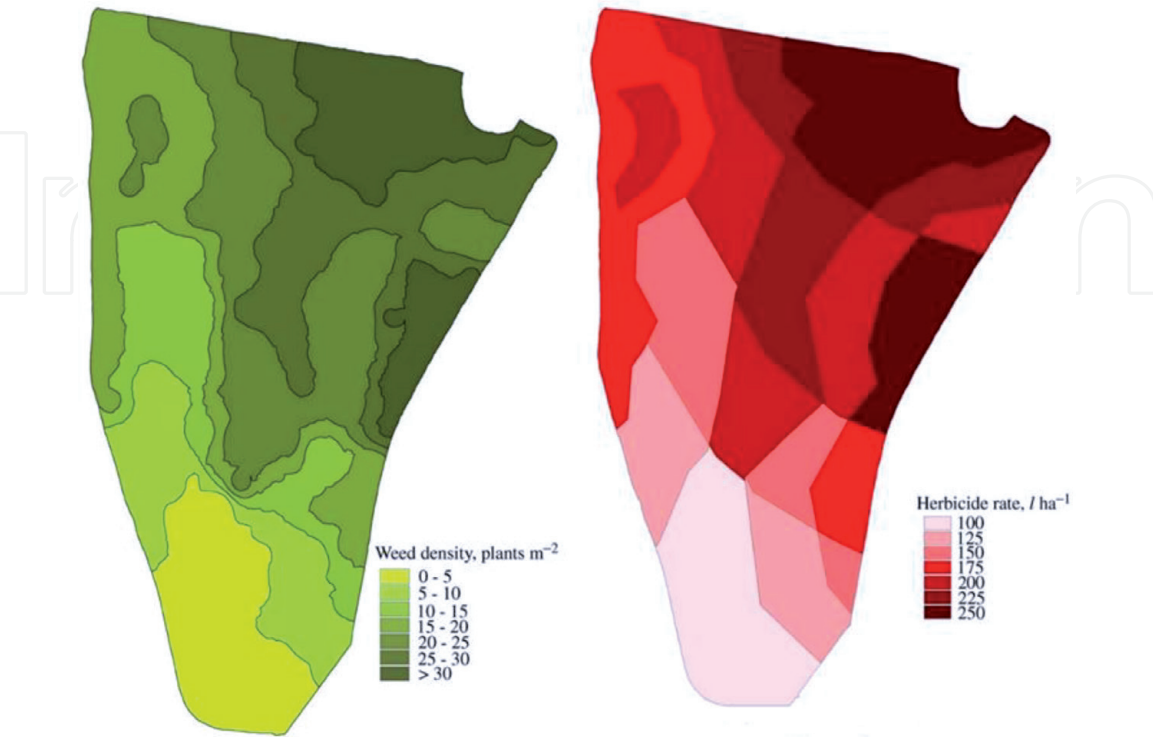
coordinate occupied by the machinery at the time of application. Thus, the operational difficulty of map-based systems is greater.

Although it has some disadvantages referring to operating costs and complexity, the map method is very efficient when used correctly and with accurate equipment. **Figure 2** shows a mapping of weed distribution in a given area and correlated with the required amount of herbicide needed to control weeds according to their density. The result of this crossing of information is a varied rate application map. In the area, there were infestations ranging from 0 to >30 plants m<sup>-2</sup>; so, it is not necessary to apply the same dose at all levels of infestations [11]. Areas with higher infestation will receive more herbicide than areas with low infestation. In the specific case, the volume of syrup varies from 100 to 250 L ha<sup>-1</sup>, which corresponds to a variation of 150%. If the volume of syrup was kept constant, there would certainly be herbicide wasting due to excess or lack in certain places. In the example of **Figure 2**, the VRA allowed uniform yield of the crop that was implanted, reduced environmental impacts, and provided savings of 29% in the amount of herbicide.

2.2 Sensor-based variable rate application (VRA)

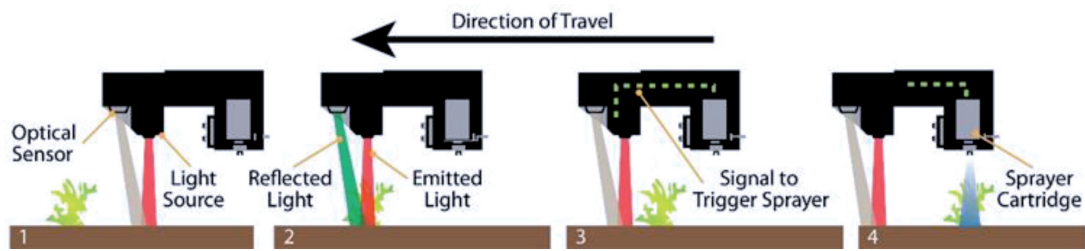
Data collection of weed presence and processing in sensor-based VRA are made fractions of seconds before herbicide application, avoiding the need to generate a previous map of the area. Sensor-based systems have the ability to vary application rate without any mapping or prior data collection. Sensors measure in real time the desired properties while they are in motion. The measurements made by the system are processed immediately and sent to the controller who will perform the application at a varied rate.

The use of sensors does not necessarily require the use of a positioning system, map generation, or extensive data analysis before making the VRA. Thus, it is an easier-to-use system, consumes less time, and has greater accuracy when compared to the map-based method. Its current limitation is related to the state of



**Figure 2.** Weed density map (left) and variable rate application (VRA) of herbicide (right). Source: Carrara et al. [11].





**Figure 3.**  
 Acting of an optical sensor in the control of spray nozzles. Source: Grisso et al. [7].

the development of sensors and algorithms with sufficient accuracy to collect and process more detailed information of plants and soil.

In **Figure 3**, there is an example of this type of method, where an optical sensor along with an infrared light source is implanted in the machinery spray bar. This set will be responsible for identifying weeds in the field by reflecting the green color of the leaves and indicating to the controller which sites will be necessary to carry out herbicide application.

### 3. Variable rate application (VRA) in preemergence (PRE)

The objective of an herbicide application in preemergency is to manage weeds that have not yet germinated, and the herbicide application is made directly in the soil so that as soon as the seeds/propagules germinate, they can absorb the herbicide. But for this to occur, the herbicide must be bioavailable in the soil solution. The application of herbicides in PRE follows different destinations due to the herbicide-soil interactions regulated by physical, chemical, and biological processes [12].

The efficiency of chemical control is associated with several factors that will determine whether the herbicides will be in the soil solution, thus being absorbed by the vegetables; leached, including groundwater; transported by the process of erosion or runoff; and volatilized [13]. In addition, they can be sorbed by soil colloids, thus becoming unavailable to plants.

The variability of soil properties can cause a differential sorption of herbicides, which, in turn, reflects on the different availability of the herbicide in the soil solution, and may generate variation in weed control [14, 15], especially in large cultivated areas where herbicide application is made in a single dose. Thus, the VRA for herbicides in PRE should obtain the main data related to herbicide retention and availability in the soil solution in order to have the correct deposition of the product.

Herbicide sorption is dependent on the interaction of the molecules of the product with the soil, and the process is influenced by the management and climate, mainly soil temperature and humidity. The main physicochemical characteristics of the soil that affect herbicide sorption are organic matter (OM), texture, pH, and cation exchange capacity (CEC). Regarding the herbicide physicochemical characteristics, water solubility ( $S_w$ ), acid/base dissociation constant ( $pK_a/pK_b$ ), octanol-water coefficient ( $K_{ow}$ ) half-life degradation time ( $DT_{50}$ ), and mainly sorption/desorption coefficient ( $K_d$ ) [10].

