Simulation-aided study of herbicide patch spraying: Influence of spraying features and weed spatial distributions

Sylvain Villette, Thibault Maillot, Jean-Philippe Guillemin, Jean Paul Douzals

Simulation-aided study of herbicide patch spraying: influence of spraying features and weed spatial distributions

S. Villette [a*], T. Maillot [a], J.P. Guillemin [a], J.P. Douzals [b]

[a] Agroécologie, AgroSup Dijon, INRAE, Univ. Bourgogne, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France

[b] UMR ITAP, INRAE, Montpellier SupAgro, Univ. Montpellier, 361 rue Jean-François Breton, F-34196 Montpellier cedex 05, France

[*] Corresponding author

E-mail address: sylvain.villette@agrosupdijon.fr

Abstract:

Patch spraying is a technological way to reduce herbicide amounts required to control weeds by triggering spraying only where weeds lie. Nevertheless, the adoption rate of this technology by farmers is still low and there is a lack of efficient tools to assess patch herbicide applications depending on spraying features and weed spatial distributions. To avoid unrealistic in-field experiments, a virtual patch sprayer is designed and computer simulations are carried out to quantify herbicide reduction possibilities and assess the ability to apply the right rate on weed patches to ensure herbicide efficiency. The spray application simulator combines the theoretical description of the sprayer using various boom section widths (from 0.5 to 24 m) with experimental data describing various nozzle spray patterns obtained from three commercial nozzles. Virtual weed infestation maps are designed using random locations of weed patches with various spatial aggregation degrees modelled by different weed coverage rates and elliptical patch sizes. Simulation results are analysed through two performance indicators: i) the herbicide reduction ratio obtained with patch spraying compared to a uniform broadcast application (on the entire field area), ii) the proportion of weed patch area on which the application rate is higher than 85% of the prescribed application rate. Computer simulations enable to estimate a simplified relationship to quantify the reduction of herbicide use as a

function of the weed coverage rate, the size of weed patches and the boom section width. This demonstrates that computer simulations provide practical tools to estimate the sprayer spatial resolution required to reach a given herbicide reduction target according to the weed spatial distribution. Simulations also demonstrate that the use of narrow section widths equipped with traditional nozzles leads to a significant proportion of weed areas exposed to herbicide under-application in the case of small patches.

Keywords: computer simulation; virtual sprayer; patch spraying; herbicide use reduction; under-application.

1. Introduction

Weeds are known to be the most harmful pests (Oerke, 2006), reducing yields and harvest quality because of their competition with crops, harvest pollution or other pest organism propagation. Thus, weed control efficiency is essential to maintain agricultural production, and the most popular approach relies on chemical-based solutions consisting of uniform herbicide applications across fields. However, this approach is reaching its limits regarding environmental concerns, health issues and herbicide-resistant weed problems.

Since weeds are generally spatially aggregated and occur in patches (Cousens and Croft, 2000), various works have addressed site-specific or patch spraying for post-emergence herbicide applications (Gonzalez-de-Soto et al., 2016; Paice et al., 1995; Rasmussen et al., 2019; Shearer and Jones, 1991; Stafford and Miller, 1993). They have considered variable-rate applications or binary intermittent on/off applications. Thus, numerous remote (Thorp and Tian, 2004) and ground–based (Wang et al., 2019) weed detection techniques have been designed, for map-based or real-time approaches. Recent works demonstrated that new weed detection algorithms reached high level of crop-weed classification accuracy especially in the case of row crops such as 94.5% of good classification in maize (Gao et al., 2018). Therefore, current detection techniques provide accurate and high resolution weed maps (1.78 mm/pixel in Gao et al. (2018)). Moreover, the development of fast switching control actuators and RTK GPS auto-steer systems have improved the spatial accuracy of patch spraying. Thus, new sprayers enable to open or close each nozzle with a satisfying accuracy following the travel direction as measured by Gonzalez-de-Soto et al. (2016) who reported an average distance error of only 44 mm with a standard deviation of 66 mm using a unmanned patch sprayer designed for on/off applications. These results were obtained with a robot speed of 3 km/h and an area to be treated divided into cells of 0.5×0.5 m. The accuracy of commercial sprayers has also been recently studied by Rasmussen et al. (2019) with a weed map divided into 1 m^2 grid squares. The authors measured that 89-96% of weed target areas were actually sprayed with 3 m boom sections at a travel speeds of 6-8 km/h, 89-92% with 0.5 m boom sections at low travel speeds (2.5-3 km/h) and 77-85% with 0.5 m boom sections at 4 to 4.5 km/h. Considering the incorrectly sprayed area outside the weed patches, the sprayed area reached 42-108% of the target areas with 3 m boom sections at 6-8 km/h but only 2-4% with 0.5 boom sections at low travel speeds (2.5-3 km/h) and 7-8% with 0.5 boom sections at 4 to 4.5 km/h.

For two decades, various experimental works assessed patch sprayer prototypes and conducted field trials to estimate on the reduction of herbicide amounts required for weed control (compared to a uniform broadcast application). For example, in maize, Gutjahr et al. (2012) used a sprayer with an on/off control and equipped of three tanks with three herbicides against three weed groups. The herbicides were applied separately with spray boom sections of 9 m in width according to three binary application maps with a resolution of 9×9 m. Then, the average herbicide reduction was 10% for annual broadleaf weeds, 34% for annual grass weeds and 93% for perennial weeds. For the same crop, in four maize fields, Castaldi et al. (2017) obtained herbicide reductions from 14 to 39.2% using spray boom sections of 2 m in width and binary weed maps with a resolution set at 2×2 m. In another recent study, Esau et al. (2018) reach an herbicide reduction of 78.5% in wild blueberry fields infested of hair cap moss by using a real-time detection device and a sprayer equipped of boom section of 1.5 m in width. These few results illustrate that the reduction of herbicide amount varied over a wide range depending on herbicide spraying parameters and uncontrolled weed spatial distributions. Consequently, experimental studies showed potential reductions expected by using patch sprayers but they are not suitable to investigate how spraying features and weed spatial distributions affects herbicides reductions. Moreover, in most studies, the size of weed map cells is larger than the sprayer footprint and limits the application resolution.

To highlight more general trends and results, some authors have proposed establishing models to describe spraying performances relating to weed spatial distribution characteristics and sprayer key features. Wallinga et al. (1998) used distance measurements to describe weed spatial distribution and suggested to interpret the cumulative distribution function of point-nearest weed distances as an estimate of the amount of herbicide that an ideal patch sprayer can use relative to a whole field application. The ideal patch sprayer was assumed to apply a full rate of herbicide to a circular zone around each weed, irrespective of actual sprayer technical constraints. The authors estimated the herbicide reduction: 15% for a sprayer operating at a spatial resolution of 4 m, 38% at 2 m, 59% at 1 m and 76% at 0.5 m. The establishment of such relationship between herbicide reduction and spraying spatial resolution is interesting but the curve provided by the author only correspond to one specific weed spatial distribution characterised on a very small plot (32.4×18 m). Moreover the circular application assumed for the ideal sprayer differs from how actual sprayer works. Carroll and Holden (2009) addressed the performance of a patch sprayer depending from control time, forward speed and boom section width. In particular, they simulated patch spraying on a set of weed maps established with a resolution of 1 m/pixel and classified in nine categories. They computed a spray application index and modelled this index as a function of two variables (*i.e.* boom section width and control time) and three regression parameters. The values of these three parameters were computed for each weed map class. The choice of this global index does not enable to estimate the herbicide reduction or the proportion of weeds correctly sprayed. Recently, Franco et al. (2017) addressed the problem of selecting the appropriate precision spraying technology for weed management. They performed simulations using two virtual weed maps built with a high number of small circular patches or only few bigger circular patches respectively. The spraying was simulated with section width of 1 to 40 m. As in the other studies, the authors observed that the potential herbicide savings not only depend on spraying resolution, but also on the weed coverage rate and the spatial distribution of weed patches. Franco et al. (2017) modelled the relative sprayed area as the sum of the weed coverage rate and a function of the total width of the boom and the width of each boom section. This regression model was deduced from only two simulated weed maps with very close weed coverage rates (10% and 10.9%) and cannot be generalized for a wide range of coverage rates. Furthermore, the model does not integrate any independent variable related to patch size or weed aggregation degree.

