Sensor Sprayers for Specialty Crop Production

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Due to intense pressure from pests and diseases, specialty tree crops such as fruits, nuts, and ornamentals currently rely on regular applications of pesticides to produce marketable varieties. Many of the pesticide application technologies used today are based on air-assisted sprayers, also known as air-blast sprayers. These sprayers are versatile, reliable, and can be modified to fit many types of crops, all of which are reasons for their continued popularity.

But despite their popularity, air-blast sprayers have long had a reputation for inefficient application. These sprayers were first developed in the 1950s when orchard trees were commonly 20 feet (6 meters) tall or more; today, trees are typically 6.5 to 13 feet (2 to 4 meters) tall. Losses to the ground of 30% to 50% of spray and off-target drift from 10% to 20% are common for air-blast sprayers. Current trends such as limited labor and negative public opinion of pesticide use in agriculture have pressured farmers to improve the efficiency of pesticide applications.

Sensor-controlled spray systems were first designed in the 1980s as a way to reduce labor costs and pesticide waste. Sensor sprayers can help growers use fewer chemicals and less water while maintaining good pest control. Sensor-controlled spray systems are receiving renewed interest as their reliability has improved and more options have become available. This publication provides an overview of current sensor sprayer technology specifically for use in perennial crop systems, such as nurseries, orchards, and vineyards.

Types of sensor sprayers

There are three basic types of sensor sprayers (Figure 1):

1. Standard sprayers manually controlled with constant spray volume output.
2. Sensor sprayers that are actuated (on/off) by canopy presence and output a constant spray volume.
3. Canopy adapting sprayers for which the sensors actuate the spray (on/off) and actively modulate sprayer outputs (for example, spray volume and air flow) in real time according to crop canopy characteristics.

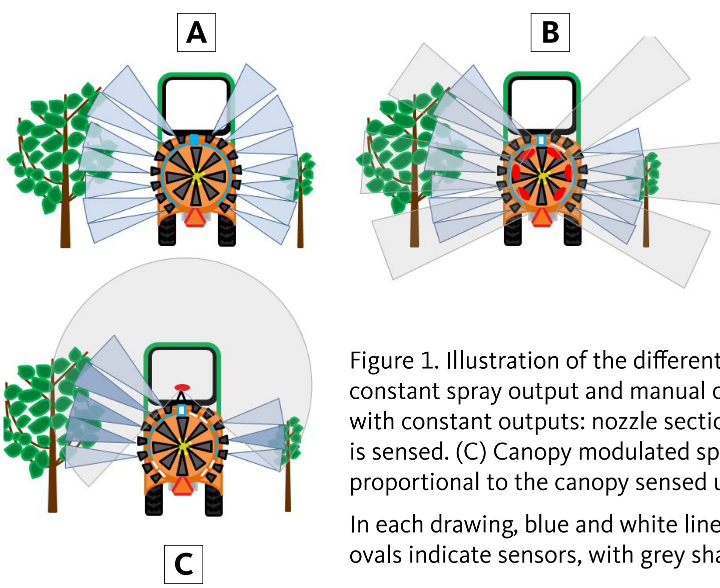

Figure 1. Illustration of the different sensor sprayer types. (A) Standard air-blast sprayers with constant spray output and manual operation. (B) Canopy actuated (on/off) sensor sprayer with constant outputs: nozzle sections are automatically turned on and off as plant material is sensed. (C) Canopy modulated sprayer: individual nozzles apply a volume of pesticide proportional to the canopy sensed using a single sensor.

In each drawing, blue and white lines around the sprayer perimeter indicate flow control; red ovals indicate sensors, with grey shapes illustrating emitted waves.

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Standard sprayers are controlled by the driver, who manually turns the sprayer on when spraying a crop area and off when exiting a row or crop area (Figure 1A, page 1). On/off sensor sprayers operate by using an "automatic" mode on the spray controller that automatically turns individual nozzles or sections of nozzles on or off depending on whether an object is sensed in the sensor zone (Figure 1B). Crop adapting sprayers are similar to on/off sensor sprayers but also change spray flow rate, air flow volume, air flow direction, or a combination of these variables in response to crop canopy characteristics such as leaf density and canopy volume (Figure 1C). Most on/off sensor sprayers and crop adapting sensor sprayers can also be operated in manual on/off mode if the sensor is malfunctioning and spraying needs to continue.

