Precision Agriculture and Crop Protection
(Precisielandbouw en Gewasbescherming)

Definitions and the relation between precision-applications and the authorisation procedure of PPPs

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Preface

The use of plant protection products (PPPs) is part of the primary production process in agriculture. Besides chemical PPPs, also biocides, natural PPPs and low-risk PPPs are used. The sector has set itself the clear goal of keeping application of PPPs as low as possible. Precision-application of PPPs, besides a reduction in the total dose applied, effects the exposure of different protection goals. Precision-application thus could play a role in the exposure assessment for the authorisation of PPPs. The term *Precision Agriculture* is used in multiple ways and clear terminology lacks. This report aims to clarify the terminology, focused on crop protection related to the authorisation of PPPs. This study was conducted by Wageningen Plant Research (WPR) in the research theme BO-43 – Sustainable Food Supply and Production & Nature – Sustainable Crop Protection, project BO-43-102.01.012 funded by the Dutch Ministry of Agriculture, Nature and Food Quality.

Summary

Precision agriculture is earning its place in the Dutch agricultural sector, with crop protection as one of the main points of attention for many farmers. Precision-application of plant protection products (PPPs) can, besides reduction in the amount applied, result in a lower exposure of different protection-targets to PPPs. Taking these effects into consideration, precision-applications for crop protection could play a role in the exposure assessment of PPPs in the authorisation procedures. The term *precision agriculture* is used in multiple, different ways and clear definitions lack. This report aims to define the terminology regarding crop protection through precision application of PPPs. Precision agriculture is defined as "Exactly meeting the needs of plants or animals within space and time while respecting economic and social boundaries and taking into account environmental aspects". In the proposed terminology, an application is only a precision-application if site-specific measurements are done <u>and</u> a site-specific decision is made <u>and</u> this decision is subsequently carried out site-specifically. For precision-applications, two methods of operation are defined. In *on-the-go* precision-applications, measuring, decision-making and application are all done in real-time. In *chained* precision-applications, measurement, decision-making and application need not happen at the same time. Specifically for crop protection, three types of precision-application can be identified. In a *variable rate* application, the whole field is treated while the dose is varied to meet the conditions in each location. In a *spot-spraying* application, for each location the decision is made whether application is required before doing so. Finally, a *hybrid* form exists where *variable rate* and *spot-spraying* are combined: For each location the decision is made whether application is required and only <u>if</u> application is required, subsequently the appropriate dose is determined. As the term *dose* plays an important role, it is split into:

- Advised dose, depicting the dose advised by the producer of the PPP
- User dose, depicting the dose chosen by the user based on knowledge and experience
- Minimal effective dose, depicting the dose which (in theory) is just high enough to reach the desired goal of the application, taking into account the local conditions at the moment of and on the position of application
- Application dose, depicting the dose sent to the sprayer as required application-rate
- Applied dose, depicting the dose as actually applied by the sprayer

Multiple precision-applications for crop protection are illustrated using examples from practice. For every example, the methods used to site-specifically measure, decide and apply are described in detail. Additionally, a discussion on how different application-technologies can contribute to a higher efficiency during application is included.

Precision agriculture and the assessment methodologies for the authorisation of PPPs are then discussed together. Variable rate applications mainly influence the applied dose per location; spot-spraying applications mainly influence the locations where application takes place; hybrid applications influence both these aspects. The proposed definitions and presented examples from current agricultural practice offer leads for the exposure assessment methodologies of PPPs in the authorisation procedure. Multiple challenges and opportunities within this procedure, such as left-over spraying fluid, influence of variability within a field and data-exchange, are discussed in the discussion-chapter. It is concluded that multiple opportunities exist to make steps towards inclusion of precision-techniques into the assessment methodologies for the authorisation of PPPs.

1 Introduction

Precision agriculture (PA) is becoming an important aspect in Dutch Agriculture. A survey conducted in the first half of 2020 with 203 Dutch arable farms as respondents (Kempenaar *et al.*, 2020), resulted in 85% of the respondents indicating they use Global Navigation Satellite Systems (GNSSs) in their farming operation, with the main application in autosteer systems. The adoption rate of precision-techniques for crop protection is lower, with ~20% of respondents indicating to use these techniques. Higher adoption rates for these techniques result in a louder debate on what qualifies as precision agriculture (techniques) and what does not. Essential for fruitful debate are clear definitions, which currently lack. Aim of this document is to clarify part of the terminology regarding PA, focusing specifically on crop protection and the application of plant production products (PPPs). In the debate on crop protection and specifically the authorisation procedures for PPPs, an important aspect currently is the effects of precision-application of PPPs on the environment and thus the impact on authorisation of PPPs. On top of a clear view of the actual impacts and compliance, clear terminology is essential for this debate. This document will clarify the terminology by proposing a classification system for precision-applications for the application of PPPs. To clarify the proposed classification system, examples from current agricultural practice are included in this document, explaining the exact methods used. Per precision-application, results obtained in the Dutch National Experimental Garden for Precision Farming (NPPL) up to 2020 are included.

This report focusses on different aspects of precision-application of PPPs with respect to the exposure of protection goals as these are included in the assessment methodologies for the authorisation of PPPs. An explorative view on these aspects and how they may be included in the assessment methodologies for the authorisation procedures of PPPs is included.

2 The term “Precision Agriculture”

This report identifies precision agriculture (PA) as frame-concept. PA is defined as “Exactly meeting the needs of plants or animals within space and time while respecting economic and social boundaries and taking into account environmental aspects”. As PA is seen as a key-aspect in making agriculture more sustainable (in the wide sense of the word), it is cited at any opportunity. The first step thus is to clearly define the term and context. In the posed classification-system, an application classifies as precision-application if the application involves at least the following three steps:

1. Site-specific **measurement**
2. Site-specific **decision** of optimal treatment (rate)
3. Site-specific **execution** of optimal treatment

Measurement requires inspection of the crop, using sensors to record the state of the crop, what the crop might be lacking and/or which discomforts the crop might experience. **Decision** requires interpretation of the measurement-data, possibly taking into account other (measurement) data, in order to come to the optimal treatment (application rate of PPP(s) in this case). **Execution** consists of treatment with the dose of PPP(s) as decided in the **decision**-step. In this terminology, only when all three steps are explicitly made does an application qualify as precision-application. This definition explicitly categorizes application techniques which, for example by making mechanical adjustments to the sprayer, only apply on bed or row as non-precision, unless the steps measurement, decision and execution are clearly made per location in the field. These mechanical adjustments however, as precision-applications, do influence the required dose of PPPs and could thus play a role in the authorisation procedure of PPPs (please refer to chapter 6). In combining the three steps of a precision-application, two separate work-forms can be identified: the *on-the-go* application and the *chained* application.

2.1 On-the-go precision-application

An *on-the-go* application is characterized by the fact that the three steps of measurement, decision and execution are all done at once, i.e. *on the go*. A sensor, decision-rule and method of execution are all combined in one integrated process. During application measurements are done, which are directly fed into the decision-making process, which in turn sends the decision (whether or not to apply and, if application, the application rate) to the execution-method, which executes the instructions immediately. Regarding *on-the-go* applications, it is important to note that the exact total amount of PPP(s) which will be required to treat the entire field is not known in advance.

2.2 Chained precision-application

A *chained* application is characterized by the fact that measuring, decision-making and execution need not happen at the same time. This means measurements can be done using a system optimized for measuring and/or measurements can be done at a moment where conditions are optimal for doing the measurements. The obtained measurement data can subsequently be interpreted by a decision support / making system while also taking into account other information, such as weather data, historical data or data comparable to the current measurement. As data of the entire field is available, the decision-process can be done using a decision-rule fit for the observed variation in the data and/or field. Additionally, the process can be set-up such that a limited amount of available resource(s) (for example PPPs) can be distributed over the field optimally (though this might involve compromising). Execution can subsequently be done at a moment where conditions are optimal for application.