Virtual experiments based on numerical simulations appear as the best approach to characterize herbicide patch spraying when various sprayer resolutions and various weed spatial distributions need to be compared. Nevertheless, at the present time, there is still a lack of patch spraying model to describe interaction of parameters that affect the reduction of herbicide amount. Moreover, from the best of our knowledge, all herbicide spraying simulations presented in the literature assumed a uniform application of herbicide on the sprayed areas. This does not take into account the uneven application in the transverse direction that occurs when narrow boom sections or individual nozzles are controlled independently involving a lack of multiple spray overlapping. Although this risk of under-application has been identified for decades (Paice et al., 1995), no study has addressed or characterized this patch spraying weakness, which can lead to weed-control failure and emergence of herbicide-resistant weeds (Neve and Powles, 2005).

The objective of the present work is to develop a computer simulation model of intermittent on-off patch spraying to investigate the influence of nozzle spray patterns, boom section widths, weed infestation rates and weed spatial distributions on herbicide reduction, as well as on under-application area occurrence. The paper demonstrates that the use of computer simulations enables to establish a simplified relationship to quantify the reduction of herbicide use as a function of the spatial weed distribution (defined by weed elliptical patch size and coverage rate) and the boom section width. It also demonstrates that computer simulations enable to estimate the weed area rate exposed to herbicide under-applications related to nozzle spray patterns and section widths in the case of narrow weed patches.

2. Materials and Methods

Herbicide patch spraying was simulated combining virtual weed maps and a virtual sprayer. The virtual weed maps were designed using random locations of weed patches with various spatial aggregation degrees modelled by different weed coverage rates and elliptical patch sizes (*cf.* section 2.1). A virtual spraying was designed using experimental nozzle spray patterns (*cf.* section 2.2.1) and simulating the herbicide application with different boom section widths (*cf.* section 2.2.2). Two indicators were computed to assess the reduction of herbicide amount and the application efficiency (*cf.* section 2.3). The algorithms have been developed with the software Matlab (2019).

2.1 Modelling infestation map

In this paper, virtual binary maps were used to simulate weed maps that could be derived from weed detection and localization devices used on crops or bare soil. These maps include virtual weed patches that are perfectly defined and localised in the field. In order to put the emphasis on the impact of weed patch size and coverage rate, and on the ability of the sprayer to apply herbicide on weeds, the binary weed maps were simulated by placing full elliptical patches at random positions on virtual field bands. The theoretical shape of weed patches tends to be elliptical because of natural dispersal processes and elongated in the direction of field traffic (Dieleman and Mortensen, 1999; Paice et al., 1998) because of seed movements caused by soil tillage and crop harvesting (Barroso et al., 2006; Cousens and Croft, 2000). Therefore, in this paper, the representation of weed patches were simplified by considering elliptical patches oriented in the direction of cultivation operations (that is also the travel direction of the virtual sprayer) in accordance with the anisotropy in patch expansion due to directional management practices (Humston et al., 2005). Thus, elementary elliptical patches were defined by only two parameters: their width (w_w) and length (l_w). Because of the random distribution of the elementary ellipses, their overlapping provides a greater variety of shapes, size and orientation for weed patches resulting from the aggregation of several elementary ellipses.

The virtual field bands were 72 m in width, 20 000 m in length, and computed with a spatial resolution of 0.025×0.025 m/pixel (*i.e.* pixels of 6.25 cm²). For the simulations, the bands were made of 20 successive segments of 1000 m so that 20 cumulative values of the parameters of interest can be computed (*i.e.* on band lengths from 1000 to 20 000 m) and the convergence of the assessment indicators can be checked (see section 2.3). The band width corresponds to a central sprayer pass with a working width of 24 m and two adjacent bands. This ensures to avoid edge effects due to patch location bias or lack of spray overlap on central pass borders. A set of virtual field bands were computed for various weed coverage rates set at 5, 10, 20, 30, 40 and 50% of the total area; various ellipse lengths of 0.5, 1, 2, 4, 8, 16 and 32 m; and various width to length ratios of 0.2, 0.5 and 1 (ellipses are circles when the ratio is 1). Thus, a set of weed patch maps were simulated representing various infestation rates and aggregation degrees. Considering the same weed coverage rate, the aggregation degree increases when the size of ellipses increases. Because of the random distribution of ellipses, their overlapping provides a variety of shapes for distinct weed patches. Fig. 1 illustrates two examples of virtual weed infestation maps presenting the same global coverage rate but obtained for two contrasted patch sizes.

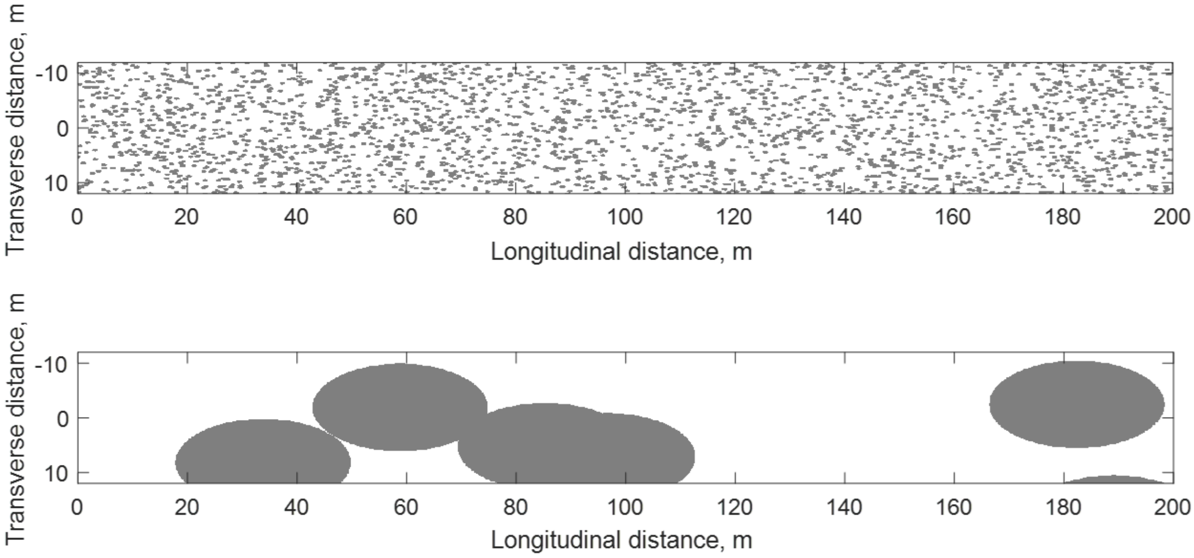


Fig. 1. Example of areas extracted from weed maps simulated for small elliptical (l_w = 1 m, w_w = 0.2 m) patches (upper row) and large elliptical (l_w = 32 m, w_w = 16 m) patches (bottom row) with a coverage rate of 20%.

