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Summary

Sensor guided precision sprayers were developed to automate the spray process with a focus on emission reduction and identical or increased efficacy, with the precision agriculture concept in mind. Within the project "Innovations2" sensor guided precision sprayers were introduced to leek, strawberry, and pear production systems. This paper focusses on the combination of sensor signals and spray technique. The development of decision algorithms from sensor data and the translation to applied spray volumes is explained. Validation of the spray distribution was made with spray deposition trials in the case study of the strawberry sprayer. The sensor guided sprayer applied on average 11% less spray volume per hectare than conventional boom spraying, with an increased spray deposition on strawberry leaves of 56% on average. The decision algorithm that was used to convert crop canopy density to applied spray volume rate is still under development and has to be improved to balance between lowering the dose and keeping acceptable efficacy. Though, to realise accurate decision algorithms, thorough dose effect studies are required in addition to spray deposition measurements that validate the technical spray results.

Key words: Precision agriculture, sensors, spraying, GPS, GNSS

Introduction

In the Netherlands, the level of integrated pest management in practice still has to increase a lot to come to an acceptable level of societal accepted food production. Therefore, and with special focus on groundwater protection, a project was started named "Innovations2", in Dutch "Innovaties in het Kwadraat" (Hees *et al*., 2011). Within this project integrated pest management solutions are introduced into strawberry production systems, leek production systems and pear production systems. The system innovations focus on soil management, fertilisation, and on pesticide application and efficacy. This paper specifically focusses on the innovations made into pesticide application technology for strawberry, leek and pear production. Within these production systems canopy density spraying (CDS) (van de Zande *et al*., 2010) was introduced by combination of various sensor and actuator technologies, tailored to the specific food production systems. The development of the sensor guided precision spray technologies based on measuring the canopy density was fed by knowledge from preceding projects like the CASA sprayer from the EU ISAfruit project (Wenneker *et al*., 2009) and the developments in previous projects with canopy density spraying in the SensiSpray project in potato growing (Michielsen *et al*., 2010). In the three production systems, major parallel developments and strategies were used to come to a practical spray application solution that resulted in a reduction in spray drift, reduction in total amount of plant protection products used, together with an efficacy at the same or an increased level as of conventional boom spraying. The process of combining sensor signals, decision algorithms, and actuators in the integrated automated spray technology is described in this paper.

Materials and Methods

Explanation of sensors and actuators proposed in the three systems

In the first system for strawberry spraying shown in Fig. 1, a combination was made of GreenSeeker sensors and pneumatic actuated multi-nozzle bodies (Lechler VarioSelect). The GreenSeeker sensors were chosen as they are able to measure the Near infrared Difference Vegetation Index (NDVI) as a continuous measure of the amount of vital biomass present. The strawberries are grown on beds with a tramline distance of approx. 1.5 m width. The sprayer consisted of three sections and so the sprayer working width was 4.5 m. Above each strawberry bed one GreenSeeker sensor was mounted, that controlled the nozzle bodies that were mounted 0.25 m apart. The sensors were configured at a 10 Hz update rate. Based on the measured NDVI signal, the applied volume rate was adjusted by switching on or off additional nozzles within each section. Each nozzle body had four different nozzles, resulting in 16 possible volume rates. The specific task of volume rate adjustment was accomplished by tailor made decision algorithms to assure correct application rates for practical circumstances. During spray application sensor signals and activated nozzles and spray pressure were logged. The advances of this canopy density based spraying system are expected in the following aspects. Firstly the tracks of the tractor and between beds are not sprayed, and secondly, the amount of spray volume is automatically adjusted to the growth stage of the strawberries.

Fig. 1. Strawberry air-assisted spraying system consisting of GreenSeeker sensors in combination with Lechler VarioSelect pneumatic nozzle bodies.

In the second system for leek spraying a combination was constructed from WeedIT agricultural sensors and solenoid activated nozzles. The WeedIT sensors measure the presence of living green plants by inducing chlorophyll fluorescence in the plants and measuring the amount of emitted fluorescent light. Originally these systems were designed for weed control on pavements, though the detection technique is also suitable for spot spraying on local small targets of minimum size of 0.1 m × 0.1 m. For the leek spraying system the sensors provide an on-off signal for each 0.1 m section at ground surface. The system consisted of nine sensors covering 0.5 m each, resulting in a 4.5 m wide sprayer addressing 45 individual nozzles (TeeJet TP4001). The system did not contain user configurable settings for variable application rates. The concepts and advances for canopy density spraying are in this system foreseen at the point of automatic banded application and on-off switching at small growth stages of the leek.