Each herbicide will have a type of behavior in different soil classes. Therefore, to perform VRA in PRE, a previous study of sorption and desorption of the herbicide molecule in the soil type of interest is necessary for the VRA to be efficient. Currently, the technique for sorption and desorption studies of herbicides most

used and mentioned in the literature is liquid or gas chromatography. The chromatographic technique can identify individual compounds quantitatively and qualitatively even at small concentrations, being very useful to identify herbicide concentrations in a solution. However, sorption and desorption studies can also be performed with radioisotopes ( $^{14}\text{C}$  and  $^3\text{H}$ ), in addition to bioassay with plant species sensitive to herbicide [16–18].

Data on soil characteristics are difficult to obtain with sensors in the field; so, most methods for applying herbicides in PRE are based on the generation of maps from laboratory analyses of soil samples. From soil information and herbicide sorption and desorption, a map is interpolated with application information at varying rate [10].

A study of sorption and desorption of the herbicide cyanazine was carried out in different soils (**Table 2**). From this study, the herbicide application was recommended based on soil texture and OM content. Herbicide doses increase as clay and OM contents increases.

Thus, for the application of PRE, herbicide is necessary to analyze the soil’s physicochemical properties to interpolate the VRA map. **Figure 4** contains the VRA map in which the different colors represent doses of herbicide to be applied. In this study [15], the use of VRA in PRE decreased the total amount of herbicide by 13%. In addition to the herbicide economy, it should be considered that other benefits are obtained such as better efficiency in weed control, which can help in an increase in productivity, in addition to reducing environmental risks.

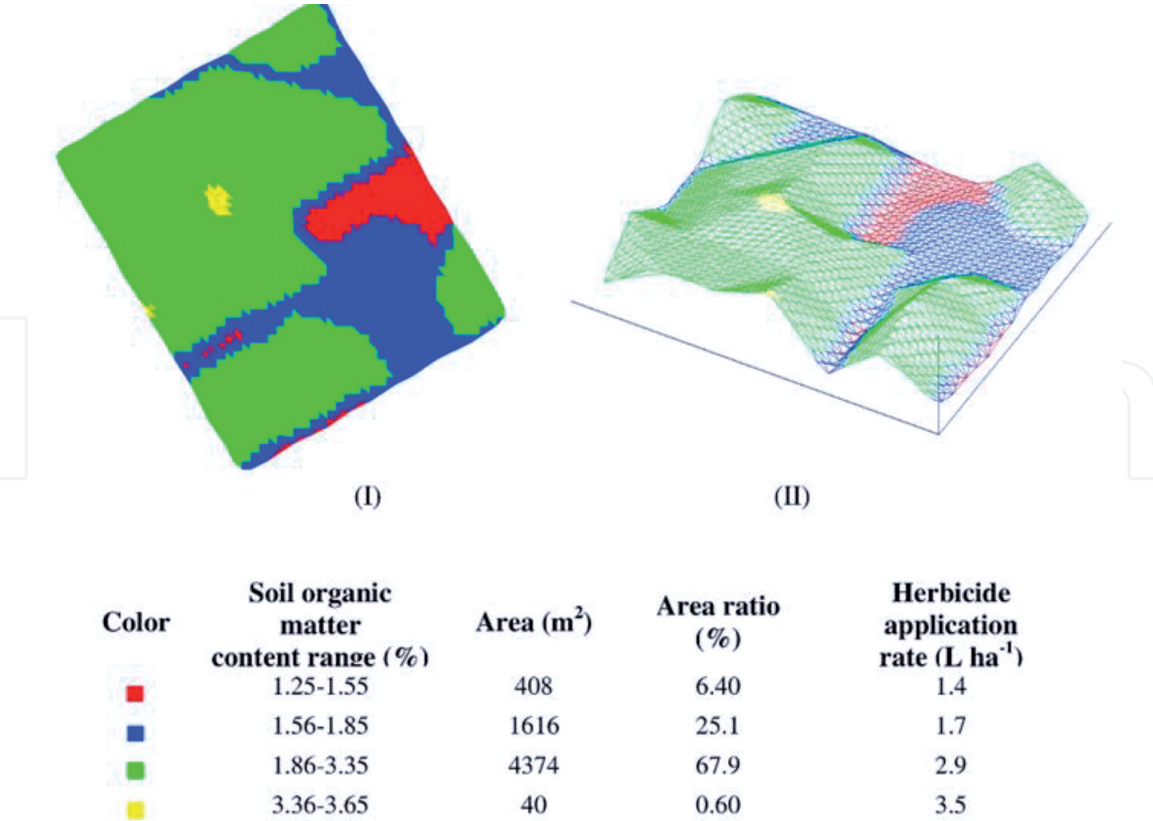
Laboratory analyses of soil characteristics are very efficient and accurate. The major disadvantage is the high costs of soil analysis, compromising its use for very large areas. An alternative to map the soil characteristics responsible for herbicide retention and availability without the need for labor collection and analysis is the use of electrical conductivity sensors in the field. The mapping of electrical conductivity with the aid of GPS is a simple tool, which is used to estimate soil texture, in addition to other properties [19]. This quantification considers the clay and ion contents in the soil, resulting in significant correlations [20].

An example of a sensor used to measure electrical conductivity is the VARIS 3100 platform (**Figure 5**). The operation of the equipment consists in the emission of an electric current by two intermediate discs, while two internal discs and two external discs detect the potential difference, which occurs in the electromagnetic field generated in the soil resulting from the applied electric current [21]. The spacing between the discs is calculated so that values of electrical conductivity are measured at depths of 0–0.30 m and 0–0.90 m. Data obtained in the field can be

Soil texture	Soil organic matter content (%)					
	<1.0	1.0	2.0	3.0	4.0	≤5.0
Sand	0.60	0.75	1.25	1.50	1.75	2.00
Sandy loam	0.75	1.25	1.50	1.75	2.00	2.25
Loam, silty loam, silt	1.25	1.50	1.75	2.00	2.25	2.50
Sand clay loam, clay loam, and silty clay loam	1.50	1.75	2.00	2.25	2.50	2.75
Sandy clay, silty clay, and clay	1.75	2.00	2.25	2.50	3.75	3.00
Peat or muck	Not recommended					

Source: Mohammadzamani et al. [15].

**Table 2.**  
Recommendation of doses of cyanazine ( $\text{L ha}^{-1}$ ) according to the texture and organic matter content of the soil.



**Figure 4.**  
Two-dimensional (I) and three-dimensional (II) maps for variable rate application (VRA) of cyanazine.  
Source: Mohammadzamani et al. [15].



**Figure 5.**  
Veris Platform® 3100 to measure the electrical conductivity of the soil. ESALQ/USP, Piracicaba, SP, Brazil.

visualized, recorded, and exported, since the sensor has a data logger. Data collection occurs with moving equipment, coupled to a tractor and the whole process can be georeferenced by a global navigation satellite system (GNSS) receiver. According to the manufacturer’s instructions, two tests must be performed to confirm the correct calibration of the equipment. After data collection, the electrical conductivity is correlated with the clay content for the generation of a textural map.