2.2 Modelling patch spraying

Several virtual spraying configurations were developed as based on the replication of simulated transverse spray distribution patterns derived from experimental measurements or theoretical shapes.

2.2.1 Transverse spray patterns

Different transverse spray patterns (TSP) were considered to model the spray deposit under single nozzles. First, a rectangular pattern was designed as the uniform distribution of the product sprayed by a fictitious idealized nozzle. This theoretical spray pattern was centred under the nozzle and the spray width was set equal to the nozzle spacing s_N. Thus, this provides a uniform coverage over the length of a boom section when all nozzles of the section are switched on. Moreover, this uniform distribution is obtained without any overlap of the sprays of adjoining nozzles and it is not affected by the boom height. This idealized situation was traditionally assumed (mostly implicitly) for patch spraying simulations in the literature (Franco et al., 2017). Second, more realistic spray patterns were deduced from experimental measurements for three commercial nozzles with different spray top angles and different distribution shapes: a low-drift flat fan nozzle with a wide angle (CVI 110 02 supplied by Albuz Company), a low-drift flat fan nozzle with a narrow angle (IDK 90 02 supplied by Lechler Company) and an even flat fan narrow angle nozzle (TPE 80 03 supplied by Teejet Company). The transverse spray distributions of the CVI and IDK nozzles were measured at Julius Kühn-Institute, Braunschweig, Germany by Herbst (2019) using a 25 mm channel spray patternator. The experiments were carried out by placing the nozzles at 0.6 m height, with a constant water pressure of 2 bar. For each of these two kinds of nozzle, the reference spray pattern was computed as the average curve resulting from nine measurements corresponding to three repetitions with three different nozzles of the same series. The spray pattern of the even flat fan nozzle was derived from measurements carried out with a 60 mm channel spray patternator and published by Hassen et al. (2013) for a TPE 80 03 placed at 0.5 m height, with a constant water pressure of 2 bar.

For the three actual nozzles, the TSP at a specified boom height h was deduced from the reference TSP measured at the original experimental height h_0 following the method described by Mahalinga Iyer and Wills (1978). Once the TSP of a single nozzle has been computed at a specified height h, the distribution curve was resampled each 25 mm so that the spatial sampling was the same for all nozzles and all simulated boom heights.

Then, the spray pattern under the whole boom or under a particular boom section was deduced by summing all corresponding nozzle patterns after translating them with respect to the nozzle spacing (set at 0.5 m). The virtual flow rate was normalized so that the mean application rate was set at the unit value in arbitrary units (AU) after overlapping of the spray patterns.

In order to select relevant boom heights for each kind of nozzle, the coefficient of variation (CV) of the spray deposit (ISO 5682-3, 2017) was computed as a function of the boom height. This was numerically computed considering a boom width of 24 m and according to standard specifications (ISO 16119-2, 2013) by simulating a 100 mm groove patternator. Fig. 2 illustrates the curves of CV values drawn with respect to the boom height for the three actual nozzles (CVI 110 02, IDK 90 02 and TPE 80 03). The curves reached minimum values at particular boom heights that are optimal heights regarding spraying uniformity.

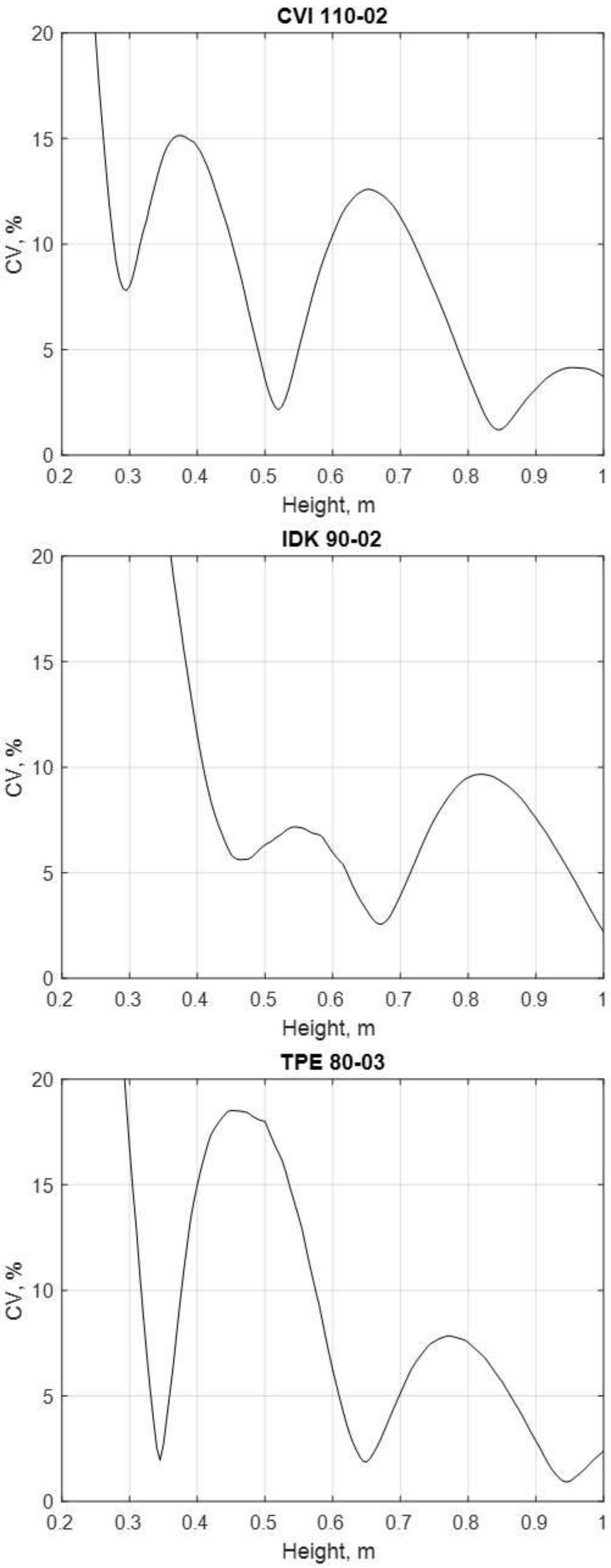

CVI 110-02
CV, %
Height, m
IDK 90-02
CV, %
Height, m
TPE 80-03
CV, %
Height, m

Fig. 2. Coefficient of variation (CV) of the spray deposit with respect to the boom height for three different actual nozzles: CVI 110 02 (top), IDK 90 02 (middle) and TPE 80 03 (bottom). CV values were computed considering a boom width of 24 m and a nozzle spacing of 0.5 m.