On/off sensor sprayers are available in a variety of configurations through many sprayer manufacturers. Canopy adapting sensor sprayers are available, but currently there are not many options. Market pressure to decrease chemical use in specialty crops will continue to improve and expand sensor sprayer options.

Sensor sprayer components

Although there is a wide range of sensor sprayer brands and configurations, almost all have the same components. Components of the sensor system are designed to input data such as ground speed and crop characteristics and actively modify spray output to match the crop shape.

Crop sensing systems

Crop sensing systems are the "eyes" of the sprayer; they determine crop shape by emitting and receiving signals. Commercially available crop sensing systems emit either infrared, near-IR beams, or ultrasonic waves. Generally, many signals per second are emitted. Some of these signals bounce off a physical object (ideally the crop) and return to the sensor receiver.

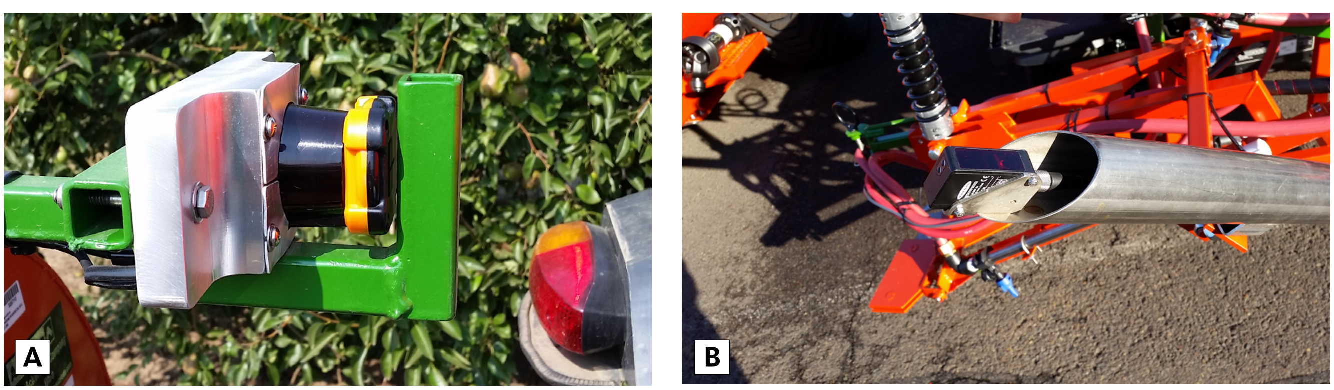
The time of flight (TOF) is the duration between when the signals are emitted and received. TOF is used to calculate the distance from the sensor to the physical object.

The individual signals can be put together to measure the plant shape. These plant measurements are then used in real time to apply pesticide precisely where it is needed. Sensors vary in viewing angle width, so sometimes multiple sensors are needed to control all the nozzles on a sprayer.

Infrared sensors

Infrared (IR) sensors used in commercial spray systems detect IR radiation emitted from plants. Atmospheric conditions such as humidity and temperature have little impact on IR sensing accuracy. However, light intensity, plant and leaf appearance, and driving speed can affect the accuracy of these sensors. Light conditions during dawn and dusk, when red wavelengths are more abundant, are known to interfere with IR sensor functioning. Applicators can operate IR sprayers in standard mode during dawn and dusk if they are forced by other conditions to spray during these times of day.

Currently, IR sensors have a relatively short sensing distance and narrow viewing width. For example, a commercially used IR sensor (QMT42, Banner Engineering, Minneapolis, Minnesota; Figure 2A) detects a 2.4-inch (6-centimeter) diameter zone 10 feet (3 meters) away from the sensor. The inability to resolve characteristics of plant structure makes IR sensors more suited to straightforward applications, such as triggering the sprayer on and off at a plant.