3 Categorization of precision-applications for plant protection products

Besides separation in two work-forms, *on-the-go* and *chained*, the nature of precision applications for plant protection products (PPPs) can be divided into three categories:

1. Variable rate application
2. Spot-spraying application
3. Hybrid application where spot-spraying is combined with variable rate application

Please note that the categorization as proposed above mainly focusses on differences in the 2nd and 3rd step of the precision-application, which are decision-making and execution of the decision per location. Variable-rate application and spot-spraying application can also coincide, resulting in a hybrid form where spots are treated with variable rate. The three application-methods are summarized in Table 1, with examples for each of the categories explored in chapter 4.

Table 1 Different forms of precision applications for plant protection products

	Variable-rate application	Spot-spraying application	Hybrid application
Goal of application	Adjust application-rate based on situation	Only apply where necessary	Only apply where necessary, adjust application-rate based on situation
Method	Change application-rate	Turn on/off machine and/or nozzles	Turn on/off machine and/or nozzles, change application-rate
Will the entire field receive treatment?	Yes	Preferably not, but might (turn out to) be necessary	Preferably not, but might (turn out to) be necessary

The word *dose*, in this case referring to the amount of crop protection product applied on a specific area, will be extensively used throughout this report. Based on the origin of the dose, specific terms are used:

- *Advised dose*
  The advised dose refers to the dose as advised by the manufacturer of the crop protection product. This dose is currently used for calculations required to obtain authorisation. It is mentioned in the legal instructions for use established by the national PPP authorisation authority. Application of a higher dose than the advised dose is not permitted.
- *User dose*
  User dose refers to the dose that growers, possibly in consultation with a crop protection advisor, select as the optimal dose to achieve desired effects after an application. This dose is often lower than the advised dose.
- *Minimal effective dose*
  The minimal effective dose refers to the dose that is theoretically just high enough for the product to be effective under the given conditions. This minimal effective dose depends on several factors and can be calculated (approximated) using decision models if these models are available for the PPP in question.
- *Application dose*
  The application dose is the dose which is sent to the sprayer for application. The systems on

the sprayer will try and achieve this dose by controlling the flow per second. This dose can differ from the minimal effective dose, as explained in paragraph 3.1 and by figure 1

- *Applied dose*
  Applied dose is the dose actually applied by the sprayer. The applied dose can differ from the application dose due to (technical) limitations of the sprayer. If the situation in the field requires large differences in application dose in areas located directly besides each other, the sprayer could need time to adjust the application rate resulting in differences between the application dose and the applied dose.

3.1 Variable-rate application

In a variable-rate application, the dose is adjusted to match what is required per location. Fundamental principle of a variable rate application is that application is necessary everywhere in the field. For each location in the field, the minimal effective dose is determined based on measurements to provide the crop with optimal care using a minimal input of PPP. This means that application of the PPP is done everywhere, but the dose varies.
Currently, most machines capable of variable application can apply only a single dose over the entire working width. This is adjusted once or twice every metre. If multiple measurement datapoints are available within one working width, a calculation step is required to determine the application dose. During the decision process, calculations are performed at the level of detail of the measurements and only as a last step of the decision process the results are translated into the working width of a particular sprayer. Figure 1A illustrates this: There are 11 measurement data points under the spray boom, therefore 11 minimum effective doses are calculated. Only as a final step these are converted to one application dose. Depending on the application and the PPP used, it can be preferable to have the machine apply the highest or the lowest minimum effective dose within the working width, as illustrated in Figures 1B and 1C. The latest generation sprayers can be equipped with a system where per nozzle (often placed at 0.5 m or 0.25 intervals) the dose can be changed up to ~25 times per second.

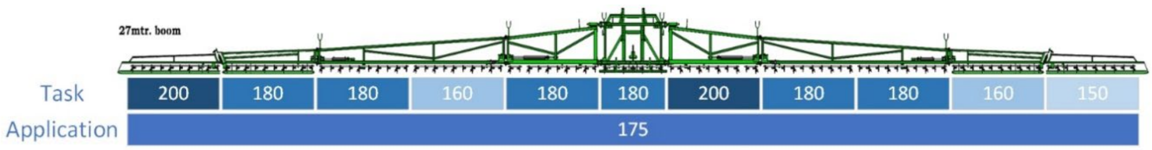

Figure 1A Average application based on detailed task-map

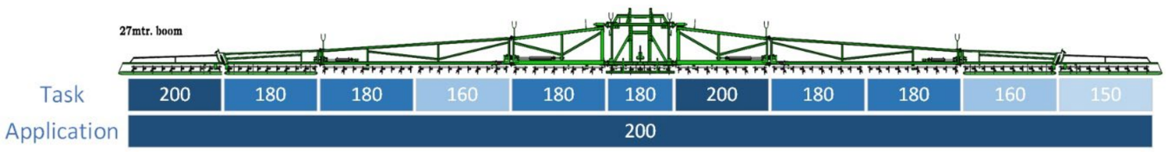

Figure 1B Maximal application based on detailed task-map

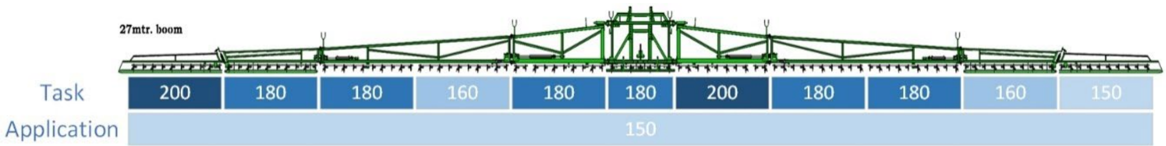

Figure 1C Minimal application based on detailed task-map

3.2 Spot-spraying application

For a spot-spraying application, the basic principle is that the PPP is only applied in areas where application is required. Different indicators can be used to determine whether application is necessary in a certain location, as illustrated in chapter 4. Many sprayers allow switching on and off nozzles per 3 or 6 m working width to enable spot-spraying application. The latest generation of sprayers can be equipped with a system where each nozzle (often placed at 0.5 m or 0.25 m intervals) receives instructions ~25 times per second, so that each individual nozzle can be turned on and off with high precision.

3.3 Hybrid application

A hybrid application combines the characteristics of a variable-rate application and a spot-spraying application. The first step is to determine if application is required for a specific location. Only if application is required in this specific location will subsequently be determined what the minimal effective dose for this specific location is, as in a variable-rate application. Hybrid applications currently used in practice are mostly based on scientific decision models with models of crop growth, soil and/or weather as components in the decision-process.

4 Examples of precision applications for plant protection products

In this chapter, the different types of precision application are illustrated using examples from current agricultural practice. The purpose of these examples is to get a better idea of the differences between the types of application and to give an overview of the different precision applications for plant protection products (PPPs). To get an idea of the potential of the different applications, quantitative information is included in each example. In addition, experiences from the *Dutch National Experimental Garden for Precision Farming* (NPPL) are presented. Crop protection is one of the main points of attention in this project, largely originating from the participants' desire to make their production process more sustainable. This yields practical experience and data on the impact and effects of the various precision-applications.

4.1 Variable-rate applications

Two variable-rate applications from practice are illustrated as examples of precision applications in this category. These applications are *variable-rate soil herbicide application* and *variable-rate haulm killing application*.