Table 2 presents the six operating conditions selected for the study. For each actual nozzle, the boom heights were chosen near to the optimal values. The selected values were rounded to the nearest 0.05 m to keep a practical meaning. For all selected heights, the CV values were lower than 7%, corresponding to a uniform spray in accordance with ISO 16119-2 2013. An additional indicator δCV_h was computed to compare the sensitivity of the CV (*i.e.* spray uniformity) to the boom height for each selected situation. This indicator was defined as follows:

$$\delta CV_h = MAX\left(CV(h_s + \delta h), CV(h_s - \delta h)\right) - CV(h_s) \quad (1)$$

where, $CV(z)$ is the value of the CV when the boom height is set at z, h_s is the boom height corresponding to the selected spraying situation, δh is the variation of the boom height. In table 2, δCV_h was computed when δh was 0.05 m (the smallest step according to the assumption made before).

For the six nozzle operating conditions, Fig. 3 illustrates the spray patterns obtained for a set of adjoining nozzles as well as the resulting cumulated application rate along the boom width (*i.e.* after overlapping of the spray of each individual nozzle).

Table 2

Main characteristics of the six nozzle operating conditions. CV is the coefficient of variation and δCV_h is the maximal increase of the CV value when the boom height fluctuates plus or minus 0.05 m.

Operating condition	**Nozzle**	**Shape of the transverse spray pattern**	**Boom height h_s (m)**	**CV (%)**	δCV_h
C1	Fictitious	Perfect rectangle	All values	0	0
C2	CVI 110 02	Triangular	0.5	3.6	6.6
C3	IDK 90 02	Triangular	0.5	6.3	0.8
C4	IDK 90 02	Triangular	0.7	3.9	3.6
C5	TPE 80 03	Even	0.35	2.7	14.0
C6	TPE 80 03	Even	0.65	1.9	4.4

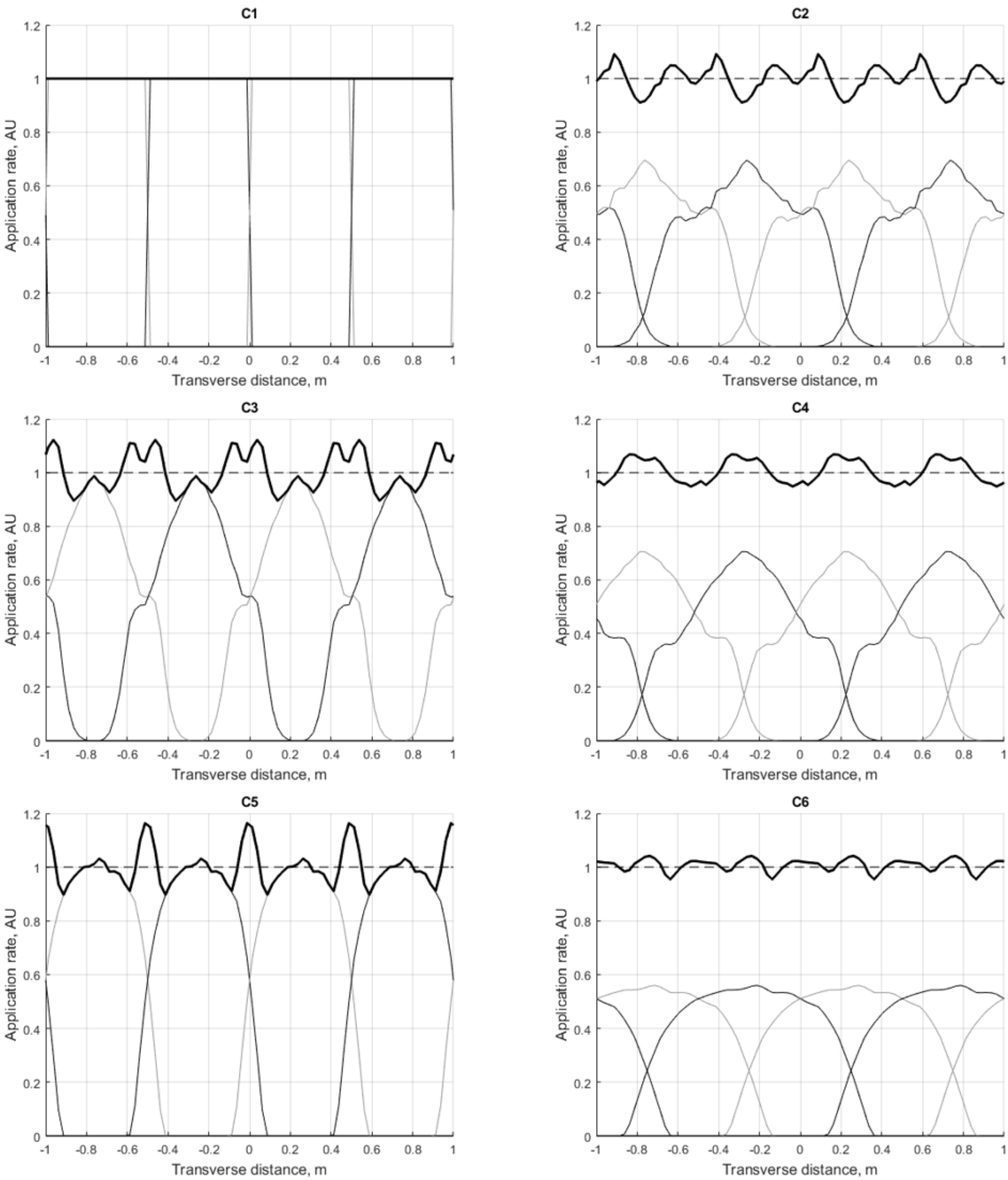


Fig. 3. Transverse spray patterns of adjoining single nozzles (thin lines alternatively grey or black for successive neighbouring nozzles) and global boom transverse spray patterns resulting from cumulated applications (bold line). The corresponding mean application rate (dotted line) along the boom is at the unit value (in Arbitrary Unit (AU)) for all operating conditions C1 to C6 (Table 2).

2.2.2 Nozzle control depending on weed presence

The patch sprayer was simulated using a simple model. The virtual boom was equipped with 48 nozzles spaced every s_N = 0.5 m. The nozzles were grouped together to form fixed section widths, which were independently controlled. Simulations were implemented with sections of 1, 2, 4, 6, 12, 24 and 48 nozzles (corresponding to section widths from 0.5 to 24 m). The spraying simulator was developed to obtain a spatial distribution of the spray deposit considering the spray overlap between adjacent nozzles, adjacent sections and adjacent sprayer passes (passes were spaced according to the sprayer boom width).

Instead of applying the herbicide on the whole simulated field, the model allowed site-specific spraying by switching on each section only when weeds (at least one pixel of the weed map) were present under the "weed detection width" of the section. Since nozzles were spaced every 0.5 m, the weed detection width of a section composed of N_N nozzles was assumed to be $N_N \times 0.5$ m. For example, in the case of nozzles controlled independently, the weed detection width was of 0.5 m centred under each nozzle as depicted in Fig. 4. Depending on the nozzle type (*i.e.* depending on TSP), the spray width can extend more or less widely from the detection width.