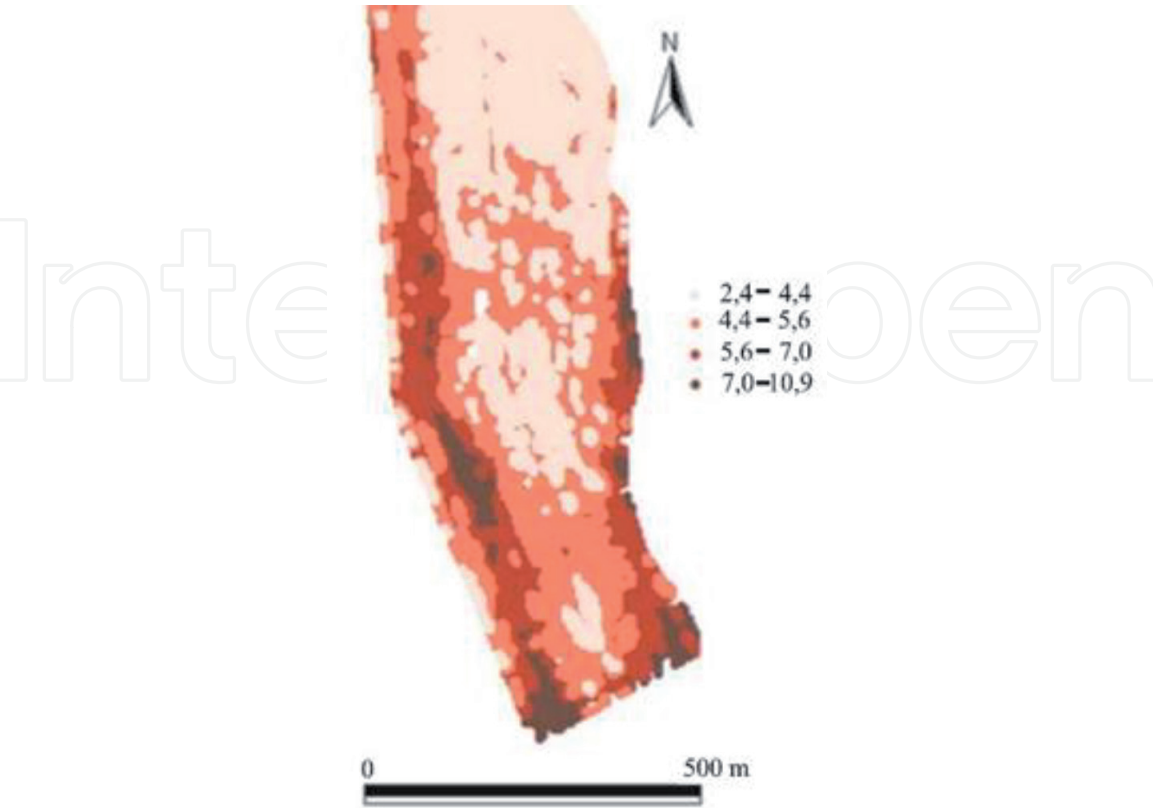


Studies show that the electrical conductivity measured by contact sensor adequately reflects the variation in clay contents of the studied soil, being efficient to generate soil texture maps, including in no-tillage areas [21]. **Figure 6** shows a conductivity map elaborated with the data collected in VARIS 3100; the lowest conductivity values correlated with lower clay contents. However, for high clay contents, the model was less efficient. Thus, the mapping of electrical conductivity can be a useful tool in the design of more homogeneous areas, which present more similar soil conditions.

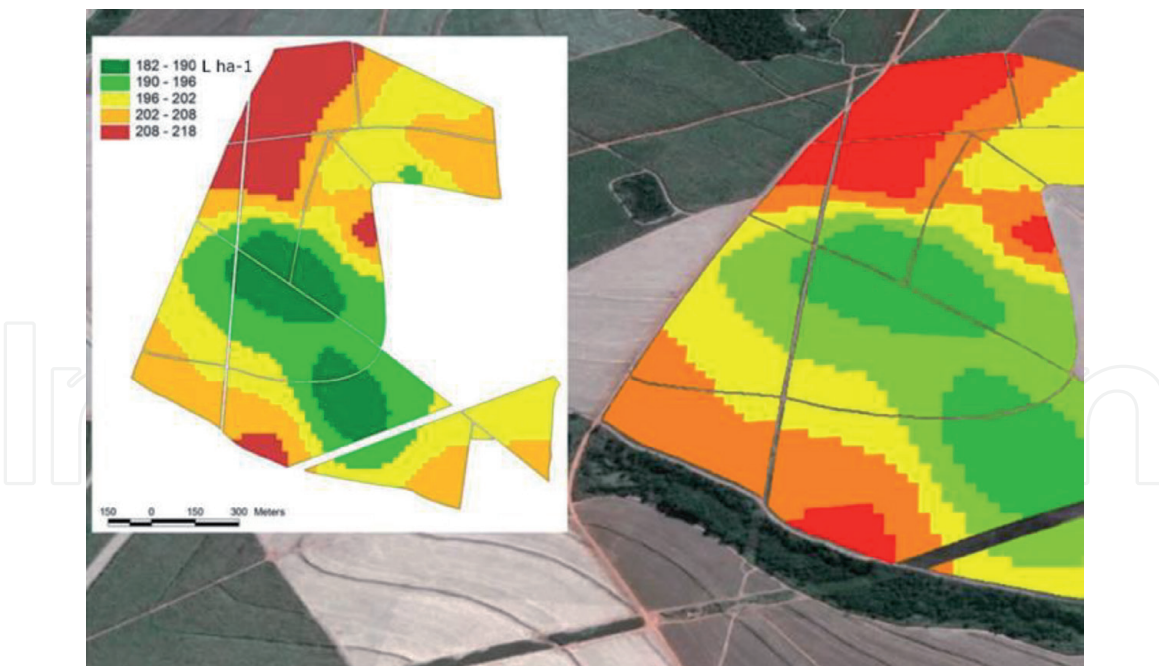
Considering that other factors such as moisture, salt concentration, and total carbon remain in the same conditions, soils with higher clay contents conduct more electricity than those with sandier texture. However, these factors may vary and affect the correlation between electrical conductivity and soil texture. Therefore, as the electrical conductivity method does not quantify the CEC and soil OM contents, the use of the same may have reduced efficiency in some situations.

There are companies on the market that provide the VRA service for herbicides in PRE, one of which is APagri which has the HTV® method which consists of a process developed and patented for the application of herbicides in PRE at the varied rate based on maps (**Figure 7**), that considers the clay, OM, and CEC content of the soil [22]. The objective is to adjust the dose according to the soil ability to retain each type of herbicide so that the final concentration in the soil solution is equal regardless of the position in space.

Due to technological limitations, there is still no VRA available on the market for PRE herbicides based on sensors that read, process, and apply the herbicide without the need for the generation of maps. One of the great challenges of this market is precisely to eliminate this stage, in view of the costs of generating the maps.



**Figure 6.**  
*Interpolated map of electrical conductivity measured with mobile contact measurement equipment. Source: Machado et al. [21].*



**Figure 7.**  
*Variable rate application (VRA) map drawn up with the system HTV®. Source: APagri [22].*

#### 4. Variable rate application (VRA) in postemergence (POST)

The purpose of a POST application is to control weeds that have already emerged in the field. Thus, the target of the application is the aerial part of the plant species. For the VRA to be used in POST, it is necessary that the system has information about the weed population in the area. This information can be collected by the map-based and sensor-based systems. Therefore, both methods can be used VRA in POST.

##### 4.1 Map based: weed mapping

The literature mentions several methodologies for weed mapping, where each one has its specificity. Some have processing algorithms to differentiate monocot and eudicot plants [23]. Others use machine learning with deep neural network to identify weeds [24, 25]. However, all have the principle based on the quantitative and qualitative identification of the infested area, generation of the recommendation map, and integration with the VRA system.