Photos: Brent Warneke, © Oregon State University

Figure 2: (A) Infrared sensor used in sensor sprayer applications (QMT42, Banner Engineering, Minneapolis, Minnesota; (B) LiDAR sensor (UTM-30LX/LN Hokuyo Automatic Co. Ltd., Osaka, Japan) used in the "Intelligent Spray System".

Even with their limitations, the low cost of IR sensors makes them economically viable for commercial sprayers. IR systems are used on air-blast systems for foliar applications of pesticides. An example of a commercially available IR system is the Banner Eye System (Rears Manufacturing, Coburg, Oregon) that uses a single IR sensor on each side of the sprayer to trigger the release of spray.

Ultrasonic sensors

Ultrasonic sensors emit high-frequency sound waves to measure objects. A sonic emitter generates an ultrasonic sound wave, a sensor detects the returning sound wave, and a chronometer measures the time of flight of the wave. The TOF of the wave gets translated into the distance of the object from the sensor. This technique is similar to how bats echolocate to navigate and search for food. When arranged in an array, ultrasonic sensors can detect objects that are 4 inches (10 centimeters) or larger. This accuracy allows for a calculation of canopy volume that is similar in accuracy to taking manual measurements.

Typically, many ultrasonic sensors are mounted on each side of the sprayer to control sections of nozzles independently. Individual sections of nozzles are then turned on and off to match sprayer output to crop architecture. Bumps and swaying from rough driving conditions can change the accuracy of the ultrasonic sensor because movement affects the angle of signal detection. Ultrasonic systems can be used effectively for foliar applications of pesticides in small fruit orchards, other orchards, and nursery fields.

The initial patents on ultrasonic sensors expired decades ago; continued off-patent development has improved their quality and capability while reducing costs. Comparatively, ultrasonic sensors are more expensive than IR sensors but less expensive than laser sensors. Examples of currently available systems are Smart Spray (Durand Wayland, LaGrange, Georgia) and Sonic Spray (Gillison Variety Fabrication, Benzonia, Michigan).

Laser sensors

Most laser sensors used in agriculture emit light beams in a two-dimensional plane around the sensor using a mechanical scanner. These are called LiDAR sensors, which is an acronym for “light detection and ranging.” LiDAR sensors have been used for decades in the forestry sector to determine canopy structure and forest density.

Compared to other sensors, LiDAR most accurately measures crop characteristics. LiDAR sensors (Figure 2B, page 2) send out many laser pulses per second in a wide field of view (270 degrees or more) and measure the TOF to plants and other objects. These measurements are called a point cloud. The point cloud can then be further processed to produce three-dimensional scans of the field, which can be used in variable rate spraying. LiDAR sensors emit waves that are thinner and that diverge less from their point of emittance than ultrasonic sensors, allowing for millimeter resolution of plant structures.

LiDAR sensors are enclosed in waterproof casing because they have delicate moving parts inside the scanning apparatus. There are many LiDAR sensors available for industrial applications, including agriculture. An example of a commercially available sensor sprayer system using a LiDAR sensor is the Intelligent Spray System (Smart Guided Systems, Indianapolis, Indiana).

Ground speed sensors

Maintaining accurate ground speed sensing is critical to ensure correct functioning of sensor sprayers because the computer directly controls the release of spray material based on this input. Sensor spraying systems are not directly connected to the speedometer on the tractor, so a separate speed sensor is needed.

Sensor sprayers sense and accommodate for speed in various ways. Ground speed sensors are used in combination with crop sensors to sync spray release to plant characteristics as the sprayer moves through the field. In systems without a speed sensor, spray timing can be improved by adjusting the position of the sensors and the delay triggers to have a direct effect on when the sprayer turns on and off after objects are sensed. Other spray systems derive speed measurements from tractor wheel attachments or with speed sensors that use radar waves similar to Doppler technology to measure ground speed without moving parts (for example, RVS III, Dickey-John Corp., Auburn, Illinois).