The on/off nozzle control on weed presence was assumed to be perfect: an instantaneous application was assumed, without any delay in sprayer response time or any smoothed herbicide rate transition in the travel direction (Carroll and Holden, 2009). Furthermore, herbicide applications are simulated considering spray patterns as measured in static situation using conventional spray patternators irrespective of any in-field spray pattern change or displacement related to travel speeds (Lebeau, 2004), wind conditions (Faqiri and Krishnan, 2005; Krishnan et al., 1993), or boom movements (Langenakens et al., 1999; Ramon and De Baerdemaeker, 1997). These simplified operating conditions are nevertheless representative of practical herbicide application at low travel speeds (frequently required by real-time weed detection systems and autonomous sprayer robot) in no-wind conditions.

Carrying out simulations, herbicide application maps were obtained with the same spatial resolution as the input weed maps (*i.e.* 0.025 × 0.025 m/pixel). The application was at the target rate when the value of the application map pixels reached the unit value (in Arbitrary Unit).

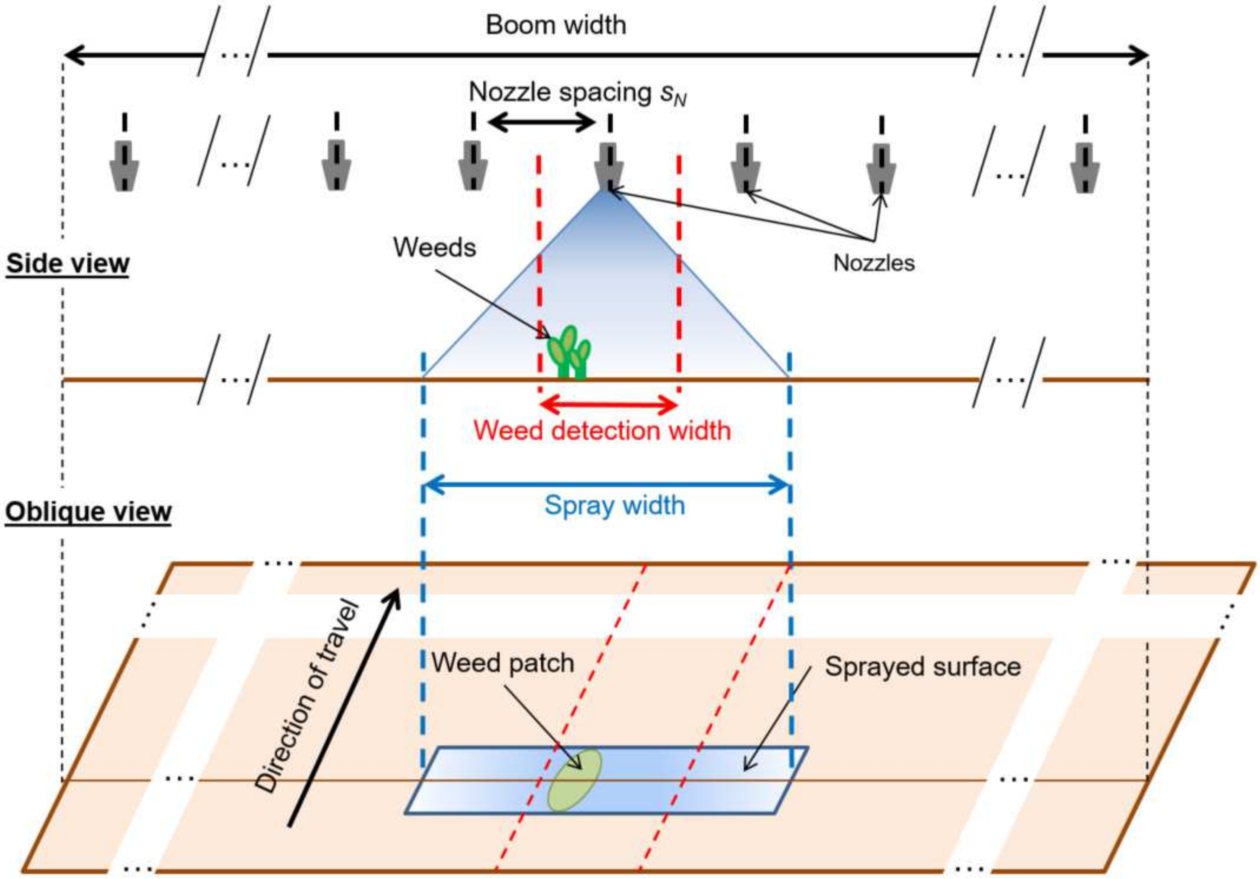


Fig. 4. Illustration of the weed detection width and the spray width in the case of nozzles controlled individually (only one nozzle is switched on in this example).

2.3 Spraying indicators

Two indicators were designed to assess the reduction of herbicide use and herbicide application efficiency. These indicators were computed on the surface corresponding to the virtual sprayer pass for the all length of the virtual field. The reduction of herbicide use was analysed through the dimensionless sprayed amount ratio τ_Q defined as:

$$\tau_Q = \frac{Q_S}{Q_T} \qquad (2)$$

where: Q_S is the amount of herbicide used in the case of a patch application and Q_T is the amount of herbicide required for uniform application at the target application rate on the entire field area.

To measure the efficiency of the spray application, a second indicator was defined as the proportion of weed patch area on which the application rate is higher than α percent of the prescribed application rate:

$$\tau_{WA>\alpha} = \frac{A_{WA>\alpha}}{A_W} \quad (3)$$

where: $A_{WA>\alpha}$ is the weed area on which the application rate is higher than α percent of the prescribed application rate and A_W is the total weed coverage area in the field.

In this paper, the threshold α was arbitrary set at 85% to provide a simple indicator related to the proportion of weed area receiving an application rate considered high enough to be lethal. The value of 85% was chosen lower than the minimal value of the application rate obtained after overlapping (Fig. 3), so that $\tau_{WA>85\%}$ would be 100% in the case of a blanket application on the whole field.

The values of the two assessment indicators are included in the bounded interval [0, 1]. For each spraying situation, the indicator values were computed on 20 iterations of the cumulative lengths of the virtual fields (*i.e.* from 1000 to 20 000 m in length). The convergence of the indicator values was checked by computing the maximum difference between the last value and the last five iteration values. The convergence was achieved slower in the case of biggest patches (32 m in length), nevertheless the maximum difference was lower than 0.013 for all situations when 20 iterations were computed. For most situations, the convergence was reached more rapidly during the first iterations. However, in this study the final value obtained for 20 000 m was used for all situations.

3. Results

Combining six weed coverage rates, seven patch lengths, three width to length ratios and seven boom section widths, 882 spraying simulations were computed for each of the six operating conditions C1 to C6 (Table 2). The results of these simulations were analysed regarding the sprayed amount ratio τ_Q and the ratio $\tau_{WA>85\%}$ of weed area exposed to more than 85% of the target application rate.