Fig. 2. Leek spraying system consisting of WeedIT sensors in combination with solenoid activated nozzles spraying 0.10 m × 0.10 m targets.

The third system for pear spraying was built upon the experiences of the CASA sprayer from the ISAfruit EU-project and the PreciSpray EU-project (Wenneker *et al*., 2009). In these preceding projects the basal ideas for canopy density spraying in fruit orchards were founded and shaped. The spraying system consists of a Hokuyo URG laser scanner sensor combined with Lechler Varioselect pneumatic actuated nozzle bodies. The laser scanner sensor was chosen as it outperforms ultrasonic sensors in terms of number of measurements per time unit and accuracy. Furthermore the sensor is compact and robust and can be easily interfaced. The cross-flow fan sprayer consists of five sections left and right, 10 sections total. The total of 72 nozzles are distributed over the sections in groups of eight, eight, eight, eight and four nozzles from bottom to top of the cross-flow unit respectively. Each nozzle can be activated individually at an update rate of 3.5 Hz, as this results in a good spray cone and spray result. The laser scanner is mounted at 1.5 m height and has a radial scanning distance of 4.0 m, large enough for conventional tree row spacings of 3–4 m. The sprayer nozzles are distributed at 0.3 m distance from 0.4 m height to 3.1 m height. The sprayer hardware is built upon a standard KWH cross flow sprayer. The applied volume rates for each sprayer section could be adjusted by switching on or off additional nozzles in multiples of one, two, three or four identical nozzles. The tailor made decision algorithm to adjust the spray volume based on tree row volume was specifically made within this project, taking into account previous research from, for example, Walklate *et al*. (2002). The advances of canopy density based spraying in pear was foreseen at the points of: no spraying where gaps were detected in the crop foliage; reduced spraying when minimal crop foliage was present, optimal spraying where large amounts of crop foliage was present.

Experiments performed

The three different prototype spraying systems were introduced in the year 2011. The prototype systems were subjected to a lot of testing and gathering of data. The sprayers were all made in duple, and are used on practical farms in the Netherlands, to get the most of interaction with future users of the technology. One of the main challenges was to gather sensor data of different crop growth stages to develop decision algorithms. These decision algorithms are crucial in canopy density based spraying systems, as they dictate the volume rate to be applied and automate a task conventionally performed by the sprayer operator. In field experiments for development of decision algorithms, only data was gathered for the strawberry and pear spraying system. For leek no data was gathered for decision algorithm development, as the leek sprayer only had to make

Fig. 3. Canopy Density Spraying system in pear consisting of a laser scanner in combination with Lechler Varioselect pneumatic actuated nozzle bodies.

on-off decision that was already well implemented. For strawberries, NDVI data was gathered from three growth stages in a practical situation. For pear and apple, laser scanner data was gathered during spring, summer, and autumn in different training systems of orchards to gather data for decision algorithm development. For both the fruit and the strawberry system GPS data was included in the sensor data, such that plots of fields could be easily made.

When prototype decision algorithms were made, field experiments were conducted to determine the volume rates that were applied on the crops. Volume rates were measured in strawberry, pear and apple. The applied volume rates of the CDS systems were compared with standard farmers practice. When possible or required, based on the GPS data files, the decision algorithm was adjusted to reach acceptable application rates.

When the sensor based application was at an acceptable level, this means the spray application was at a correct mean volume applied and the spray application was visually correct, spray deposition trials were made. These spray deposition trials were made to validate the practical value of the decision algorithms. Spray deposition was measured in strawberry, leek and pear. Though, in this paper we present the result of the deposition measurements in strawberry as an example case study. The spray deposition measurements in the two other cropping systems are analogue and still in progress.

Results

Sensor signals recorded during different growth stages

The laser scanner signal from one of the experiments in an apple orchard is shown in Fig. 4. The point cloud of the raw 3D measurements was first segmented in the five sections in height. The section height limits were: 1.0, 1.5, 2.1, 2.7, and 3.1 m. These limits were based on the mechanical properties of the sprayer and were not specific to the orchard training or tree structure.