Remote sensing is generally considered one of the most important technologies for precision agriculture. This technology can be used in weed mapping. Remote sensing can monitor many crops and vegetation parameters through images at various wavelengths. Images can be acquired by satellites, manned aircrafts, or unmanned aerial vehicles (UAV). However, satellite imagery is often not the best option because of the low spatial resolution of images acquired and the restrictions of the temporal resolutions as satellites are not always available to capture the necessary images [26]. Considering the use of manned aircrafts, usually it results in high costs, and many times, it is not possible to carry out multiple flights to obtain more than a few crop images. UAVs' ability to fly at a low altitude results in ultra-high spatial resolution images of the crops (i.e., a few centimeters). This significantly improves the performance of the monitoring systems. Furthermore, UAV-based monitoring systems have high temporal resolution as they can be used at the user's will. This enhances the flexibility of the image acquisition process [27]. In addition, UAVs are a lot simpler to use and also cheaper than manned aircrafts. Moreover,

they are more efficient than the ground systems as they can cover a large field in a short amount of time and in a non-destructive way, which is very important. UAVs can gather images and derive data from the whole field that can be used to generate a precise weed cover map depicting the spots where the herbicide are needed in different rates [28].

A variety of different types of sensors can be used in an agricultural UAV depending on the different vegetation parameters that should be monitored. The main sensors used that meet the limitations mentioned above are: visible light sensors, red, green, and blue (RGB) color model, multispectral sensors, hyperspectral sensors, and thermal sensors. RGB are relatively low cost compared to the other types and can acquire high resolution images, are easy to use and operate, and are lightweight [29]. In addition, the information acquired requires simple processing. However, they are inadequate for analyzing a lot of vegetation parameters that require spectral information in the non-visible spectrum. Thus, commonly are used with the other types of sensors.

Multispectral or hyperspectral imaging sensors can acquire information about the vegetation's spectral absorption and reflection on several bands. Spectral information can be significantly helpful in assessing a lot of biological and physical characteristics of the plants. This information is important to determinate which weed species are in the field [30]. Multispectral and hyperspectral sensors are frequently used, despite their higher costs. However, a drawback of these sensors arises from the fact that it is required to apply more complex preprocessing methods in order to extract useful information from the captured images. The preprocessing procedure of spectral images often contains the radiometric calibration, geometric correction, image fusion, and image enhancement. The main difference between multispectral and hyperspectral sensors is the number of bands (or channels) that each sensor can capture and the width of the bands. Multispectral sensors capture 5–12 channels, while hyperspectral images can usually capture hundreds or thousands of bands, but in a narrower bandwidth. Multispectral sensors are used much more frequently than hyperspectral sensors due to their lower cost, but hyperspectral technology appears to have a lot of potential and is considered the future trend for crop phenotyping research. Thermal infrared sensors capture information about the temperature of the objects and generate images displaying them based on this information and not their visible properties. This type of sensors is used for very specific applications (irrigation management). As a result, they are not frequently used in remotely piloted aircraft applications of UAV systems that focus on monitoring other characteristics of the crops [26–28].

UAVs can acquire information for various features of the cultivated field by using specialized sensors. However, as mentioned above, there is still no standardized workflow or well-established techniques to analyze and visualize the information acquired. The most commonly used image processing methods to analyze UAV imagery for weed mapping are photogrammetry and machine learning. Photogrammetry regards the accurate reconstruction of a scene or an object from several overlapping pictures. Photogrammetric techniques are very commonly used in all types of applications as they are also required to create vegetation indices maps. However, photogrammetric techniques are in most cases used to compliment other types of data processing methods [29].

Machine learning is used to process the data acquired, for prediction and/or identification purposes, with great results in many domains. Machine learning techniques are often applied in precision agriculture to exploit the information from the large amount of data acquired by the UAVs. Machine learning is able to estimate some parameters regarding the crop growth rate, detect diseases, or even identify/discriminate objects in the images [30].



The most promising technique for weed mapping is machine learning, especially those based on object-based image analysis (OBIA). Weed detection with UAVs based on object-based image analysis appears to be at an advanced stage and can be used for specific weed management.

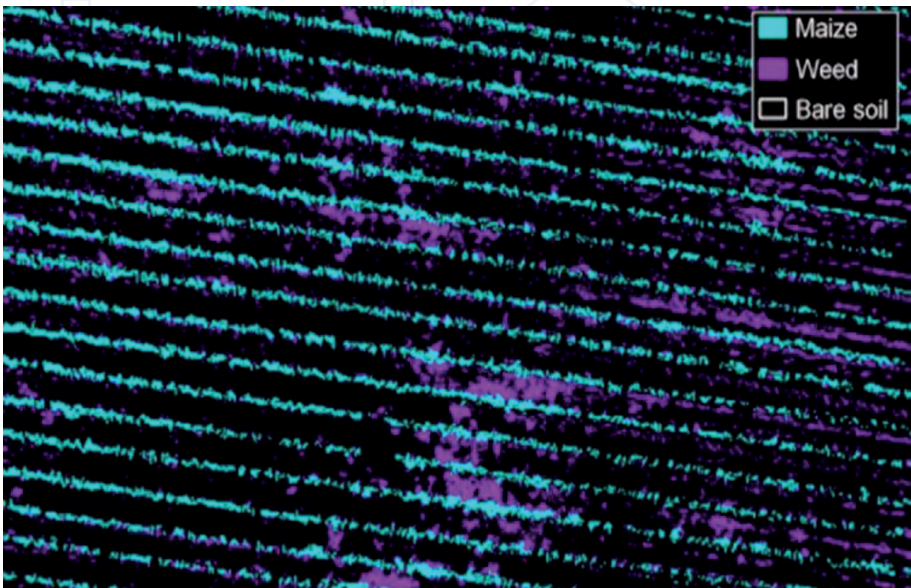
In an example of weed mapping performed on corn, an UAV coupled with a six-band multispectral camera (visible and near infrared range) was used to map the area (**Figure 8**).

After mapping, an OBIA procedure processes the data and generates a classification of weed, crop, and bare soil (**Figure 9**).

The identification and delimitation of the weeds allows generating maps showing the infestation level (**Figure 10**). The information of this map can be integrated into VRA system and used for POST herbicide application. In this study, weed-free areas corresponded to 23% and areas with low infestation (<5% of weeds) to 47% of the total, indicating a high potential to reduce herbicide application [31].

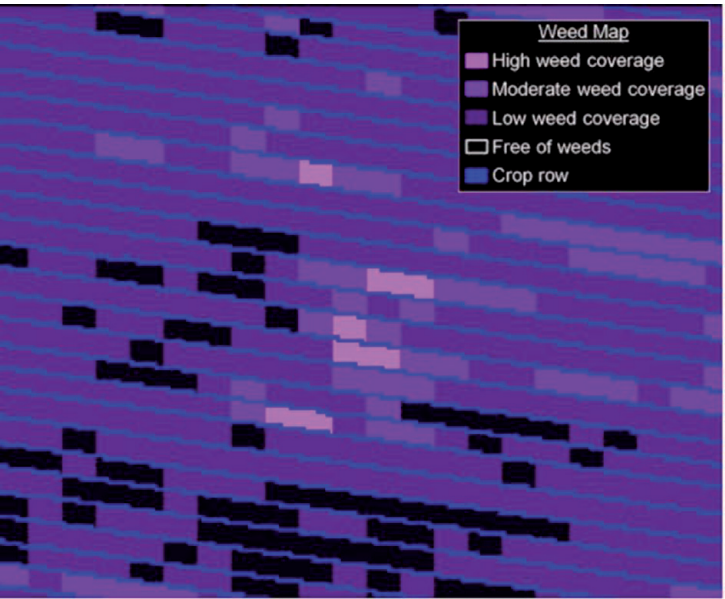


**Figure 8.**  
*Unmanned aerial vehicle (UAV) used for weed mapping. Source: Peña [31].*



**Figure 9.**  
*Partial view of the outputs of the object-based image analysis (OBIA) procedure: classified image with crop, weeds, and bare soil. Source: Peña [31].*