Operator interface

All sensor sprayer systems have a controller that allows the operator to customize the characteristics of the system. Some control systems are adjusted mechanically, with potentiometers that modify the sensor-spray delay, and a spray controller that allows the operator the choice to spray or avoid targets (Figure 3, page 4). Other systems have an operator interface with an LCD screen and buttons that allow for more precise adjustments of

Table 1: Pros and cons of sensors used in sensor-based spraying systems[1]

Sensor type	Measurement method	Pros	Cons
Infrared	• Detection of infrared waves emitted or reflected from plants	• Little impact of temperature and humidity on sensing accuracy • Low cost	• Red light intensity and driving speed affect sensing ability • Narrow field of view and short sensing distance • Unable to determine plant structure characteristics
Ultrasonic	• Measurement of the distance to objects using sound waves • Uses time of flight concept	• Ability to determine plant structure characteristics • Relatively easy to implement	• Limited resolution of plant structure • Need multiple sensors to detect plant structure
LiDAR	• Measurement of the distance to objects using laser beams • Uses time of flight concept	• Rich data acquisition capability • Fine resolution of plant structure • High speed of measurement	• Data acquisition affected by tractor bouncing, which requires correction • Delicate moving parts inside sensor

[1]Modified from Zhang et al., 2018.

the sensor settings. For example, the operator can turn off zones of the sprayer that would be pointed at the ground and trunks when their spray target is the canopy. Other settings that the operator can adjust include the maximum distance the sensor will detect and the lag time from when the sensor sees something to when the nozzles turn off. Some systems also have flow control and GPS mapping components.

Spraying with sensor sprayers

Pesticide material savings are most significant when sensor sprayers are used in areas with sparse foliage or irregularly shaped crops. Variability in the size of plants across a field is common in some perennial cropping systems. Variability can be due to multiple plant varieties, the death of plants or limbs, and replanting. For example, orchards where sick trees are removed and replaced have a mosaic of different age classes and sizes of canopies. This can also occur in tree nursery production systems where different age classes are planted in close proximity to one another.

Sensor sprayer efficacy

Pest and disease control with sensor sprayers is similar to that of standard sprayers. In a nursery, it was shown that powdery mildew on flowering dogwood (*Cornus florida*) was controlled to a similar extent with a canopy adapting sprayer as with a standard air-blast sprayer. This was accomplished in addition to a 56% reduction in spray volume. When ultrasonic sensors were used to actuate nozzles in one-, three-, and seven-year-old apple orchards, apple rust mite (*Aculus schlechtendali*) and pear psylla (*Cacopsylla pyri*) were both controlled with similar efficacy to standard sprayers. Pear psylla lives on young shoots located at the perimeter of the plant, next to gaps where the sprayer turns on and off. Similar control of pear psylla with standard and sensor sprayers shows that the sensing technology adequately covers small plant tissues with spray. Apple scab (*Venturia inaequalis*) and apple powdery mildew (*Podosphaera leucotricha*) also were controlled to a similar extent using sensor sprayers or standard sprayers.

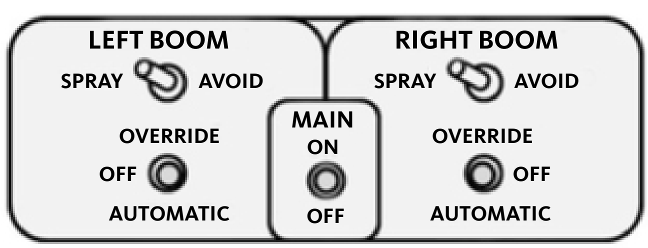


Figure 3. Illustration of a spray controller for a sensor sprayer system. The upper switch pair controls whether the sprayer turns on (spray) or off (avoid) when an object is sensed. The lower switch pair controls whether the sprayer will use the sensors (automatic) or be fully on (override). Other spray controllers can have more options.