4.1.1 Variable-rate soil herbicide application

Variable-rate soil herbicide application is one of the precision applications for crop protection currently used in practice. This chained application starts with **measuring** soil properties: lutum and organic matter contents are mapped. This can be done using one of the available soil scanning techniques. Alternatively, companies have started to offer these maps based on drone- or satellite observations. To **decide**, per location in the field, on the application dose, the user inputs their user dose which is subsequently adjusted per location in the field, based on the soil properties and characteristics of the PPP. Additionally, decision support models which calculate the minimal effective dose based on soil characteristics are available, of which the model in Akkerweb (succeeded by FarmMaps) (Kempenaar et al., 2013) is an example. For application on sandy soils (lutum percentage < 10%), the model in Akkerweb uses organic matter content to determine the minimal effective dose. On heavier soils where the lutum percentage is > 10%, the minimal effective dose is determined based on the lutum percentage. **Application** is done using a variable-rate application capable sprayer. Before application, the user prepares his tank mix, which contains a fixed concentration of PPP. In many cases, variable-rate application capabilities of the sprayer are limited to one application rate for the working width. This is taken into account while preparing the task-map with application rates by converting the minimal effective doses into one dose over the entire width of the spraying boom (see section 3.1 and Figure 1).

Variable-rate application of soil herbicides is illustrated using a plot of onions of 8.33 ha, grown in 2019 on sandy soil (lutum < 10%). Figure 2A shows the map of organic matter made based on **measurements** from a Veris MSP-3 soil scanner. The farmer decided to use the PPP Wing-P as a soil herbicide after the crops emerged. Instructions on the label of Wing-P (14881-W1) indicate an advised dose of 4.0 l/ha for application in onions post-emergence. The **decision** model for variable application of soil herbicides in Akkerweb (FarmMaps) (Kempenaar et al., 2013), taking into account the organic matter map of the field, calculated an average minimum effective dose of 1.32 l/ha with a maximal dose of 1.54 and a minimal dose of 1.13 l/ha. The map displaying minimum effective doses is shown in Figure 2B. Compared to the advised dose, a reduction in applied PPP of 67% is achieved using this variable-rate application. For **execution** on a sprayer which was capable of variable-rate application over its working width of 24 m, the map was translated. Grid cells of 10 x 24 m were created based on the average dose under each cell (see Figure 1) and the amount of spray mixture to be applied is converted to spray volume (l/ha) instead of the dose of the PPP. The grid cells were placed such that the sprayer (working width 24 m) is over one cell at a time. This map instructs the sprayer to adjust the dose every 10 m, a choice which was made to keep the number of cells in the task-map limited in order to avoid over-flowing the terminal used to control the sprayer.

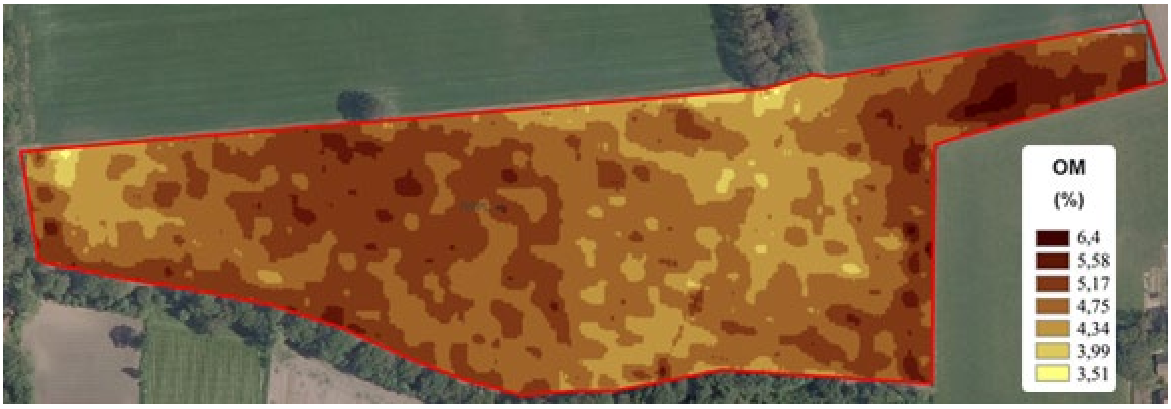

Figure 2A Map of organic matter created by Veris MSP-3 soil scanner

Figure 2B Minimal effective dose of Wing-P, in litres of PPP per hectare

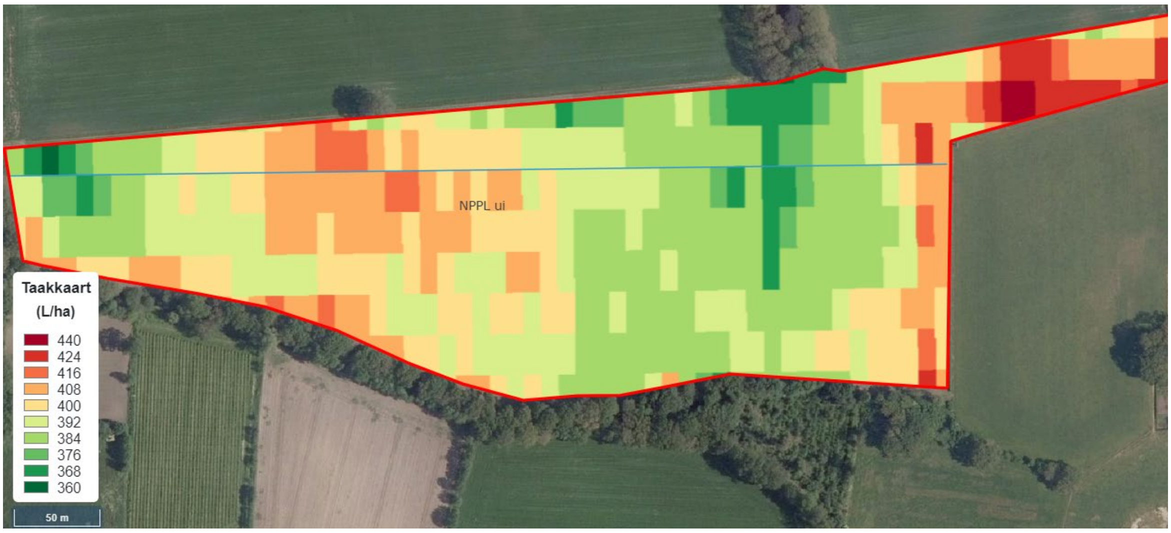

Figure 2C Task-map displaying spray volume adjusted to working width of the sprayer, in litres tank-mix per ha

Multiple participants in the NPPL applied this precision-application over multiple years. Results indicate an average reduction of applied PPP of 13% with respect to the user dose previously used by the farmers. It should be noted that the growers rarely applied the advised dose. Instead, they often used a lower dose (user dose) based on practical experience. Reductions are highly dependent on soil variation. Due to high variation in organic matter content within fields, one farmer was able to achieve a PPP use reduction of 27% with a precision application compared to a non-precision application based on user dose. Another farmer, whose field showed only limited variation in soil characteristics, achieved an 8% reduction with this precision application, compared to a non-precision application based on user dose. This clearly indicates the influence of variations within a field on the (potential) reduction in applied PPP using this variable-rate application.

4.1.2 Variable-rate haulm killing application

The variable-rate haulm killing application uses the minimal effective dose for haulm-killing agents, based on measured vital potato foliage, for efficient potato haulm killing. This application can be executed both on-the-go and in a chained way of working.