3.1 Analysis of the sprayed amount ratio

For all spraying simulations, the sprayed amount ratio τ_Q was analysed with respect to the boom section width. For example, for the operating condition C1, Fig. 5 depicts the evolution of τ_Q as a function of the boom section width for various weed coverage rates and for two contrasted examples of weed spatial distributions (*i.e.* weed patches of 0.2 and 8 m in width). Overall, τ_Q increases (*i.e.* herbicide reduction decreases) with the section width or the weed coverage rate. Furthermore, considering the same global coverage rate, the reduction of herbicide use is more important in the case of weeds aggregated in large patches than in the case of weeds dispersed in small patches. Fig. 5 also shows that the patch size directly affects the sensitivity of the herbicide reduction to the section width and the coverage rate. In a more refined way, in the case of small patches of 0.2 m in width, with a low weed coverage rate of 5%, the required amount of herbicide is very sensitive to the boom section width. The herbicide amount is approximately 19% with 1-nozzle sections, 50% with 4-nozzle sections and almost 87% with 12-nozzle sections. Moreover, regarding the effect of the infestation rate, the amount of herbicide approximately rises to 61% and 95% for 1 and 4-nozzle sections respectively when the coverage rate reaches 20%. In the case of large patches of 8 m in width, the reduction of herbicide use is more important no matter the spray section width and the infestation rate. Moreover, the ratio τ_Q is less sensitive to the spray section width and the infestation rate. In this case, the difference observed in the ratio between the use of narrow or large section widths is highly reduced. For example, when the weed coverage rate is 10%, the ratio τ_Q is 11% with 1-nozzle sections, 19% with 12-nozzle sections and less than 30% with 24-nozzle sections.

Comparing all simulations, the results show that the ratio τ_Q is not affected by the operating conditions (C1 to C6) thanks to the virtual flow rate normalization used in this study (*cf.* section 2.2.1). This normalization ensures that the mean value of the application rate obtained after overlapping is the same for all kind of nozzle and operating conditions (C1 to C6) for the same boom section width and same virtual weed spatial distribution (*i.e.* same weed coverage rate and same patch size). It also ensures that the herbicide amount virtually applied by a single nozzle is the same whatever its spray pattern. However, the surface area on which the same amount is sprayed by a single nozzle obviously depends on the nozzle spray pattern.

The simulation results have been used to study the impact of the weed spatial distribution on the sprayed amount ratio τ_Q. For constant values of weed coverage rate, section width and spray pattern, simulations show that the ratio only depended on patch width regardless their lengths in the travel direction. This is explained by the number of switched-on sections that are only depending on the width of the patches and by the cumulated surface area of patches that is constant for a given infestation rate whatever the patch shape.

Using successive regression analyses to fit the curves representing τ_Q as a function of the section width for different weed coverage rates and patch sizes, a mathematical expression has been designed to model the ratio τ_Q as follows:

$$\hat{\tau}_Q = 1-\left(1-\tau_w\right)^{\left(1+\frac{4w_s}{\pi w_w}\right)} \qquad (4)$$

where: $\hat{\tau}_Q$ is the estimated value of τ_Q, τ_w is the weed coverage rate (in [0, 1]), w_w is the width of the weed patches (in m) and w_S is the boom section width (in m).

The section width w_S is also expressed as follows:

$$w_s = N_N \times s_N \qquad (5)$$

where: N_N is the nozzle number of the section and s_N is the nozzle spacing (which was set at 0.5 m in this study).

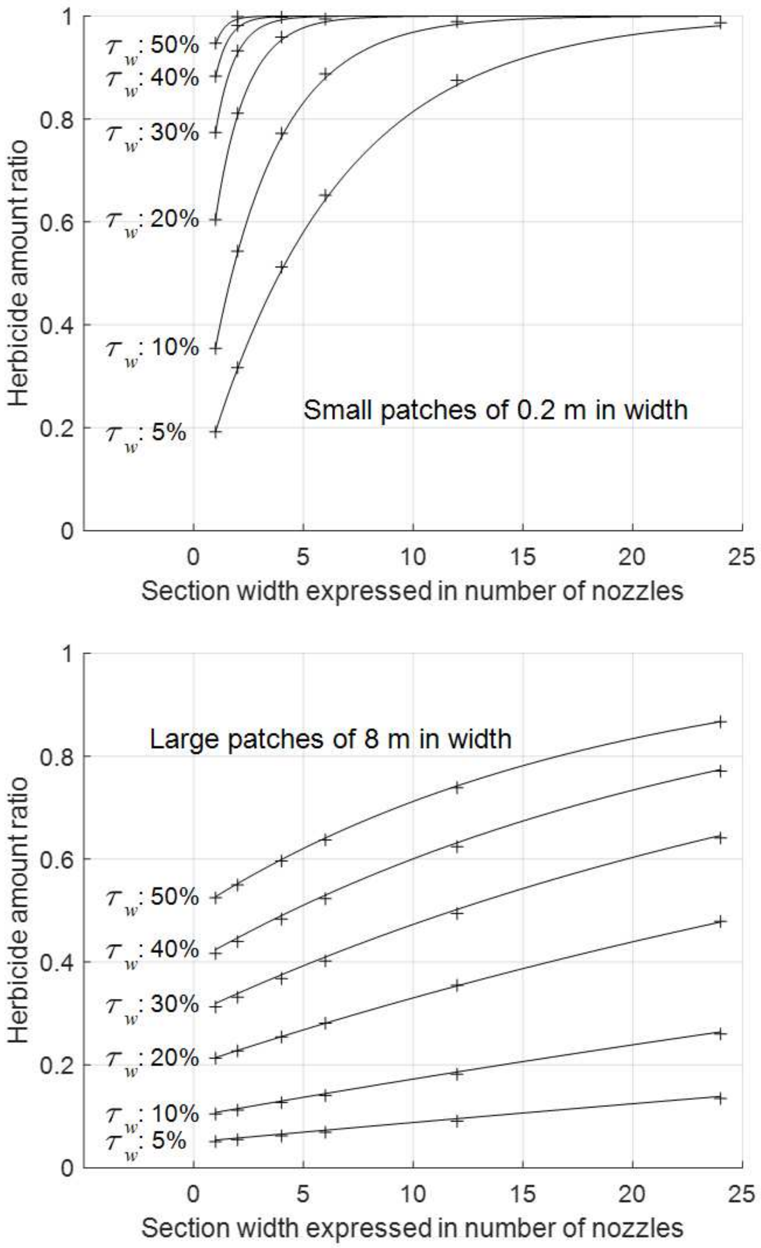


Fig. 5. Herbicide sprayed amount ratio τ_Q with respect to the section width (expressed in number of nozzles spaced 0.5 m apart) for small patches of 0.2 m in width (top) and large patches of 8 m in width (bottom) for various weed coverage rates (τ_w). +: results of spraying simulations carried out for operating conditions C2; continuous line: results of the model designed in Eq. (4).