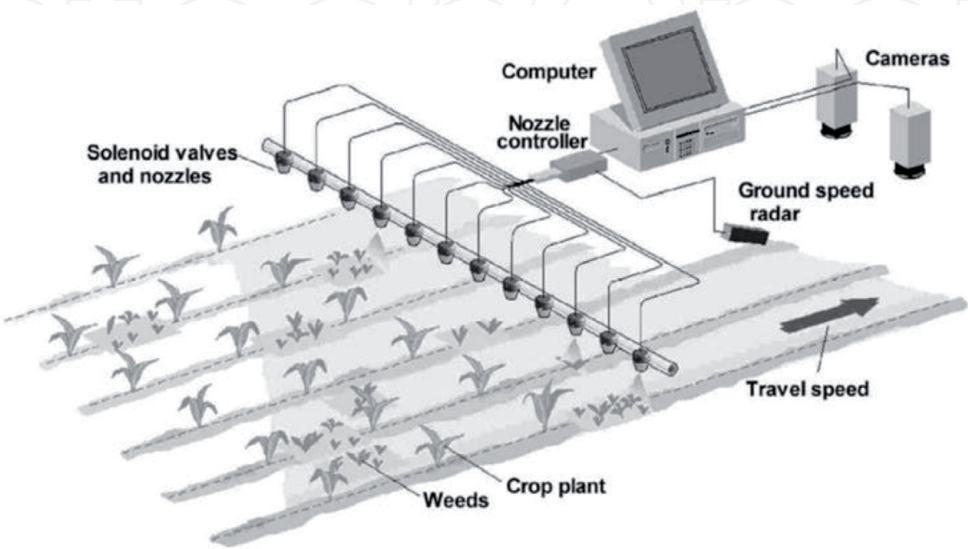
**Figure 10.** Partial view of the outputs of the OBIA procedure: weed coverage map showing three levels of infestation (low, moderate, and high), crop rows, and weed-free zones. Source: Peña [31].

When data collection and map generation is done for POST herbicide application, the whole process must be done as quickly as possible because in a few days, the weed dynamics can be changed and infestation levels can increase, making the recommendation map obsolete.

4.2 Sensor based: real time

When applying POST herbicides using a real-time based sensor method, there is no need of a prior area mapping. Spraying is based on sensors attached to the sprayer responsible for detecting weeds and applying the herbicide dose. In **Figure 11**, there is a basic model for this application type.

In real-time-based sensor method, the optical sensor collects data that are immediately processed by the computer, where the locations and doses to be applied are determined. This information is sent as a command to a nozzle controller.



**Figure 11.** Sensor-based VRA model for POST herbicide application. The system includes a multiple-camera vision system, a ground speed sensor, and nozzle controller. Source: Tian [32].

In the spray boom, each nozzle is opened or closed by a solenoid valve connected to the controller, so that the nozzle controller can vary the flow applied or the total opening and closing of each nozzle. The presence of a GPS system is not essential for the operation of system, but it does provide guidance to the machinery operator and is useful for recording sprayed areas. The database can be used to improve weed control in the following years, especially for perennial species that reproduce vegetatively, in view of their stability in spatial distribution [33].

Depending on the model, the system components can vary in several characteristics. Optical sensors can be multispectral or infrared. The software can be composed from algorithms that can only identify green plants to deep neural networks that have the ability to learn to differentiate weed species. The controller can only open or close a spray nozzle or it can even coordinate the herbicide mixture and control the alternating flow of dozens of nozzles. The variations are huge, and the more research evolves, the greater the accuracy and reliability of the VRA [7, 32, 33].

Commercially, some companies have consolidated in recent years with VRA systems for application in POST with sensor methods based on real time. Among the most widespread are Weed-it and WeedSeeker.

#### 4.2.1 WEED-IT

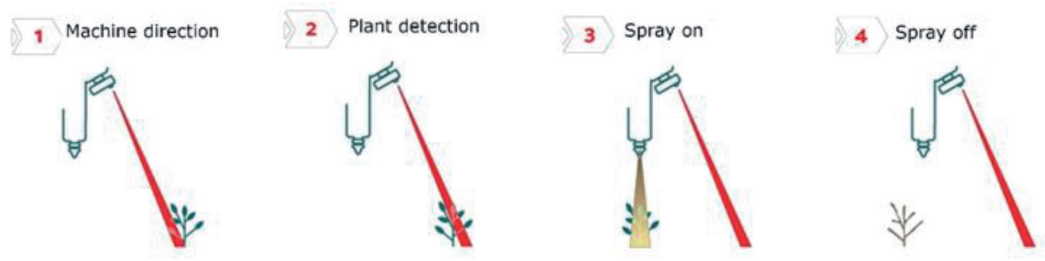
WEED-IT is a high-performance localized spraying system, formed by chlorophyll detection sensors and extremely fast valves to guarantee application only where necessary (**Figure 12**). The system is based on the principle of chlorophyll fluorescence: a light source in the set of sensors emits a constant beam of infrared light that is absorbed by the plants chlorophyll and re-emits near infrared light (NIR). This emission is detected by the sensors by performing 40,000 readings per second and capture even the lowest chlorophyll fluorescence emissions activating the nozzle set only on the identified weeds, applying only what is necessary, according to the size of the plant (**Figure 13**) [34].

The system can be installed in self-propelled and trailed sprayers, operating at speeds of up to  $25 \text{ km h}^{-1}$ . In the spray bar, each sensor is responsible for covering 1 m in width and independently activating up to five nozzles with an opening time of 1 ms. Its valves have a system for modulating the width of the energy pulses that generate extremely rapid interruptions in the spray nozzle outlet; the greater the number of interruptions, the lower the applied dose (**Figure 14**) [34].

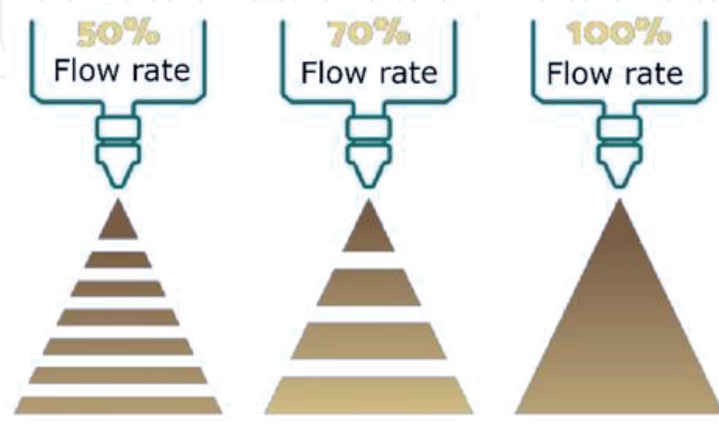
In curves or maneuvers, the speed on the outside of the bar is greater than the inside; the system is able to correct the flow along the bar to apply equal amounts of herbicide even in curves or with speed variations (**Figure 15**).