The chained version of this application is illustrated using a field of potatoes of 12.7 ha. As a result of variation in moisture-availability within the field, crop senescence showed large differences. Figure 3A shows a biomass (NDVI) map obtained from drone **measurements**. The farmer decided to do a chemical haulm killing operation, for which the PPP Quickdown is used. Instructions on the label for Quickdown (13246N W.5) advise one or two applications with an advised dose of 0.8 l/ha.
Based on the measured biomass, the decision model in Akkerweb (FarmMaps) **determined** an average dose of 0.65 l/ha to be sufficient for effective treatment. This minimal effective dose calculated by the model varies between a maximum of 0.7 l/ha and a minimum of 0.55 l/ha. The map of minimal effective doses is shown in Figure 3B. **Execution** is done using a sprayer with a working width of 45 m which allows one variable application rate over the entire working width. The map in Figure 3B is thus converted to a task-map (Figure 3C). Plots of 10x45 m are created showing the application rate for the tank-mix with a fixed concentration of Quickdown. Compared to a non-precision application, where the advised dose of 0.8 l/ha would be applied over the entire field, a reduction of 19% in the amount of PPP applied is achieved by the variable-rate application. If the entire field would be treated with the highest minimal effective dose (0.7 l/ha) calculated by Akkerweb, the reduction would be 12.5%, compared to the advised dose.

Figure 3A Biomass (NDVI) map from drone measurements

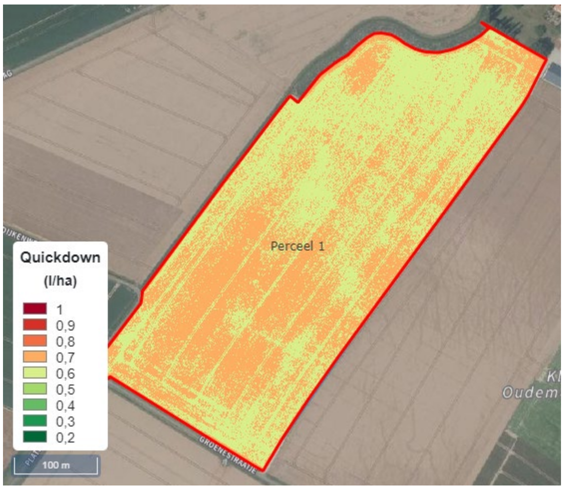

Figure 3B Minimal effective dose Quickdown (l/ha) obtained from the Akkerweb decision model

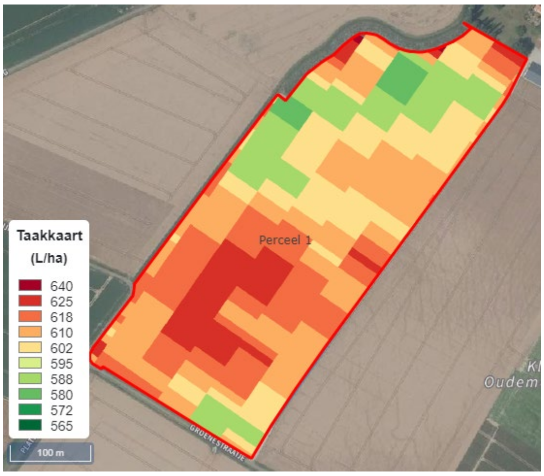

Figure 3C Task-map (taking into account sprayer dimensions) converted to tank-mix in litres per ha

Multiple NPPL-participants have worked with this variable-rate application, all focussing on potatoes. Most farmers used a sprayer which could apply one variable rate over the entire working width. To ensure effective haulm killing, farmers decided to use the created task-map in such a way that the highest minimal effective dose under the spraying boom would determine the application rate of the sprayer (Figure 1B). The reduction in PPP applied when comparing the variable-rate application to a treatment with the farmers' user dose depends on the variation within the field. Comparison of the user dose with the minimal effective dose resulted in a reduction of PPP applied between 17% and 27%.

4.2 Spot-spraying applications

One spot-spraying application from practice is presented in this section to illustrate applications in this application-category. This is the application *precision weed control using weed detection and spot spraying*.

4.2.1 Precision weed control using weed detection and spot spraying

Precision weed control using weed detection and spot spraying is an application aimed at minimizing the amount of PPP applied for effective weed control. This application can be used either on-the-go or chained.
In the chained version, images of the entire field are captured using a drone. These images, including their coordinates, are processed into one large image covering the entire field. This image effectively is the **measurement** of the field. Image analysis software subsequently processes the image,

detecting weeds which should be treated and logging the exact location of these weeds (GPS coordinates). Alternatively, farmers themselves can inspect the images on their computer and indicate the location(s) of weeds. At these locations, a herbicide application is required (**decision**). Current image analysis algorithms do not advise on a minimal effective dose for efficient control of the specific weed (patch). To ensure that the weeds and any small seedlings of the weeds are effectively treated, an application zone with the shape of a circle or square is often drawn from the centre of a detected weed. Depending on the type of sprayer (technical possibilities) and the type of weed(s) to be controlled, application zones between 25 cm and 6 m in diameter may be used. The locations of these application zones are communicated to the sprayer using a task-map. During **execution**, the sprayer will only apply the tank-mix on the application zones as indicated in the task-map, leaving the rest of the field untreated.

This application is illustrated using a field of carrots with a size of 5ha. At the start of june, a drone was used to capture images of the field (**measure**). After finishing the measurement, the images were combined to one large image covering the entire field. An image analysis algorithm was used to detect weeds, in this case mainly sow thistles, obtaining their exact GPS location (and **deciding** to apply there). Subsequently, a circular application zone with diameter of 50 cm was constructed on these GPS-locations while combining zones which overlapped. This resulted in a task-map as visualized in Figure 4, which results in an application of Boxer (10701 N W.11) at a rate of 2.5 l/ha on only 12% of the field during **execution**. A non-precision application would result in the entire field being treated with an equal dose of 2.5 l/ha Boxer (user dose). This precision-application thus results in a reduction of 88% for total PPP used when compared to non-precision application using the farmer's user dose.

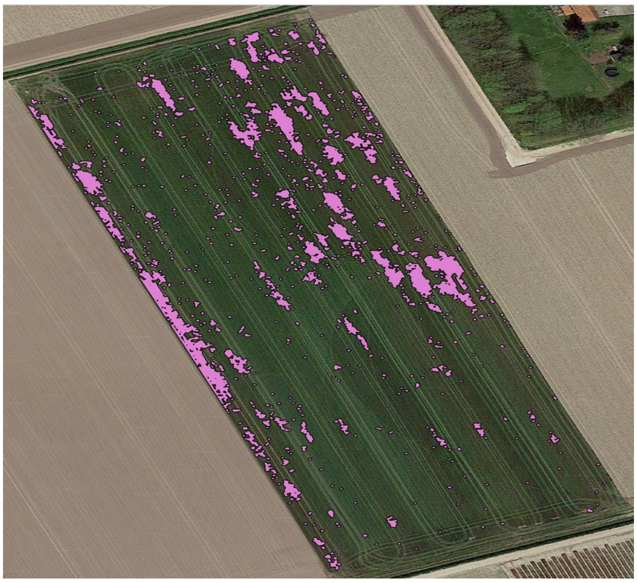

Figure 4 Task-map for spot spraying weed control of sow thistle

Precision weed control using weed detection and spot spraying was done by three NPPL-participants in five different situations. In each situation, a specific weed was targeted using a PPP authorised for use in the crop which was grown on the field at that time. The weeds were detected using an image analysis algorithm which analysed images recorded using a drone (chained application). This application can be used in multiple settings. Within NPPL it was used to target sow thistles in carrots, couch grass in onions, rumex in grassland, volunteer potatoes on bare soil and field thistle in spinach. Overall, the precision application resulted in a 45% reduction in applied PPP compared to non-precision application. This reduction is strongly linked to the weed pressure in the field. Fields with many weeds will result in a lower reduction of PPP applied compared to fields with only a few weeds. Reductions ranged from 41% to 88%. The NPPL-participants indicated they'd like to see this application in a hybrid form, where the applied dose per spot is corrected to match the minimum effective dose for that specific weed-plant, taking into account size and/or growth stage of the weed.