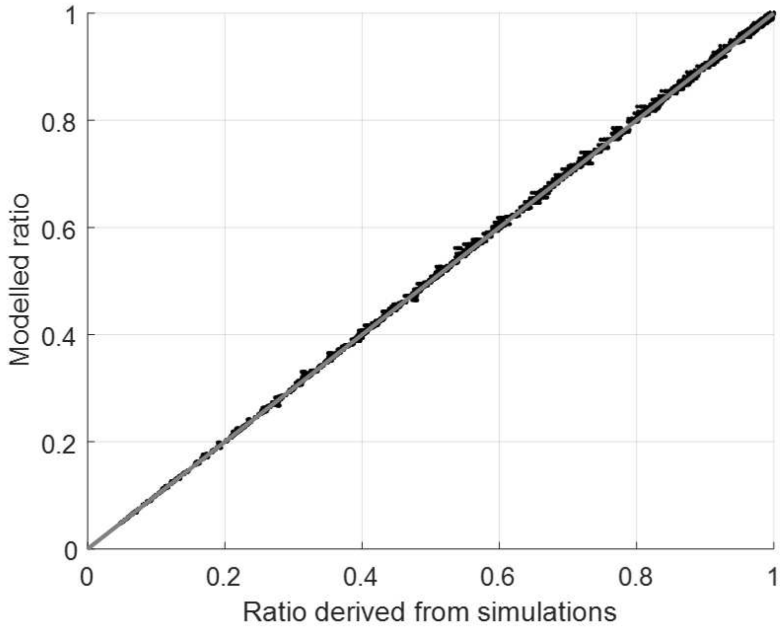


Fig. 6. Comparison of the values of the modelled sprayed amount ratio $\hat{\tau}_Q$ with respect to the values of the ratio τ_Q computed from 5292 simulations. The straight line (in grey) is the first bisector ($\hat{\tau}_Q = \tau_Q$).

For an example of two weed patch widths (0.2 and 8 m in width), Fig. 5 shows how the herbicide amount ratio values deduced from simulations are fitted by the model designed in Eq. (4). More comprehensively, Fig.6 presents the values of the modelled ratio $\hat{\tau}_Q$ computed with Eq. (4) with respect to the values of the ratio τ_Q derived from the 5292 computer simulations (882 spraying simulations considering 6 nozzle operating conditions). The figure shows that Eq. (4) provides a good estimation of τ_Q (R^2 = 0.9998). The interest of Eq. (4) is that it summarizes all simulation results and provides a convenient expression to understand how the spatial resolution of the sprayer and the spatial distribution of weeds affect herbicide reduction in the case of patch spraying. This analytical expression links the different variables affecting the reduction of herbicide and makes it easy to express one of the variables in relation to the others. In particular, it enables to determine the width of the boom section, which required achieving an herbicide reduction target in the case of an imposed weed spatial distribution. For example, Fig. 7 shows the ranges of weed spatial distributions (defined in terms of weed coverage rate and patch width) for a reduction target of at least 50% (reduction goal of the French “Plan Ecophyto II+” by 2025). According to this figure, when the patch size is greater than 2 m and the weed coverage rate less than 20%, the objective of reducing the herbicide amount by 50% (compared to a uniform broadcast application) can be achieved using boom sections of 3 m (6 nozzles). Nevertheless, for the same reduction target, nozzles need to be controlled individually when the coverage rate is 40%. The limit curves plotted in Fig. 7 are deduced from Eq. (4) as follows:

$$\tau_W < 1-\left(1-\tau_{Qmax}\right)^{\left(\frac{\pi w_w}{\pi w_w+4w_S}\right)} \tag{6}$$

where: τ_{Qmax} is the maximal value of τ_Q to reach the herbicide reduction target.

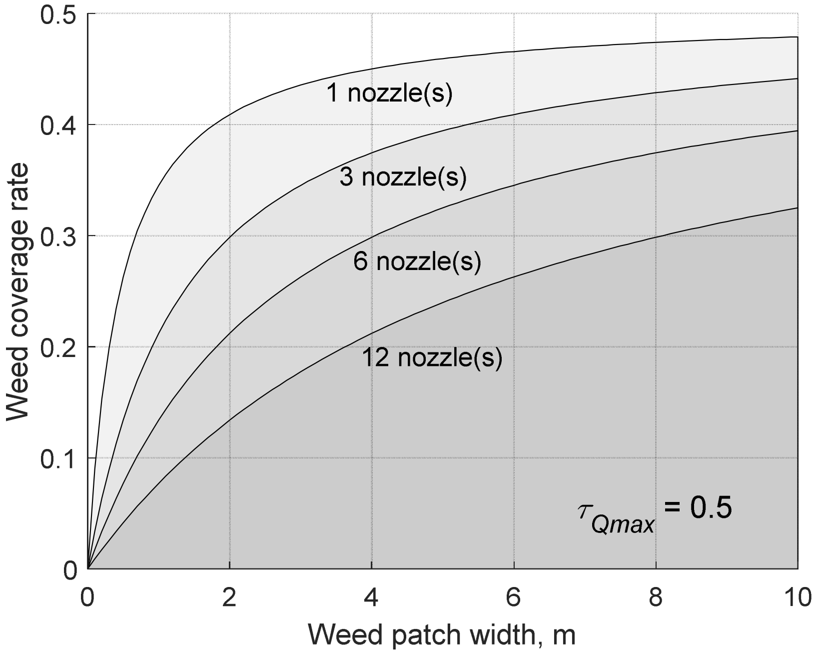


Fig. 7. Boom section width (expressed in number of nozzles spaced 0.5 m apart) required to reach an herbicide amount reduction of 50%.

3.2 Analysis of the proportion of weed area exposed to under-application

The above results show that the normalization used in this study ensures to obtain the same herbicide amount use for a given weed infestation map and a given section width for all operating conditions. Thus, it is interesting to investigate how the operating condition (*i.e.* transverse spray pattern) could affect the local application rate with respect to the prescribed rate, through the localization and quantification of under-applications.

Fig. 8 illustrates an example of simulation output obtained in the case of individual nozzles controlled independently with the operating condition C2 *(i.e.* using a 110° spray angle nozzles placed at 0.5 m in height) and when the weed coverage rate was fixed at 10%. Fig. 8 presents an extract of weed map where grey patches are weed patches, the corresponding application map and the application map restricted to weed areas only. This figure shows that depending on the position of the patch relative to the centre of the nozzle and depending on the resulting number of adjacent nozzles switched on, the product rate received by weeds in the patch may vary. In other words, some weed patches are exposed to the prescribed dose, but some other weed areas are exposed to under-application, which can lead to a weed-control failure on some areas.