An example NDVI sensor signal for strawberry is shown in Fig. 5. The figure shows the signal of the small, medium and large growth stage. The measurements show distinct differences in NDVI level between the growth stages. NDVI fluctuations within the crop row are usually smaller than the differences between the growth stages. So the expectation is that the applied volume rates will mainly change between growth stages and not within growth stages.

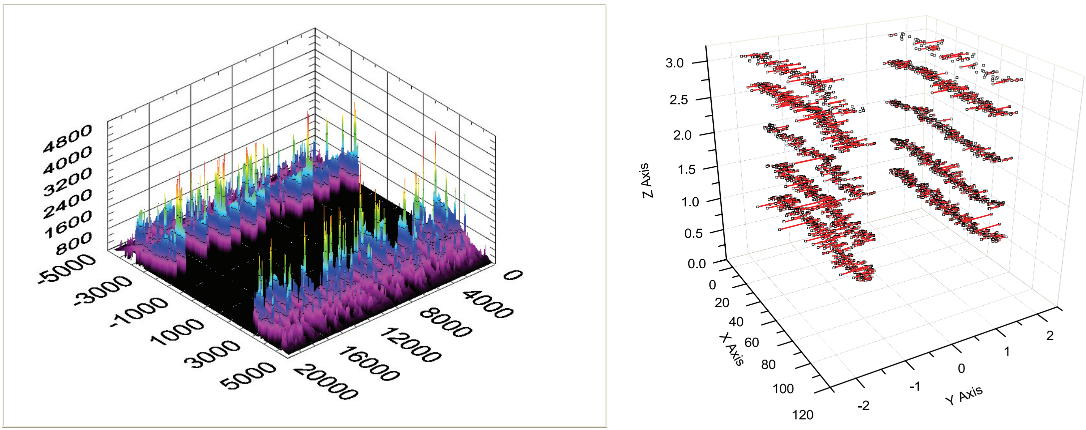

Fig. 4. Raw 3D measurement data of 20 m length within an orchard (left). Processed 3D distance data for five left and five right sections of 100 m length within an orchard (right).

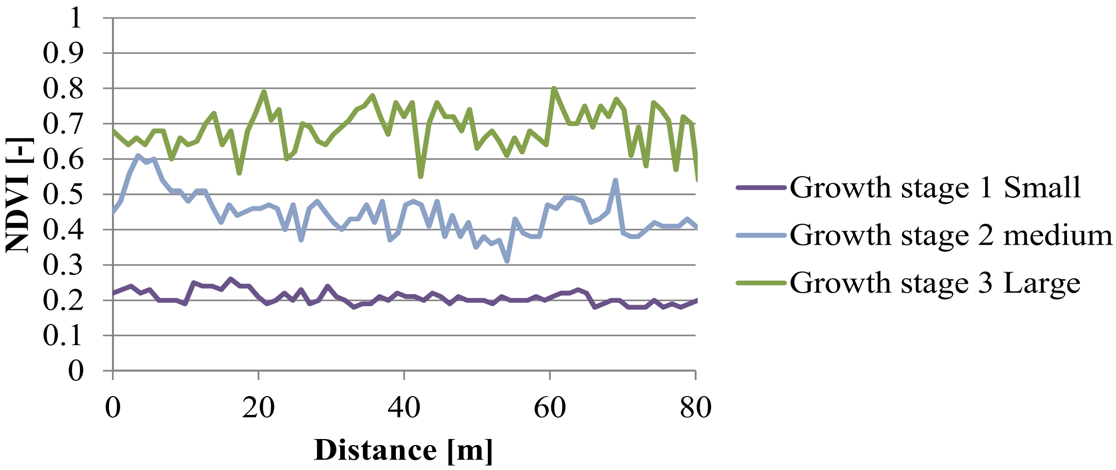

Fig. 5. NDVI measurement data of the three sections of the sprayer in the middle growth stage in strawberry as a function of travelled distance. The minimum and maximum values of the sensor are 0 and 1.0 corresponding to dead and optimal growing vegetation.