4.3 Hybrid applications

A hybrid application from practice is presented to illustrate this application-category. The application presented is *precision-spraying in tree fruit production*

4.3.1 Precision-spraying in tree fruit production

The precision-application *precision-spraying in tree fruit production* clearly shows each characteristic of a hybrid application. Sensors connected to the orchard sprayer are key in this application, as they play a crucial role in both the spot-spraying and the variable aspects of this application. During application, the sensors measure continuously to determine if the spray nozzles are located besides a tree and to determine the height of the tree. Only if the spray nozzles are located besides the biomass of a tree will they be activated. This decision is made per spray nozzle, so that spray nozzles which are not located directly besides a tree and/or spray nozzles which are above the tree will not be activated. This aspect is visualized in Figure 5 column 1. In the *on-the-go* version of this application, the application dose is determined by the biomass of the leaves, measured by the sensors. In the *chained* version of this application, the application dose is obtained from a task-map which was made earlier. Figure 5 column 2 visualizes the *on-the-go* version of this application, showing the measurement of the biomass of the tree and its leaves at different heights. The measured biomass is translated into a minimal effective dose, as visualized in Figure 5 column 3. In Figure 5 column 3, the blue bars indicate the base-dose which is always applied if the nozzle is besides a tree, even at minimal biomass. The orange bars indicate the difference between the base-dose and the minimal effective dose. Combining the blue and orange bars leads to the minimal effective dose, which is sent to the sprayer as application dose. The sprayer can individually control this rate per nozzle.

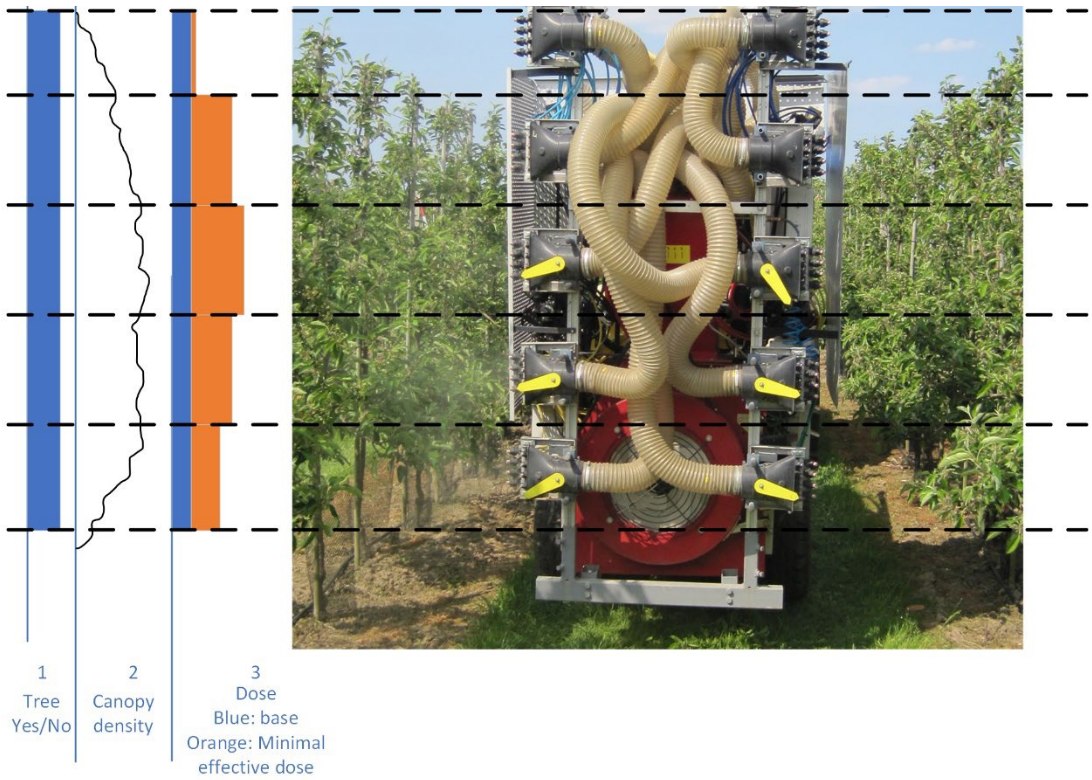

Figure 5 Technical representation of precision-application *precision-spraying in tree fruit production*

This application is illustrated using an example from the *Fruit 4.0* research-project (Ossevoort *et al.*, 2016), where camera-technologies were used to do selective blossom thinning in part of an apple orchard (Hoog *et al*, 2019). This application started by taking images of each individual apple-tree using the camera-solution. The captured images were subsequently analysed using an image analysis system capable of detecting the blossoms on the tree. Combining the camera and analysis technology resulted in a map containing the number of blossoms per individual tree (**measurement**). Figure 6A displays the results of the analysis, where each circle represents a tree and the color of the circle indicates the number of blossoms on this tree. This measurement was used twofold. First, a **decision** was made, per tree, if thinning was required at all. This was the case if more than 25 blossoms were counted on an individual tree. If thinning was required, the correct dose was subsequently calculated from the measured number of blossoms on the tree (**decision**, variable). Chemical thinning in orchards is incredibly delicate as the number of blossoms on a tree substantially influences the financial yield of a tree both in terms of quantity and quality. If a too high dose is applied during thinning, too many blossoms will be removed, resulting in a low yield. Figure 6B displays the task-map for the **execution**. The orchard-sprayer which was used could not yet vary the dose per side, which meant the application dose as shown in Figure 6B is calculated from the average minimal effective dose for the tree on the right side and on the left side of the path.

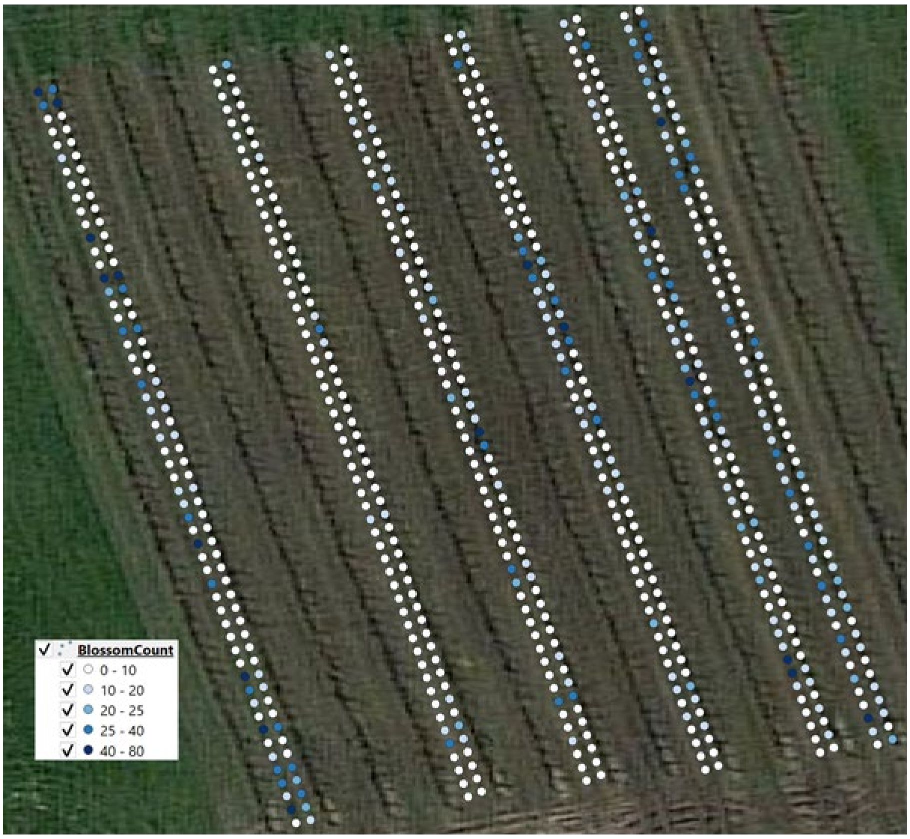

Figure 6A Number of blossoms counted per tree from the camera-images and image analysis system. Each circle represents a tree; the color indicates the number of blossoms on the tree. The measurements did not cover the entire orchard. (Hoog *et al.*, 2019, visualization updated)