Economic and labor savings

The most direct savings from sensor sprayers come from a reduction in the cost of spray materials required to treat an area. Many years of research have demonstrated that sensor sprayer systems reduce pesticide volumes, resulting in less pesticide used and lost to the environment. The savings in the volume of pesticides, adjuvants, and surfactants is proportional to the area sprayed. A reasonable range for many operations to expect is 10% to 33% pesticide volume savings, meaning fewer trips to refill the sprayer tank. While sensor sprayers are generally more efficient in operation, the amount of infield crop variability and the type of sensor used will influence how much the application efficiency is increased.

Generally, in crops with a uniform canopy, such as grape vineyards or densely planted orchards, sensor sprayers result in less savings compared to crops with a more variable canopy. For example, pesticide savings were 15% in a dense and uniform planting and 40% in a less dense planting of mature prune trees in California. That study used axial fan air-blast sprayers with ultrasonic sensors (Smart Spray, Durand-Wayland, LaGrange, Georgia).

When there is a uniform canopy, on/off sensor sprayers will be on for a large proportion of the time and will mainly act as a standard sprayer. Canopy adapting technology can be more effective at increasing application efficiency in these uniform systems. One study used pulse width modulation paired with ultrasonic sensors to make a canopy adapting system. That system applied a volume of pesticide proportional to canopy width based on a sensor measurement of tree row volume.

The canopy adapting sprayer achieved pesticide savings of 70%, 28%, and 39% in olive, pear, and apple orchards, respectively. In the study, the olive trees were 13 feet (4 meters) apart, resulting in gaps between canopies, while the pear trees were 5 feet (1.5 meters) apart. Another aspect of sensor sprayers that can save time and money is automatic adjustment of nozzles as plant growth progresses during the season. Early in the season when there is not much foliage, a sensor system automatically adjusts which nozzles are on to apply the product to the place where it is needed. This can save the operator the time it takes to manually adjust nozzles.

Labor savings from using a sensor sprayer will be more significant for a farm with more acreage because efficiencies from sensor sprayers result in fewer trips to refill spray tanks. For example, a 100-acre orchard gets air-blast sprayed at a target rate of 2 acres per hour. At 60% efficiency (due to fill-ups), the sprayer would cover 1.2 acres per hour, with the whole field taking 83 hours of work to complete. Using a sensor sprayer, the efficiency could increase to 80%, and the area covered would increase to 1.6 acres per hour. In this scenario, the field could be sprayed in 62 hours, about 20 hours less. If an operator is paid $15 an hour this would result in labor costs per acre of $12.50 for the 60% efficient sprayer and $9.30 for the 80% efficient sprayer. Therefore, using the 80% efficient sprayer could result in $315 savings for the farm per application. A larger orchard with more than one sensor sprayer would accumulate savings more quickly due to incremental increases in overall operational efficiency for each sprayer as it is added.

In addition to monetary savings, driver fatigue is reduced as the number of hours the tractor is in operation goes down. Also, fewer sprayer fill-ups lower labor and fuel costs, and reduce wear and tear on the tractor. When spray operations can be completed more quickly, then it can also be easier to fit sprays into windows of good weather. Critical application windows, such as when a plant pathogen or pest is reproducing, are also easier to cover when applications take less time. While using sensor sprayers has demonstrated savings of pesticide and time in a wide variety of systems, ultimately the decision to adopt a new technology depends on projections of economic returns specific to each operation.

Investing in sensor sprayers

Different sensor sprayer technological levels are more profitable over the sprayer's life span, depending on the type, size, and crop grown on a farm. Assuming a single commodity is grown, the larger the farm, the higher the cost of plant protection products, labor, and equipment. Therefore, larger farms could potentially recover the cost of an investment in a sensor sprayer more quickly than a smaller farm that applies less pesticide. Also, with crops that require a large number of pesticide applications throughout a season, the increased efficiency of each application using a sensor sprayer can more quickly pay off its purchase price.

An analysis of the profits related to increasing technological levels of sensor sprayers was done in wine grape vineyards and apple orchards. Standard air-blast, on/off sensor sprayers and canopy adapting sensor sprayers were compared to find the most profitable option. In the analysis, all operational costs were taken into account over an assumed six-year sprayer lifespan.