Prototype decision algorithms

The prototype decision algorithms that were developed from the sensor data from the previously explained experiments are shown in Fig. 6. The decision algorithms translate sensor values in a percentage of a maximum dose. The maximum dose is what is normally used in all practical circumstances at agricultural practice. The minimum dose is at a level what is supposed to give a

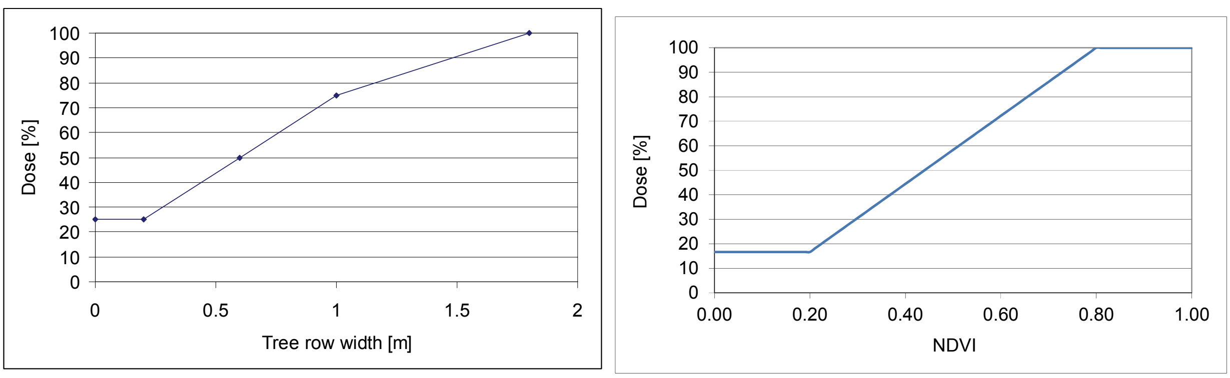

Fig. 6. Prototype decision algorithms for pear (left) and strawberry (right). The pear decision algorithm is given by the dose as function of tree row width. The strawberry decision algorithm is given by the dose as function of the NDVI.

minimum level of protection (in case of fungicides) to the crop. The slope, shape, minimum and maximum of the dose have to be based on accepted knowledge of dose effect relations and studies. Though, these agronomic aspects lie outside the scope of this study in which we focus on the technical application aspects of canopy density spraying.

Validation results of the spray deposits

In strawberry spray deposition measurements were done on three growth stages and in two repetitions. A visual representation of the growth stages is shown in Fig. 7. The first growth stage is the size of the plants that are to be sprayed for the first time with fungicides. The second and third growth stages are in strawberry production already.

Fig. 7. Strawberry growth stages during spray deposition measurements. Left picture shows smallest growth stage of just planted strawberry plants. Middle picture shows plants that just have started flowering. Right picture shows strawberry plants in full production.

The volume rates applied by both sprayers were validated by standard collectors on the ground surface. The results are shown in Table 1. The standard sprayer was set to spray 250 L ha^{-1}. The sensor guided sprayer had a variable rate and sprayed a higher volume rate at the larger growth stages. Because of the crop growth on beds, the tramlines between the beds were not sprayed with the sensor guided sprayer. This means that from the 18 nozzle bodies covering 4.5 m, six nozzle bodies were not active during application as they were above the tramlines between the beds where spraying was not required. So 33% of the field area was not sprayed by the sensor guided sprayer. This resulted in relatively lower spray liquid use per hectare as shown in the most right column of Table 1. On average the spray liquid use on one hectare was decreased by 11% due to the use of the sensor guided sprayer. This did not result in a decreased biological efficacy – visually assessed, results not shown – probably due to the higher volume rate at the beds themselves.

Table 1. *Results of spray deposition measurements on collectors on the ground surface to check the applied volume rates of the two spray techniques*

Spray technique	Growth stage	# of collectors	Average rate L ha^{-1} (on the beds)	Spray liquid use on one hectare
Standard	1	3	249	249
	2	3	275	275
	3	3	222	222
Sensor guided	1	3	312	206
	2	3	274	181
	3	3	419	277

Strawberry leaves were also taken into account in the spray deposition measurements. The deposition on leaves is visually presented in Fig. 8. The standard sprayer had lower deposition on leaves with 0.91, 0.88, and 0.71 µL cm^{-2}, whereas the sensor guided sprayer had higher deposition on leaves with 1.53, 1.37, and 1.07 µL cm^{-2} depositions for the three growth stages respectively. On average this was a 56% higher deposition on the strawberry leaves with the sensor guided sprayer. The spray deposition on the leaves was decreased at increasing growth stage for both sprayers. This seems relevant as the crop biomass and number of leaf layers increased during crop lifetime, resulting in decreased penetration of the spray cloud into the leaf layers of the strawberry plants.