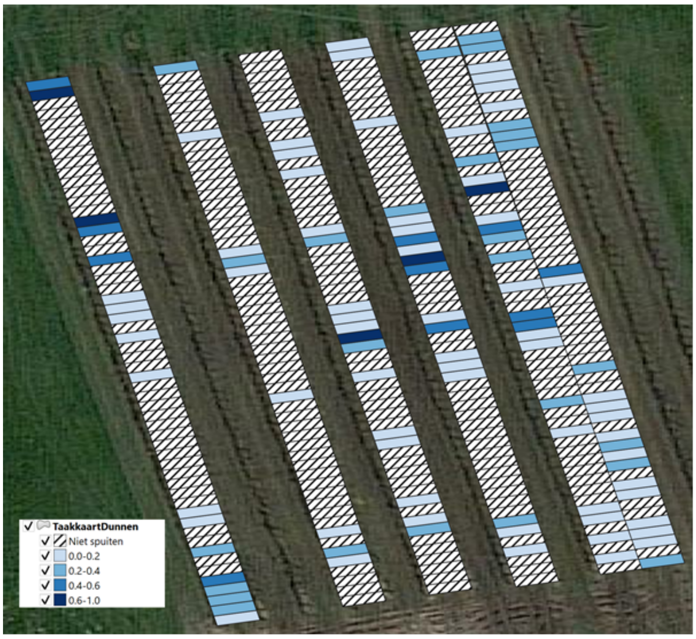

Figure 6B Task-map (relative dose) for chemical thinning based on flower-count. (Hoog *et al.*, 2019, visualization updated)

5 Overview precision-applications for plant protection products

Table 2 provides an overview of current precision-applications for the application of plant protection products. The precision applications are categorized per application-form. The degree of adoption in practice is also indicated in the table.

Table 2 Overview precision-applications for plant protection products

Application method	Application	Brief explanation	Adoption in practice
Variable-rate application	Variable-rate soil herbicide	The minimal effective dose of soil herbicide is calculated, based on soil characteristics (soil map)	Ready for wide application in practice
	Variable-rate Phytophthora protection	The minimal effective dose of herbicide for Phytophthora Infestans protection is calculated, based on two subsequent biomass measurements and growth model output.	In use by early adopters
	Variable-rate haulm killing	The minimal effective dose of haulm killing product is calculated, based on a biomass measurement	Ready for wide application in practice
Spot-spraying application	Spot-spraying for control of perennial weeds	The locations of perennial weeds are mapped and only these locations are treated during the spraying operation	In use by early adopters
	Spot-spraying for control of couch grass in flowerbulbs	The locations of couch grass are mapped and only these locations are treated during the spraying operation	In use by early adopters
	Spot-spraying for control of volunteer potatoes	A robot is fitted with camera(s) and an image analysis algorithm for detection of the volunteer potatoes. The robot has an actuator to specifically remove the volunteer potato plants	Multiple systems currently being tested in practice
Hybrid application	Precision spraying in tree fruit production	Sensor determines if sprayer is next to a tree. Sensor determines tree height and only activates nozzles at required heights. Canopy density is determined, and minimal effective dose is applied. Individual trees can be sprayed using a task-map.	In use by early adopters

6 Optimization of the application of plant protection products

Precision-application is one of the ways of optimizing the application of plant protection products (PPPs). Other methods target the third step of precision, the **execution**, by resulting in higher deposition on the target and/or a more effective method of application so that the application dose can be lower. These optimized methods of application can be part of a precision-application if these application-methods also contain a measurement and decision-step.

Conditions during application
Weather-conditions play a crucial role in the effectivity of the application of PPPs, where wind and evaporation are key aspects. At this moment multiple decision support systems (DSSs) which indicate the relative effectivity of a PPP-application based on the (predicted) weather conditions are available. However, the decision on when to apply often follows from a compromise between (predicted) weather conditions, the situation in the field and available time. Even though the minimal effective dose calculations in models often presume sub-optimal conditions during application so that a margin exists, it is essential to try and find an optimal moment for application within what is feasible. Better conditions during application result in higher on-target deposition and/or higher effectivity of the application.

Conditions during application go hand in hand with tuning the sprayer. The Dutch public-private partnership project *Innovatieve Efficiente Toedieningstechnieken* (Innovative, Efficient application-techniques) reported on-target deposition increases up to 60% could be achieved by optimizing the sprayer's tuning, compared to tuning as used in practice. This increased deposition can lead to increased effectivity of the PPPs and could be reason to decrease the application dose, thus resulting in a decrease in PPP applied.

6.1 Automatic section- or nozzle control

Sprayers can be equipped with automatic section control. This system has two ways of avoiding application in a location where application is undesired. In the first situation, information on the location and position of the spraying boom is used by the sprayer's control terminal to calculate if any part of the spraying boom is passing over an area which was already treated in an earlier pass (during the same application). If any part of the spraying boom is above such area, for example when reaching the headland or when dealing with non-parallel spraying lanes, this section will automatically be turned off by the sprayer's control terminal to avoid double treatment. In the second situation, the sprayer's control terminal constantly checks if any part of the spraying boom is outside of the field boundary or planted area additional to the double treatment checking mechanism. Parts of the spraying boom which are outside the field boundary or planted area are also automatically turned off. This functionality requires a constant calculation-process on the sprayer's control terminal where the position of each individually controllable section on the spraying boom is calculated. Newer systems allow for this process to be done on individual nozzle level instead of per section, which does require more computational power.

6.2 Sprayers for row, strip or bed specific application

Sprayers for row or bed specific application are sprayers where the nozzles are placed conform the layout of a planted or seeded field. A sprayer for row application, where nozzles are placed exactly above each crop row (Figure 7A), can for example be used in a fungicide application on a crop which has just emerged. In this situation only a few percent of the field is covered by the small crop plants, which makes a full-field application inefficient. Specifically targeting the rows of plants (and thus no longer treating the entire field) by placing nozzles only directly above the crop row results in a decrease in area treated and thus in a decrease in the total amount of PPP required to effectively treat the field. The opposite situation, where the entire field but the crop rows should be treated, can also occur. This situation is referred to as strip application. The sprayer is configured in such a way that the nozzles are placed exactly between two crop rows for treating the inter-row area. In both situations, protective tunnel-covers can be added to the sprayer (Figure 7B). These tunnels can be used either to protect the crop while treating the inter-row area or to form a protective cover around the nozzle, reducing the chances of spray drift.