For wine grape vineyards, standard air-blast sprayers were the most profitable option in operations less than 24.7 acres (10 hectares), on/off sensor sprayers were most profitable from 24.7 to 247 acres (10 hectares to 100 hectares), and canopy adapting sprayers were most profitable for vineyards larger than 100 hectares. In apple orchards, standard air-blast sprayers were the most profitable in farms less than 42 acres (17 hectares); for farms larger than that, on/off sensor systems were most profitable. Canopy adapting systems were never the most profitable sprayer option in the apple scenario, likely due to the lower cost of the pesticides used in the apple plant protection program compared to the wine grape program.

While the profit from using a sensor sprayer is the most important long-term aspect of the system, the payback period on the initial investment also plays a vital role in the decision to adopt the technology. The payback period is often one of the most important considerations when thinking of implementing new technology. The payback period for a sensor sprayer is most closely tied to the cost of plant protection treatments applied on the farm. To investigate this, researchers looked at the payback period for an on/off air-blast system (Smart Spray by Durand Wayland) in orchard crops. These researchers based their calculations on the assumption that an ultrasonic sensor sprayer would cost $15,000. They determined that pesticide material cost savings of $57, $47, and $30 per acre were achieved in peaches, almonds, and prune field trials, respectively. Therefore, fully recouping the sprayer investment would take 2.6, 3.2, or 5 years with a 100-acre farm of peaches, almonds, or prunes, respectively. A farm smaller than 100 acres would have a more extended payback period, and a larger farm would have a shorter payback period.

Sensor sprayer systems can also provide significant value when used in a supplemental role for specific tasks: for example, an IR system used to spray green suckers on trunks in hazelnut orchards. In a scenario for a 100-acre orchard and four sucker-spray events with pesticide and material costs of $11.39 per acre each, a $5,000 IR system could potentially save a grower 50% on each sucker spray and could pay for itself in just over 2 years.

Another consideration that could influence the payback period of a sensor sprayer is the degree of diversification of crops present on a farm. When transitioning from crop to crop, the operator spends less time optimizing sprayer nozzles when a sensor can automatically open nozzles in the canopy area and close them above the canopy. This could result in a quicker payback period for both small and large, diversified farms.

Environmental benefits of using sensor sprayers

The major environmental benefit of using a sensor system is a reduced chemical load on the nontarget crop environment, including beneficial organisms and workers. Sprayer drift can be broadly defined as any spray that does not get deposited on the intended target. Drift can be deposited on the ground near the intended target or can be carried farther, eventually landing on nontarget plants. Ground-deposited drift is especially common in gaps between trees, which can result in significant pesticide load on the environment. In almond orchards, on/off sensor sprayers reduced ground deposition by 72% compared to a standard axial fan air-blast system. Airborne drift from over-application is another significant source of nontarget pesticide load from air-blast sprayers. In apple orchards, 23% to 45% of the applied pesticide volume has been observed to drift off target.

Canopy adapting sprayers can be particularly effective at reducing spray drift. A study looking at three different canopy stages in an apple orchard from early to late season showed reductions in spray drift of 70% to 100% using a canopy adapting sprayer. Lower nontarget chemical loads also help decrease the rate of development of pesticide resistance because there is less pesticide residue on nontarget locations.

Other considerations include less pesticide contamination of surface and groundwater and lower chances of exposure to nontarget organisms such as beneficial insect populations and livestock. These benefits incrementally improve the vitality of the agricultural landscape and should not be overlooked when thinking of implementing a sensor sprayer.

Obtaining a sensor sprayer

In most cases, sensor sprayers are standard sprayers that have sensor components connected to the spray controller. There are two general ways to obtain a sensor sprayer:

1. Purchase a sensor system integrated into a new sprayer.
2. Purchase a retrofit kit for an existing sprayer through a sprayer manufacturer or from the sensor manufacturer.