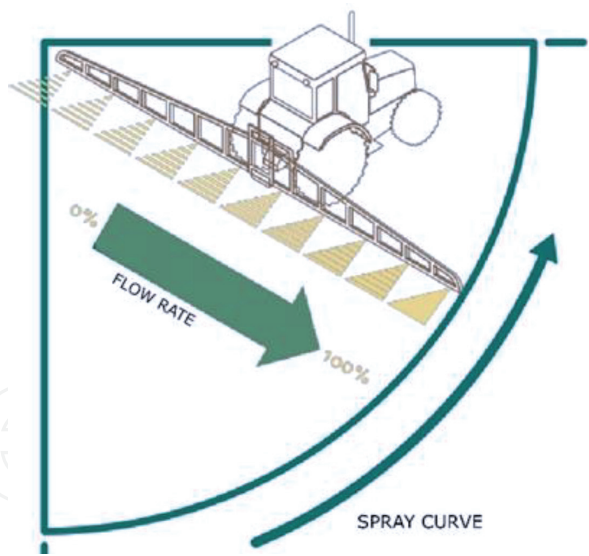
**Figure 12.**  
*WEED-IT performing application with weed detection by infrared sensors. Source: SmartSensing [34].*



**Figure 13.**  
*WEED-IT operating system. Source: SmartSensing [34].*



**Figure 14.**  
*WEED-IT valve system modulation. Source: SmartSensing [34].*



**Figure 15.**  
*Differential flow compensation system. Source: SmartSensing [34].*

The system has an important limitation. As the sensor is based only on the chlorophyll fluorescence, the system is not able to differentiate the crop and weeds, both are interpreted as living plants. Therefore, it is necessary to be careful with the application of nonselective herbicides in POST, as the crop will certainly be sprayed together with weeds.

4.2.2 WeedSeeker

The WeedSeeker is another widely used commercial system that has the same WEED-IT operate principle, where a sensor emits red and near infrared light and a

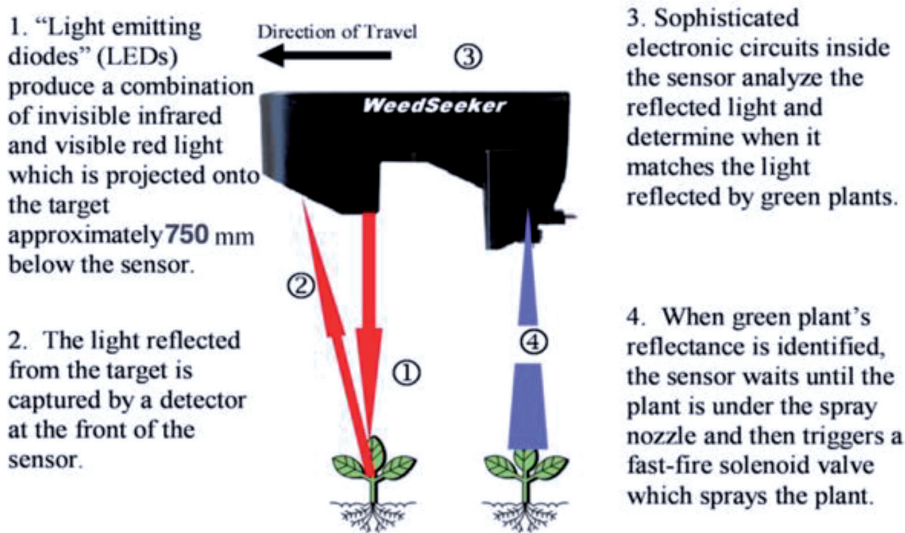


photodiode detects the intensity of the reflected light (**Figure 16**). Afterward, the reading is converted into a command to apply or not the herbicide (**Figure 17**) [35].

The system can be operated at speeds of 20 km h<sup>-1</sup> installed in trailed and self-propelled sprayers. Nozzles are opened by solenoid valves connected to a central controller. The sensor spacing is 38 cm, and each sensor controls one spray nozzle. Although WEED-IT and WeedSeeker have many similarities, some aspects differentiate the two systems. The WeedSeeker requires a prior calibration of the sensors in order for the system to operate correctly, while the WEED-IT does not require any calibration [35].

As both systems have own light source, they can perform applications at night. Both are highly efficient systems that fulfill your proposals well. There are few studies that compare two systems. In a study focused on methods of comparing commercial precision spraying technology, the authors compared the efficiency and precision of WEED-IT and WeedSeeker and however, this comparison was only undertaken with a 0.16 ha<sup>-1</sup>. In this way, WEED-IT can be more efficient for identifying newly emerged plants [35].

### How a WeedSeeker® sensor works



**Figure 16.**  
*How a WeedSeeker sensor works. Source: Trimble Agriculture [35].*



**Figure 17.**  
*WeedSeeker spray nozzles applying herbicide only to weeds. Source: Trimble Agriculture [35].*



### **4.3 Robots for variable rate application (VRA) in postemergence (POST)**

Use of autonomous agricultural robots has an interesting potential as a valuable technological tool for precision agriculture, bringing the advantage of being able to make use of the various theories in robotic control, already grounded and consolidated for applications in several other areas [36]. The main characteristic that differentiates an agricultural robot from a simple machine or implement is the freedom degree and autonomy possessed by the robot, including the need for human operation. As agricultural robots must have a high degree of autonomy, tools are necessary so that they can distinguish targets and culture in the field, as well as to orient themselves spatially during movement. The way the distinction is made is through sensors. The main sensors used are GPS real-time kinematic (RTK), cameras, gyroscope, strobe, and proximity [36–38].

The recent trend in the development of mobile robots and autonomous vehicles to perform specific tasks is mainly guided by improving efficiency and leading to operating gains (reduces soil compaction, absence of operator) when compared to the use of large machines [39]. Although much smaller than conventional agricultural machines, they can act cooperatively and perform tasks such as spraying pesticides that pose risks to humans [40]. Sprayers coupled to robots can direct spray nozzles to weeds through a computer vision system. Some models use photovoltaic plates to take advantage of solar energy and reduce or eliminate fossil fuel consumption. With all the advantages related to the autonomy and efficiency of agricultural robots, the farmer can direct his time and efforts toward other agricultural activities such as negotiating sales contracts and making investment decisions.

Robots provide precision spraying, realizing the collection of weed position and incidence information in real time and transmitting them to an atomizer or sprayer that regulates the need for more or less herbicide. Despite having many advantages, the use of robots still has points to be improved, among them are the following:

- a. Low autonomy compared to conventional machinery
- b. Operational limitations in adverse field conditions
- c. State of technological development

The current limitations present in agricultural robots are being resolved with the evolution of the available technology, since the optimization of sensors and algorithms occurs constantly, while in a few years, these limitations can be overcome. Artificial intelligence used in agricultural robots is a way of recognizing patterns so that the computer can identify weeds, pests, disease symptoms, nutritional deficiency, degree of maturation, and cut-off point in the harvest, among others. In a simplified way, artificial intelligence consists of providing the machine with as many examples of situations and decisions as possible, whether historical or simulated based on existing knowledge, so that when faced with similar circumstances, it can make a decision [37, 38]. There are several examples of robots currently used in VRA, two of which are described below.

#### *4.3.1 Robot for Intelligent Perception and Precision Application (RIPPA)*

The Robot for Intelligent Perception and Precision Application (RIPPA) is an autonomous system developed by the University of Sydney for detecting weeds and applying herbicides in microdoses (**Figure 18**) [41].



**Figure 18.**  
*RIPPA robot model. Source: Sukkarieh [42].*

The system has infrared and monochromatic sensors working with neural networks that make it possible to differentiate between crop and weed. In this way, the application and efficiency of the system are much more accurate. Due to its small size and high precision, the system is suitable for smaller areas, such as horticulture. The RIPPA is powered by solar energy through solar panels on the top of the machine. The system also has a sensor for collecting moisture and soil temperature, which makes data collection a little more complete, generating .XLS files so that the producer can create a database with information from his area. **Table 3** contains some additional information from RIPPA [41, 42].