Figure 7A Sprayer for row specific application

Figure 7B Sprayer for strip application equipped with tunnels protecting the crop during inter-row application

Slightly different from the sprayers for row specific or strip application are sprayers for bed specific application (Figures 8A and 8B). In a sprayer for bed specific application, nozzles are placed in such a way that they efficiently cover a bed and do not (or as little as possible) target the lanes in between. The opposite situation, where only the lanes are targeted and the beds are not, can also occur. Similar to sprayers for row specific or strip application, sprayers for bed specific application can be equipped with tunnels to protect the area not targeted or to house the nozzles, limiting chances of spray drift.

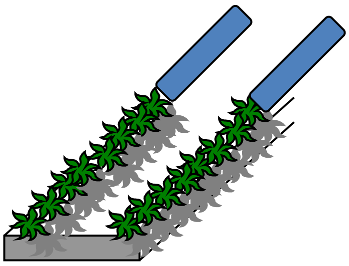

Figure 8A Row specific application (treated area in blue)

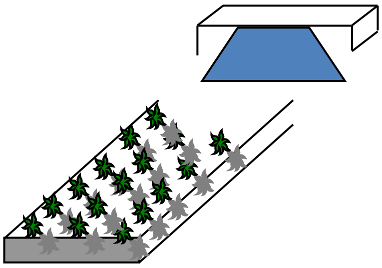

Figure 8B Bed specific application with protective tunnel (treated area in blue)

6.3 Tunnel-sprayer for orchards

In tree fruit production, a tunnel-sprayer can be used for application (Figure 9). The sprayer is equipped with a system which uses fans to create an almost horizontal airflow from the nozzles through the tree canopy to the other side of the tree. Spray liquid not deposited on the leaves or tree is captured in the outside tunnels and recirculated. The amount captured depends on the biomass-development of the canopy during the growing season. As application with a tunnel-sprayer results in a better deposition, the application dose of PPP can be decreased by up to 30% without influencing the effectivity of the application when compared to application with a traditional orchard sprayer.

Figure 9 Two row tunnel-sprayer with recirculation-system

7 Precision agriculture and the authorisation of plant protection products

7.1 Current practice

Precision-application of plant protection products (PPPs) can result in a reduction of PPP applied, resulting in more sustainable crop production. Additionally, it is suggested that precision-application of PPPs can lead to an increased yield. However, high investment costs, technical challenges and uncertainty about the effects of precision-application are show-stoppers at this moment. Results obtained from the Dutch National Experimental Garden for Precision Farming (NPPL) and other public private partnership projects currently yield insights in the potential of precision application of PPPs, providing growers with a perspective on how to apply these applications in their operations. A key point is incorporation of these precision applications in the assessment methodologies for the authorisation of PPPs.

7.2 Relation to authorisation methodologies for plant protection products

In the assessment methodologies for the authorisation of PPPs, an important aspect is the (predicted) exposure of different protection goals to these PPPs and the effects of this exposure. Protection goals are, among others, surface water, soil, non-target plants and arthropods, users and local residents. The amount of PPP deposited on the protection goal is referred to as the exposure of the protection goal. In the exposure calculation, important aspects are, among others, distance between application and the protection goal, mobility of the active ingredient(s), application technology and weather and soil conditions. In this process of determining (predicting) the exposure, the advised dose is used as the applied dose. A scenario where an entire field is treated using the advised dose is used to calculate the effects, which are subsequently assessed, leading to an authorisation under conditions or a ban on the application of the PPP. Additional conditions for application, leading to a decrease in exposure for one or multiple protection goal(s), can be included in the authorisation. Figure 10 provides a schematic view of the situation which is used by the assessment of a PPP for authorisation.

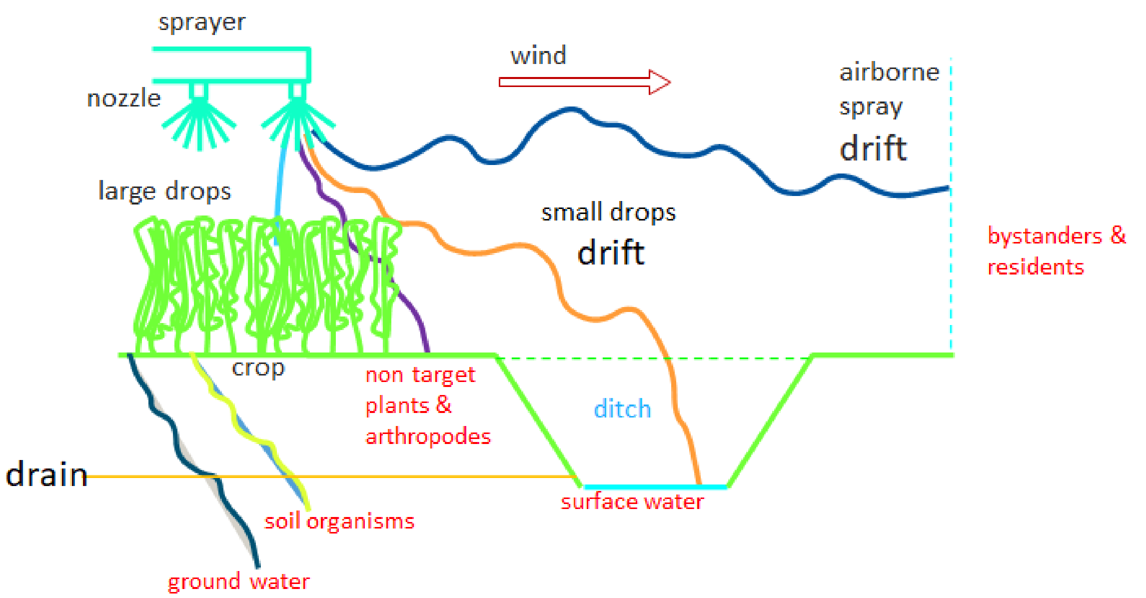

Figure 10 Schematic representation of exposure-routes and protection goals during the application of plant protection products in open field production. Position of the spray nozzle (off center nozzle) is dependent on the crop.

Precision applications for PPPs all aim at applying exactly what is needed for an effective application: protection of the cultivated crop or control of weed plants. The goal of adding precision to the application is to optimize effective deposition on the target, requiring a lower application dose and thus also reducing the exposure of protection goals. Documentation or evidence for the reduction of exposure of one or multiple protection goals precision application will result in is important for the authorisation procedures. This is discussed in more detail in the following paragraphs.

7.2.1 Variable-rate applications

Variable-rate applications aim at determining and applying the minimal effective dose of PPP per location in the field. This means the application dose and applied dose often are lower than the advised dose. For multiple protection goals, for example surface water and local residents, the combination between applied dose and distance plays an important role in the exposure. By reviewing application doses or, preferably, applied doses, by means of task-maps or as-applied maps, insights in both the applied doses and distance to the protection goals can be gained. Compared to using the advised dose and/or a constant average dose applied over the entire field, the use of these maps allows for more accurate exposure calculations.

7.2.2 Spot-spraying applications

Spot-spraying applications aim at applying only where necessary. Making a data-driven decision on the necessity of application per location in the field can lead to a significant decrease in the amount of PPP required to effectively treat the entire field. Though the application dose is not varied, a spot-spraying application influences the distance between location(s) of application and protection goals. The as-applied map or the task-map can be used to accurately calculate the exposure of the protection goals, which could be aggregated for the entire field as to provide an overview of the application and its impact.

7.2.3 Hybrid applications

Hybrid applications aim at both minimizing the application dose and minimizing the area of the field which is treated. Hybrid applications thus influence the exposure of protection goals both inside and outside the field, as the application dose is varied and the distance between application and specific protection goals can change. A lower application dose and possibly a larger distance between application and the protection goal(s) both results in a lower exposure of the protection goal.