Integrated systems

Many sprayer manufacturers include sensor systems as optional components to add on to new sprayers at the time of the order. If purchased directly from a sprayer manufacturer as an integral component on a new sprayer, a sensor sprayer can be customized for the specific application. For example, ducting can be hooked up to pull air from the sprayer fan and redirect it across the sensors if the system will be used in dusty environments. Also, more sensors can be added to increase the sprayer's sensitivity to changes in plant structure. Consult the sprayer manufacturer about the sprayer's intended use to ensure optimum sprayer design for the intended purpose.

Retrofit systems

Many manufacturers offer sensor systems as retrofits for existing sprayers. Retrofitting can facilitate more rapid adoption of sensor systems. Depending on the system desired, the cost of an IR system retrofit can range from $2,500 to $5,000. An IR system can be put on a sprayer that makes most of the foliar applications on the farm. Ultrasonic sensor-controlled system retrofits cost from around $12,000 to $16,000. These systems are typically meant for foliar air-blast type sprayers used in orchards where there are gaps between plants.

Companies that sell sensor systems

Rears Manufacturing in Coburg, Oregon sells IR and ultrasonic systems as integral components on new sprayers. They also provide a wide variety of customization services for specific sprayer demands.

Gillison's Variety Fabrication in Benzonia, Michigan manufactures the Sonic Spray ultrasonic system and offers it as an integral component or retrofit on a variety of sprayers. Their Sonic Spray system is available through several sprayer manufacturers, such as Ag Tec sprayers and Rears Manufacturing. On request, other spray manufacturers may be able to integrate their system as well.

Smart Spray is a similar ultrasonic system manufactured by Durand Wayland in LaGrange, Georgia, available as an integral component on Durand Wayland or John Bean brand sprayers.

AgOtter (a product of Insero LLC, Tempe, Arizona) is a sprayer retrofit that includes software integrated with sensors to record and map where pesticide was applied. The AgOtter system uses GPS, flow tracking, and a variable rate valve to maintain a consistent application rate across a range of ground speeds.

Many sprayer manufacturers offer a wide range of customization that could be done at a customer's request, so sensors can sometimes be integrated or retrofitted onto sprayers even if it is not explicitly listed as an option. Check with the manufacturer for availability.

Sensor sprayers as a service

Some companies specialize in retrofitting sensor spraying systems onto existing spray equipment as a service to provide agricultural businesses with the benefits of using a sensor system. This minimizes the liability of equipment failure a grower may have when outright purchasing a system. Smart Guided Systems (Indianapolis, Indiana) offers the Intelligent Spray System as a retrofit service on air-blast type sprayers, with kits available for sprayers that have up to 39 nozzles. When using the AgOtter system, farmers can buy a software service called AgHippo Live to allow real-time monitoring of the location, flow rate, and ground speed of each equipped AgOtter sprayer.

Government incentives to implement sensor sprayer systems

The Conservation Stewardship Program (CSP) is funded through the USDA Farm Bill. It offers financial assistance to farm businesses implementing conservation techniques on agricultural land. Agricultural operations approved to participate in the CSP are typically already implementing some conservation practices (such as integrated pest management) on their land. Adopting precision spray technology (such as sensor sprayers) to reduce off-target pesticide waste is one management activity for which CSP can provide incentive funds. Funds are granted annually to the farm to assist with implementing its conservation practices and provide a way to help offset the costs of purchasing a sensor sprayer.

Applications for CSP are accepted throughout the year, but there are deadlines associated with ranking applications and awarding funds for a given year. The Natural Resources Conservation Service (NRCS) administers the CSP. Contact a local NRCS office for more information on applying to the program.

References

Chen, Y., H. Zhu, H.E. Ozkan, R.C. Derksen, and C.R. Krause. Spray Drift and Off-Target Loss Reductions with a Precision Air-Assisted Sprayer. Trans ASABE. 2013;56(6):1273–1281. doi:10.13031/trans.56.10173

Dworak, V., J. Selbeck, and D. Ehlert. Ranging Sensors for Vehicle-Based Measurement of Crop Stand and Orchard Parameters: A Review. Trans ASABE. 2011;54(4):1497–1510. doi:10.13031/2013.39013

Fox, R.D., R.C. Derksen, H. Zhu, R.D. Brazee, and S.A. Svensson. A History of Air-Blast Sprayer Development and Future Prospects. Trans ASABE. 2008;51(2):405–410. doi:10.13031/2013.24375

Fulcher, A., J. McHugh, R. Collier, et al. Evaluating Variable-rate , Laser-guided Sprayer Performance and Powdery Mildew Control in *Cornus florida* 'Cherokee Princess'. In: Waikoloa, HI: American Society for Horticultural Science; 2017.