4.3.2 *BoniRob*

With characteristics similar to RIPPA, BoniRob (**Figure 19**) was developed by the partnership between the companies BOSCH and AMAZONE, in Germany. It is slightly larger than RIPPA, but it is still smaller than a small car and is capable of applying localized pesticides, collecting soil samples, and analyzing to obtain real-time characteristics such as pH and phosphorus levels [43].

Specification description	Value
Track width	1.52 m
Max crop height	0.6 m (adjustable)
IP rating	IP65
Mass (no payload)	Approx. 275 kg
Max payload	100 kg at max operating grade (12°)
Charge-time from empty	> 2 hours (dependent on charger)
Idle discharge time (no solar)	43 hours
Driving discharge time	(0.5 m/s, no solar, no payload) 21.5 hours
Max area traversed per charge (no solar)	8 hectares (~10 hours at 1.6 m/s)

*Source: Sukkarieh [42].*

**Table 3.**  
*Specification description of RIPPA.*

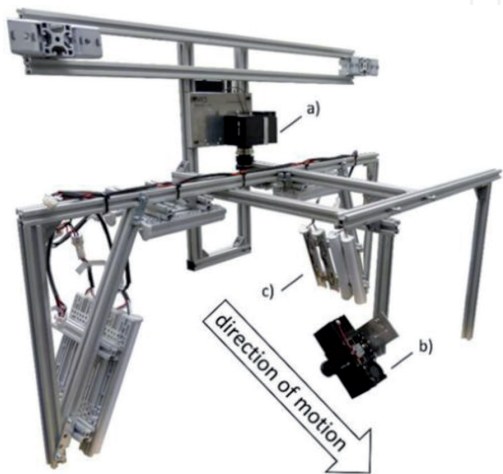


**Figure 19.**  
*BoniRob model. Source: Sellmann et al. [44].*

To ensure its operation, BoniRob has a set of cameras and sensors (**Figure 20**) that work as follows: camera “a” points to the top of the plant with the function of detecting and locating it; camera “b” is positioned to obtain a side view of the plants looking for overlapping plants. In “c,” we have a set of light-emitting diodes (LEDs) that are responsible for emitting red and infrared light to assist the cameras when capturing photos. There is also a third camera, which has a high frame rate and resolution (higher than cameras “a” and “b”) attached to the sensor responsible for spraying. This sensor, to maintain accuracy in capturing images and also during the application of pesticides, has a strobe that allows, even with variations in the terrain, the camera and the spray tip to remain in the desired position [44].

When it comes to artificial intelligence, based on the culture and species of plants you want to work with and control, machine learning takes place through the developed algorithm and is trained based on obtaining images (millions of them) that allow you to characterize the plants according to their shape, size, and color, among other parameters, allowing them to be recognized and distinguished in the face of a possible action such as spraying it or not [44].

As mentioned earlier, the versatility of agricultural robots is essential, since in the field, the conditions are highly heterogeneous. For this reason, many of these machines allow the installation of modules that perform different functions. In the case of BoniRob, we have a module for phenotypic recognition, a penetrometer, and a localized spraying mode already developed, but there are numerous other possibilities for adaptation and creation based on the particular characteristics to which the use of the machine is intended [44]. Other models of agricultural robots are being developed and gradually made available on the market. A good example is Ecorobotix (**Figure 21**), which applies microdoses of herbicide and



**Figure 20.**  
*BoniRob components. Source: Sellmann et al. [44].*



**Figure 21.**  
*Ecorobotix components. (1) Photovoltaic panels, (2) camera and artificial vision for steering and detection, (3) navigation by GPS and sensors, (4) electrical drive system, (5) rapid robotic arms with sprayers, and (6) tanks for two different products. Source: Ecorobotix [45].*

works completely autonomously. Its use is recommended after an initial standard application of herbicide, in order to replace subsequent applications and thus save an important amount of herbicide [45].

The market robots for herbicide application are still at the beginning of its development and consolidation, but it represents a new way of interacting with agriculture, revolutionizing the relationship between man and the field.

## 5. Variable rate controllers

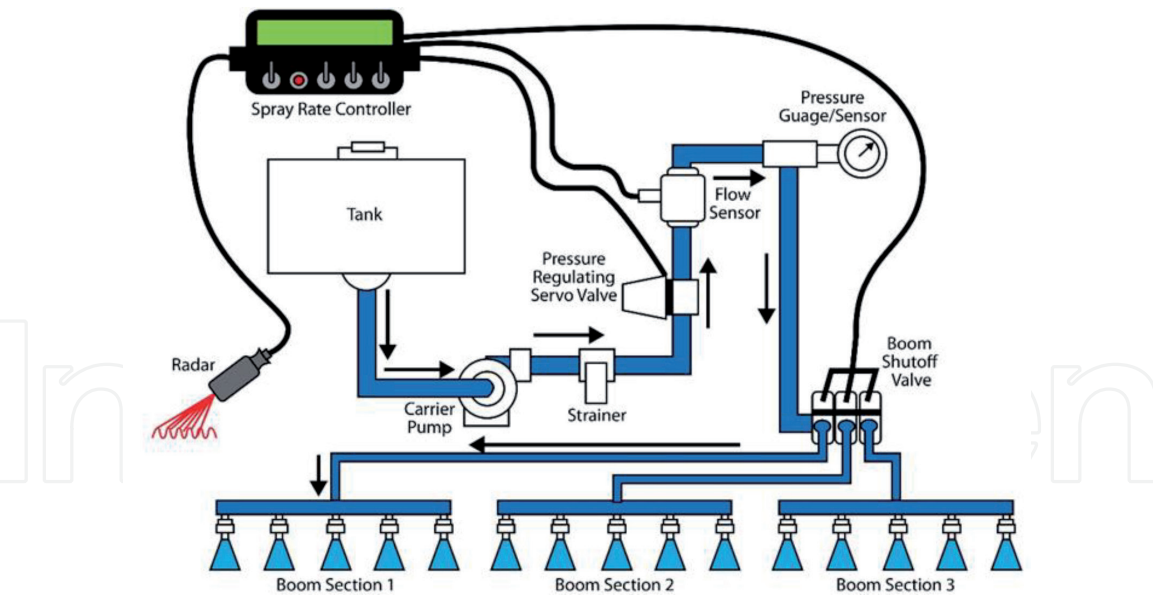
In order for the VRA to happen efficiently, it is necessary to have a high control in the spraying system responsible for the application of the herbicide. Controllers can act by modifying the pressure at the spray nozzles, or they can change the herbicide concentrations and the water flow in real time. Some of these systems are more complex, while others are simpler. The main controllers will be discussed below.

### 5.1 Flow-based control systems

In flow-based control system, only the flow and pressure are changed. There is no manipulation of the herbicide concentrations. The system has a flow meter, a speed sensor on the ground, and a servovalve with an electronic controller to apply the desired rate of the tank mixture (**Figure 22**). A microprocessor uses information about the width of the sprayer and the recommendation of the spray volume per hectare to calculate the flow rate appropriate for the current speed of the soil. The servovalve is opened or closed until equal amounts of herbicides are applied regardless of the speed of the machinery. If the controller can be integrated with a recommendation map system, a VRA can be done. These systems have the advantage of being reasonably simple. They are also able to make rate changes across the bar in 3 to 5 seconds [7, 46].