7.3 Operationalization: Task-map assessment

The reduction in PPP applied when comparing a traditional application to a precision-application will be highly dependent on the situation in the field. As each specific situation requires a task-map to be purposely made for a precision-application, the application of a specific PPP can no longer be characterized by the average applied dose and/or by assuming application occurs everywhere in the field. The applied dose per location in the field and the location of the field can directly be obtained from the as-applied map (or application dose from the task-map). Other information required to predict the exposure of the protection goals in a specific situation can often be obtained from open datasets. In the current assessment methodologies for the authorisation of PPPs the exposure of each protection goal is predicted per application with the specific PPP using the advised dose. Taking into account the task-map or as-applied map and using open data could result in a more realistic estimation of the exposure per protection goal. It is important to take into account the possibilities and/or limitations of the sprayer if a task-map is used instead of an as-applied map (refer to Figure 1). Other drift-reducing measures taken, besides a precision application, can also be taken into account in this calculation. Estimating or predicting the exposure for a specific spraying operation allows for tailor-made assessment.

7.4 Feedback on impact

When task-maps for planned precision-spraying applications are assessed, the impact this exact operation will have on the different protection goals can be communicated to the user. Based on the provided insights, the user can reconsider the planned operation and possibly decide to take extra measures which help to reduce the exposure of the protection goals. The assessment-system could possibly aid this process by suggesting measures which help reduce exposure of a specific protection goal and by helping the farmer choose the optimal moment for application, taking into account predicted weather conditions. When assessing as-applied maps for precision spraying operations, the assessment-system can provide insights in the exact impact of the spraying operation. Providing these insights is an important step towards integrated pest management, aimed at an effective application with minimal impact for the environment.

7.5 Validation

In light of the above, it is important to have insights into how precisely the task-map was actually applied in practice by the sprayer, taking into account the possibilities and/or limitations of the sprayer to exactly apply the application dose on exactly the right location (also refer to Figure 1). Only when the applied dose matches the application dose (planned) can the task-map be used to accurately calculate the exposure of the different protection goals. This information can be used to register spraying operations for compliance and to prove how much has actually been applied. An as-applied map, indicating where the sprayer applied, what the applied dose was and what the application dose was, can also be used. Assessment of the as-applied map can provide insights in the exposure of the different protection goals.

8 Discussion

Precision-applications for plant protection products (PPPs) are aimed at applying exactly what the plant needs. In a variable-rate application, the dose is varied to match the situation per location. The calculated minimal effective dose in such applications often is lower (and never higher) than the advised dose, which also effects the exposure of different protection goals. In spot-spraying applications, focus is on only applying where necessary, which influences the exposure of different protection goals. In a hybrid application, the components of a variable-rate application and a spot-spraying application are combined into one operation, also resulting in an effect on the exposure of different protection goals. To be able to include the effects of precision application on the exposure of the different protection goals in the assessment methodologies for the authorisation of PPPs, it is essential to quantify the differences in exposure per protection goal. Differences in exposure per protection goal may occur, as each protection goal has its specific challenges. Additionally, aspects related to specific precision applications must be taken into account. These aspects will be discussed in this chapter.

During the quantification of precision-applications and their impact on PPP use, average doses are mostly used as indicators. However, in the light of crop protection, knowing the average dose is not enough to accurately calculate/estimate the exposure of different protection goals. Comparing example precision application 1) where the area close to ditches requires a minimal dose (variable-rate) or no application at all (spot-spraying) to example application 2) where the area close to ditches requires the advised dose (variable-rate) or to be fully treated (spot-spraying) could result in similar average doses over the entire field, though a completely different exposure of the protection goal surface water. For the assessment methodologies to be able to take the precision application aspects into account (for example difference between examples 1 and 2), it is thus important to know exactly what was done in which location in the field. Knowing only the average dose is not enough. Additionally, the limitations of the sprayer should be taken into account. In a variable-rate application with a sprayer which can apply one rate over the entire working width (Figure 1), the sprayer's limitations could lead to a lower applied dose (Figure 1C). The level of precision, which can be on entire working width, per section of nozzles or on individual nozzle, plays an important role. To be able to assess the situation as it is/was during application, information on the situation in the field and application, accompanied by information on the sprayer and its capabilities for precision application, is required. The latest generation of machines are capable of storing this information in as-applied maps, providing information on what the machine has actually done. The quality of such maps should be a point of attention at all times.

Precision applications can also have unwanted side-effects. When working with an on-the-go precision application, the total amount of tank-mix required to treat the field is not known in advance. This could result in left-over tank-mix upon finishing the operation, which is undesired. When a chained application is used, one output of the decision-step is the total amount of tank-mix required to efficiently treat the entire field. The user can thus precisely prepare the required amount and no tank-mix should remain after finishing the operation. It is important to consider this aspect during the assessment of specific precision-applications.

Incorporation of precision agriculture and precision-applications in the assessment methodologies for the authorisation of PPPs could require data to be transferred between different data-management systems. Despite continuous efforts to make and/or keep data compatible between these systems, the exchange of agricultural data remains challenging. A large part of this challenge is the compatibility of different file-formats. Machine manufacturers have individually selected a file-format for their machinery to work with when they started implementing precision in their machines, resulting in similarities and large differences. At this moment, shape-file and ISO-XML file formats are common. However, even within these file formats differences in interpretation exist between machine manufacturers. Machine manufacturers often have configured their systems/machines in such a way that task-map files containing ambiguous information are not accepted, which means the precision-application cannot be executed. If a system for assessment of individual task-maps and/or as-applied maps is to be built, compatibility should be a key aspect from the start. Only if data can (almost always) be exchanged without problems can such system contribute to more efficient crop protection and securing the process.

9 Conclusion

Precision agriculture will become a more important aspect in crop protection. Farmers clearly see the potential of reducing the amount of plant protection products (PPPs) applied, thus resulting in more sustainable production. This report presents definitions for the classification of precision-applications for PPPs and quantifies the potential of precision-applications to achieve a more efficient application of PPPs. Examples from Dutch practice are used to indicate the potential reduction of applied PPPs. The use of variable-rate applications may result in reductions of ~10 to ~40%. Spot-spraying applications may result in reductions beyond 75%, dependent on the application and the situation in the field. Hybrid applications are still under development and are mostly applied in research-setting. This often results in qualitative information about the application and its ability to obtain the desired result.

Precision-application can have an effect on the exposure of different protection goals. This indicates is required for this aspect in assessment methodologies for the authorisation of PPPs. Variable-rate, spot-spraying and hybrid applications can, by influencing the applied dose per location in the field, have an effect on the exposure of protection goals when compared to a full-field application with the advised dose. When using precision-applications, estimates of the influence on the different protection goals can be made, providing the user with insights in the (side)effects of the operation and possibly motivating changes to the operation to limit the exposure of protection goals.

To take precision-application into account in the assessment methodologies for the authorisation of PPPs, transparent and well-founded knowledge on the applications and their effects is necessary. It is important to ascertain to which extent a specific precision-application contributes to a reduction in the exposure of the protection goals. Additionally, it is important that the provided facts on exposure of protection goals and the effectivity of the application are generic. The assessment of task-maps and the analysis of as-applied maps helps to create this desired transparent knowledge.

10 Next steps

The project “Development of tools for systematic assessment” (BO-43-102.01-013) will continue by relating the presented terminology and examples to the exposure of protection goals. Case-studies will be done in which task-maps from practice and research will be used to situation-specific and location-specific assess the exposure of different protection goals. These case-specific exposures per protection goal will be compared to the exposure calculated for a full-field application of the applied PPP with the advised dose. The influence of precision-application on the exposure of the protection goals can be made more explicit by assessing each case in different ways and by comparing the calculated exposures per protection goal.

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