Giles, D.K., P. Klassen, F.J.A. Niederholzer, and D. Downey. "Smart" sprayer technology provides environmental and economic benefits in California orchards. Calif. Agric. 2011;65(2):85–89. doi:10.3733/ca.v065n02p85

Koch, H., and P. Weisser. Sensor equipped orchard spraying-efficiency, savings and drift reduction. Asp Appl Biol 57. 2000;(57):357–360.

Niederholzer, F. Smart sprayers make sense for orchards. Western Farm Press. https://www.westernfarmpress.com/smart-sprayers-make-sense-orchards. Published 2009. Accessed November 20, 2018.

Miller, M., C. Seavert, and J. Olsen. Orchard Economics: The Costs and Returns of Establishing and Producing Hazelnuts in the Willamette Valley. Oregon State Univ Ext. 2013.

Pergher, G., R. Gubiani, and G. Tonetto. Foliar deposition and pesticide losses from three air-assisted sprayers in a hedgerow vineyard. Crop Prot. 1997;16(1):25–33. doi:10.1016/S0261-2194(96)00054-3

Pimentel, D. Amounts of Pesticides Reaching Target Pests: Environmental Impacts and Ethics. J Agric Environ Ethics. 1995;8(1):17–29.

Schumann, A.W., and Q.U. Zaman. Software development for real-time ultrasonic mapping of tree canopy size. Comput Electron Agric. 2005;47(1):25–40. doi:10.1016/J.COMPAG.2004.10.002

Sedlar, A.D., R.M. Bugarin, D. Nuyttens, et al. Quality and efficiency of apple orchard protection affected by sprayer type and application rate. Spanish J Agric Res. 2013;11(4):935. doi:10.5424/sjar/2013114-3746

Solanelles, F., A. Escolà, S, Planas, J.R. Rosell, F. Camp, and F. Gràcia. An Electronic Control System for Pesticide Application Proportional to the Canopy Width of Tree Crops. Biosyst Eng. 2006;95(4):473–481. doi:10.1016/J.BIOSYSTEMSENG.2006.08.004

Stover, E. Sensor-Controlled Spray Systems for Florida Citrus. Univ Florida Ext. 2002.

Tona, E., A. Calcante, and R. Oberti. The profitability of precision spraying on specialty crops: a technical–economic analysis of protection equipment at increasing technological levels. Precis Agric. 2018;19(4):606–629. doi:10.1007/s11119-017-9543-4

Verweij, P.E., E. Snelders, G.H. Kema, E. Mellado, and W.J. Melchers. Azole resistance in *Aspergillus fumigatus*: a side-effect of environmental fungicide use? Lancet Infect Dis. 2009;9(12):789–795. doi:10.1016/S1473-3099(09)70265-8

Wandkar, S.V., Y.C. Bhatt, H.K. Jain, S.M. Nalawade, and S.G. Pawar. Real-Time Variable Rate Spraying in Orchards and Vineyards: A Review. J Inst Eng Ser A. 2018;99(2):385–390. doi:10.1007/s40030-018-0289-4

Zhang, Z., X. Wang, and Q. Lai, and Z. Zhang. Review of Variable-Rate Sprayer Applications Based on Real-Time Sensor Technologies. In: Automation in Agriculture–Securing Food Supplies for Future Generations. InTech; 2018. doi:10.5772/intechopen.73622

Zhu, H., R. Rosetta, M.E. Reding, et al. Validation of a Laser-Guided Variable-Rate Sprayer for Managing Insects in Ornamental Nurseries. Trans ASABE. 2017;60(2):337–345. doi:10.13031/trans.12020

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