Depending on the speed, problems with drift can occur, as the flow sensor and servovalve control the flow of the tank mixture, allowing variable pressure rates to be delivered to the spray nozzles. Thus, high speeds can represent an increase in the pressure of the nozzles and a consequent decrease in the droplet spectrum.



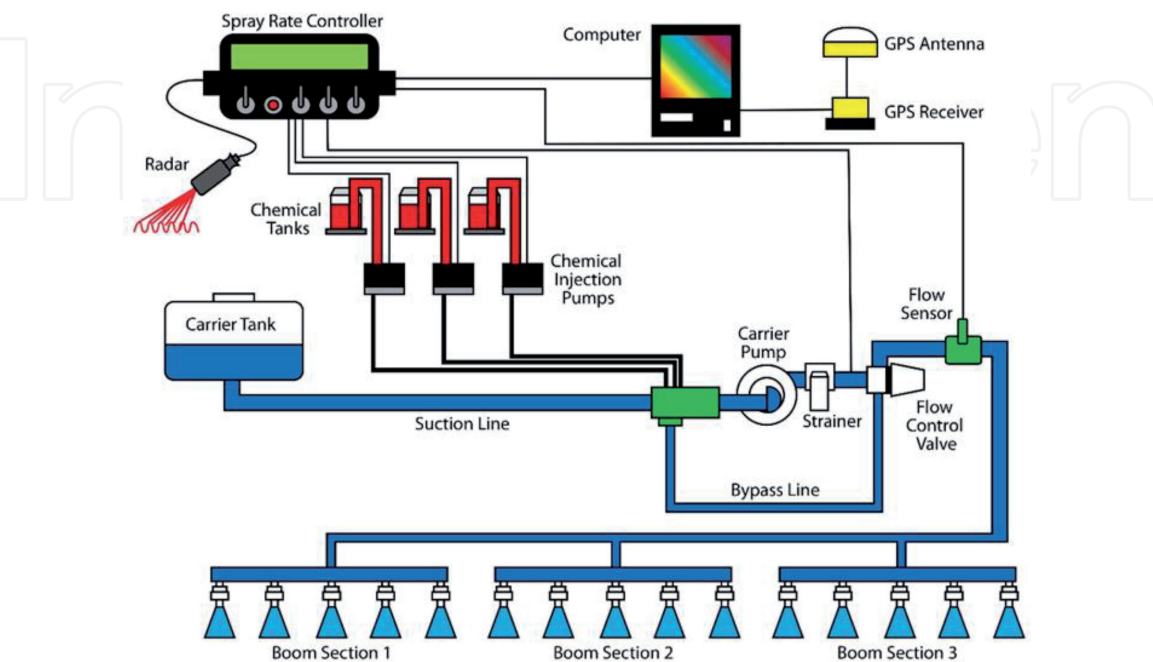


**Figure 22.**  
VRA spraying system that is a flow-based system of application rate. Source: Grisso et al. [7].

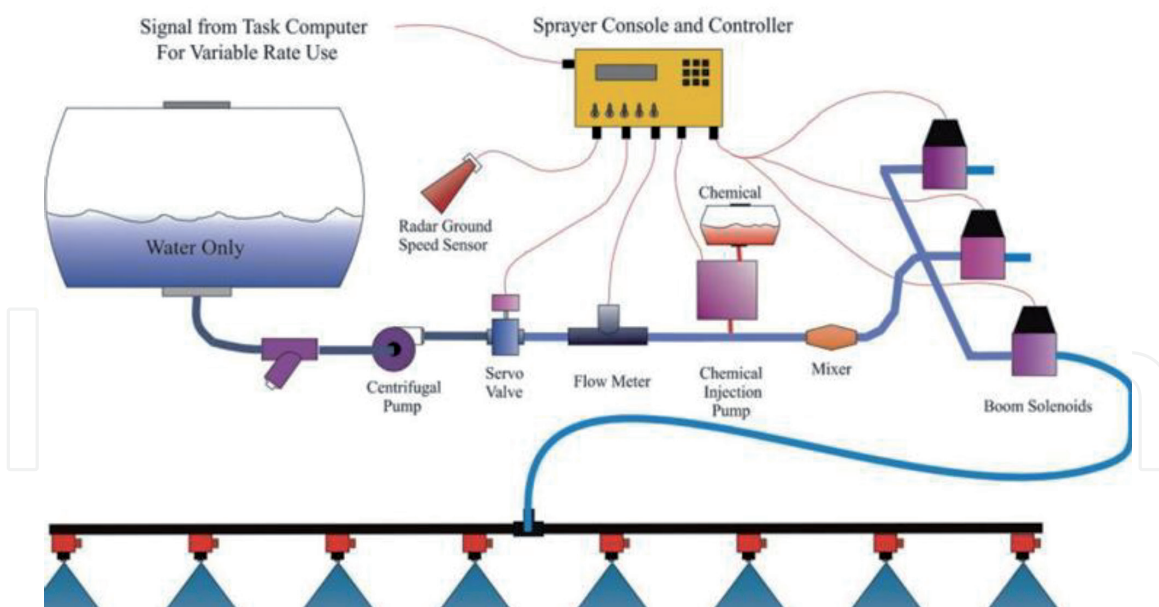
5.2 Chemical direct injection systems

In this system, the mixture is prepared with direct injection of the chemical in a flow of water. This system (**Figure 23**) uses a controller and a pump to manage the chemical injection rate instead of the flow rate of a tank mix [46]. The water flow rate is constant and the herbicide injection rate is varied to accommodate changes in soil speed or changes in the prescribed rate.

With the chemical injection, there is no leftover mixture and the direct contact of the operator with toxic products is reduced [10]. The system allows you to control the desired size and spectrum of droplets, since the variation of the application rate does not depend on the flow and pressure on the spray nozzles. Its main disadvantage is the long transport delay between the chemical injection pump and the discharge nozzles at the ends of the boom.



**Figure 23.**  
VRA spraying system that incorporates chemical injection technology. Source: Grisso et al. [7].



**Figure 24.**  
 A direct chemical injection system with carrier control. Source: Rashidi and Mohammadzamani [46].

### 5.3 Direct chemical injection with carrier control

In this system, there is control of the herbicide injection rate and water flow rate to respond to changes in speed or application rate. A control circuit manages the injection pump, while a second controller operates a servovalve to provide a corresponding water flow (**Figure 24**). Such a system provides a mixture of constant concentration. The system can have many of the advantages of the previous two systems. There is no leftover mixing; the operator is not exposed to chemicals in the tank mixing process; the variation from one rate to another occurs quickly. The disadvantages include related to the complex system, higher initial costs, problem in delivering variable rates of liquid through in the nozzle spray, and modulated spraying nozzle control systems [10, 46].

## 6. Conclusions

The variable rate application (VRA) of herbicides has great potential for use in agriculture because it allows better control of weeds at lower costs and reduction in the use of inputs and environmental contamination. The main techniques available are based on the generation of application maps and the use of sensors in real time to identify weed infestations, which can be used in the preemergence (PRE) and postemergence (POST) of weeds. Both modalities are equally important in integrated weed management. VRA systems still require relatively high investment, restricting their use. The constant improvement of the VRA should further increase its benefits and reduce the costs of adopting the system, allowing its use by more farmers. The use of precision agriculture in farming systems is a path of no return, in view of the conjuncture of food production needs and scarcity of natural resources. Thus, VRA tends to be used more and more frequently until possible complete replacement of the conventional way of using herbicides in agriculture.

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### **Author details**

Alessandro da Costa Lima and Kassio Ferreira Mendes\*  
Department of Agronomy, Federal University of Viçosa, Viçosa, MG, Brazil

\*Address all correspondence to: kfmendes@ufv.br

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