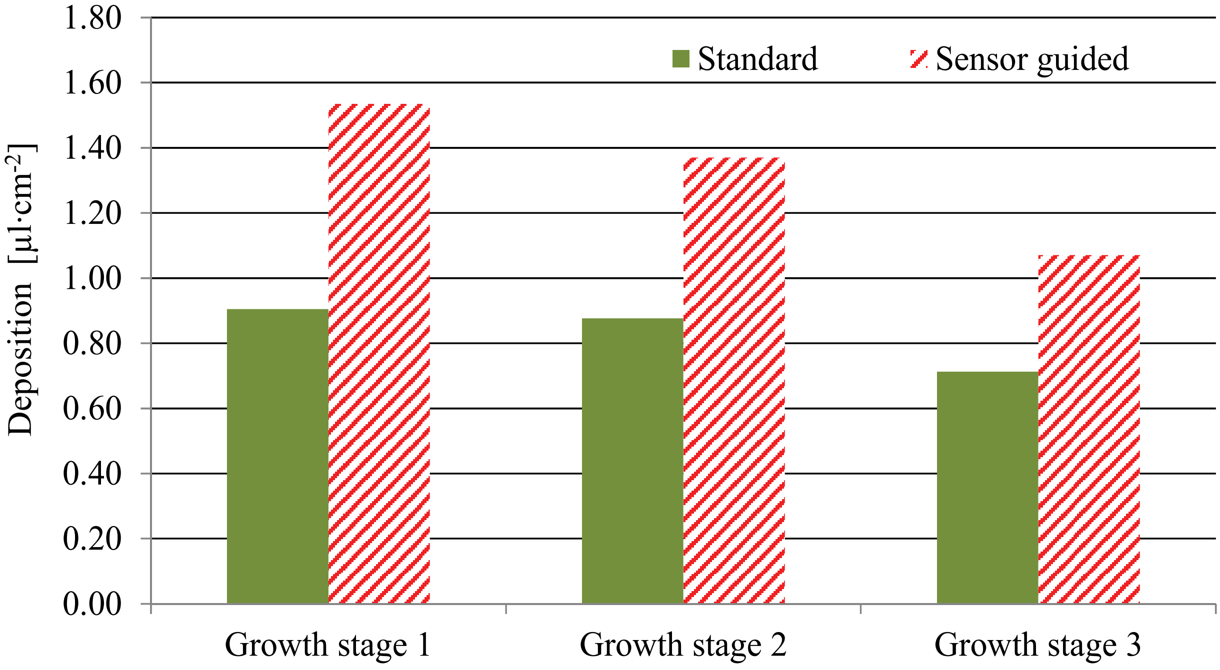

Fig. 8. Spray deposition on strawberry leaves presented for the three growth stages and two types of sprayers.

Discussion

The results presented in this paper are of the prototype CDS sprayers introduced at practical farms. It was good to integrate the practical experience of farmers into the development process. At the same time it appeared that knowledge is lacking on how to translate sensor signals measuring crop growth stage to spray volume rates to be applied. Especially, to generalise the decision algorithms concept to different crops is an ongoing process in communication with farmers, advisors and researchers.

During sensor guided spraying, farmers do not know on beforehand the amount of spray liquid that will be used on their fields. Therefore it is hard for them to predict how much water they should put in the tank to prevent surplus spray liquid. It would be good to help them predict from previous applications what they should put in their sprayers. On the other hand direct chemical injection systems could be of help as well, as the spray liquid is then mixed at the time of application.

Knowledge is lacking on the process of spray deposition within a crop canopy. Large differences exist between the spray deposition in the flat surface beneath the sprayer and the spray deposition on the plant surface of the crop. This causes difficulties in the development of decision algorithms, where relations have to be made between sensor signals and volume rates to be applied on the crop.

Acknowledgements

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