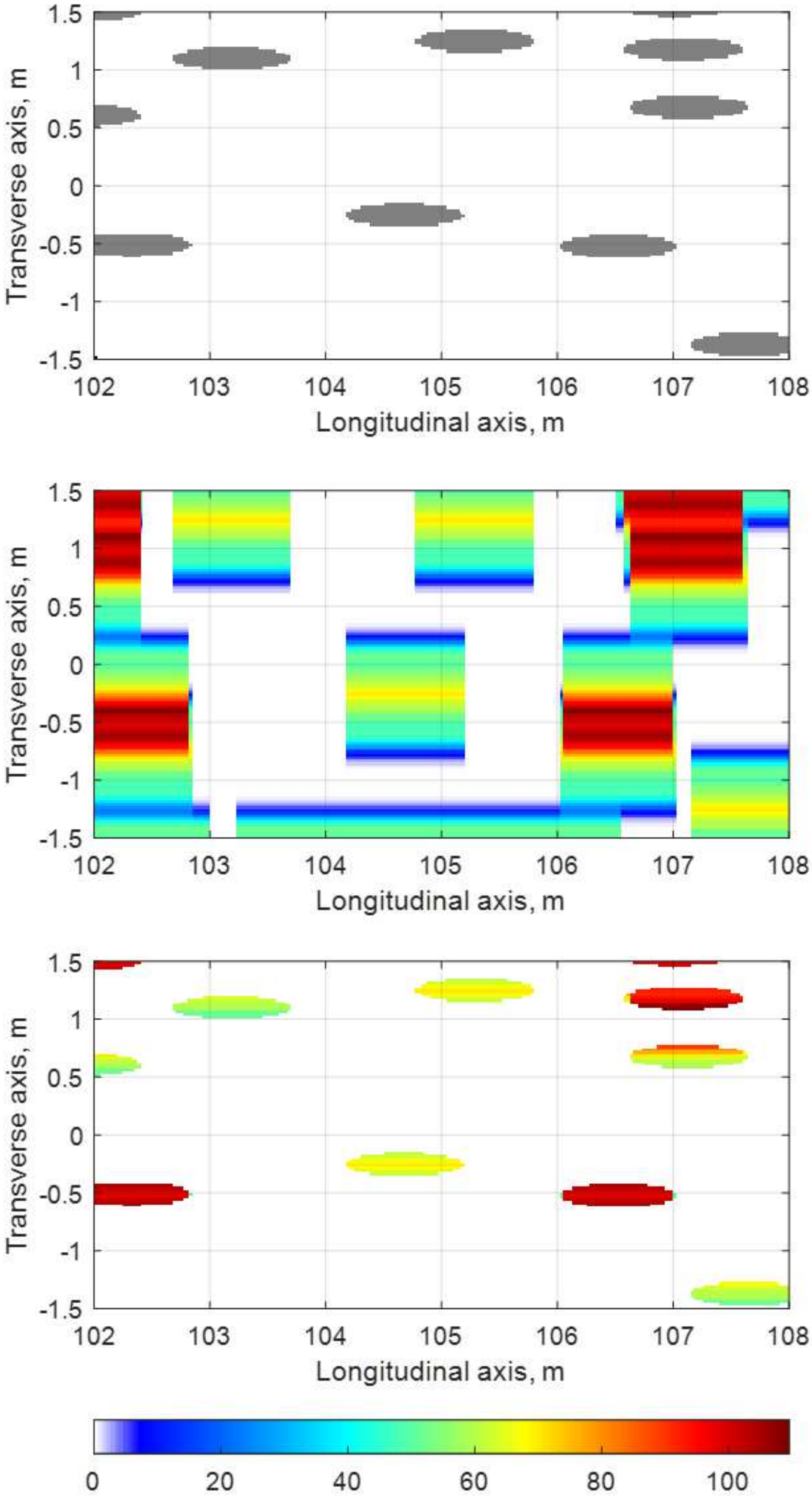


Fig. 8. Example of herbicide application in the case of small patches (l_e = 1 m, w_e = 0.2 m), individual nozzles controlled independently and operating condition C2: extract from a virtual weed map (top), application map (middle), application rate on the weed patches (bottom). The colour scale is representative

of the application rate expressed in percentage of the prescribed dose. (For interpretation of the references to colours in this figure legend, the reader is referred to the web version of this article.)

In order to study how section width and coverage rate affect the ratio $\tau_{WA>85\%}$, and thus quantify the area exposed to an application rate close to the prescribed dose, spraying simulations have been carried out using virtual infestation maps (*cf.* section 2.1). Fig. 9 depicted the results of simulations computed for the operating conditions C1 to C6 and when weeds were assumed to lie on small elliptical patches of constant size (l_w = 1 m, w_w = 0.2 m). In the case of a perfect rectangular spray pattern (C1), the application rate is obviously the same on the entire sprayed surface whatever the number of adjacent nozzles that are switched on simultaneously. Consequently, $\tau_{WA>85\%}$ is 100% for all weed coverage rates and all section widths. Nevertheless, no commercial nozzle provides this idealized spray pattern. For all other configurations (C2 to C6), the first observation that can be drawn from the curves is that reducing the boom section width results in decreasing the value of ratio $\tau_{WA>85\%}$ and thus increasing the proportion of weed areas receiving an insufficient herbicide rate. Thus, in the case of small patches and use of narrow section widths (*i.e.* less than four), a significant proportion of weed areas receives an insufficient application rate to ensure weed control and is exposed to a sublethal dose. Moreover, two groups of operating conditions are highlighted in Fig. 9: C2, C4 and C6 on one side, and C3 and C5 on the other. The curves of the first group show similar results. Indeed, in these operating conditions, the proportion of weed area on which the application rate is higher than 85 % of the rated dosage can drop to approximately 40% when nozzles are controlled individually. On the opposite, C3 and C5 provide the most favourable results with $\tau_{WA>85\%}$ higher than 77% for C3 (standard 90° spray angle nozzle at 0.5 m height) and 94% for C5 (even 80° spray nozzle at 35 cm height) in the case of nozzles controlled individually.

The operating conditions C3 and C4 correspond to the same flat fan nozzle (90° spray angle) but differ by the boom height, which is higher for C4. Fig. 9 shows that the C4 operating condition gives the most unfavourable ratio values (increasing weed areas exposed to under-application) compared to the C3 operating condition. Similar results are observed for the C5 and C6 operating conditions. The differences observed between C3 and C4, respectively C5 and C6 are due to the proportion of overlap between adjacent sprays. The overlap is less than 100% in the case of C3 and more than 100% in the case of C4 due to the use of the same nozzle at two different boom heights (higher in C4 than in C3). Consequently, when only one standard flat fan nozzle is switched on, the overlap is not achieved and the application rate on the sprayed area is lower in the case of C4 than in the case C3 since the same herbicide amount is applied on a wider spray width in C4 than in C3. These phenomena are all the more marked between C5 and C6 since even spray flat fan nozzles are designed for banding application and to give even coverage from a single nozzle. Thus, the trapezoidal shape of the transverse spray pattern obtained with an even nozzle leads to a very limited overlap in C5 so that the application rate remain close to the prescribed rate on the sprayed area whatever the number of adjacent nozzles simultaneously switched on (including the case of a single nozzle).

Regarding the operating conditions from C2 to C6, C3 and C5 provide the most favourable results because they correspond to conditions where the overlap between adjacent sprays is limited. In other words, these are conditions where the transverse spray patterns of a single nozzle are the narrowest. Consequently, in C3 and C5 the application rate remains high in the detection area (0.5 m in width) centred under the nozzle although only one nozzle is switched on. Comparing C3 and C5, the ratio $\tau_{WA>85\%}$ is better when the even spray flat fan nozzle is used (C5) since the shape of the transverse spray pattern is adapted to spraying with single nozzles. Nevertheless, when several adjacent nozzles are switched simultaneously, the spaying uniformity (*i.e.* the CV value) is very sensitive to the boom height. Thus, regarding δCV_h the operating condition C5 is the most sensitive spraying situation to boom height variations (*cf.* Table 2). With this in mind, the use of even nozzles with very limited overlaps (C5) appears as a good solution to reduce the risk of under-application on small weed patches only when the boom height is controlled very accurately. However, the quality of the spraying lacks of robustness in the case of boom height variations. In comparison to the reference scenario C5, decreasing or increasing the boom height would lead to local under- or over-application with a risk of weed control failure or lack of herbicide selectivity towards the crop.

When the number of nozzles per section is greater than four, the impact of the nozzle type is significantly reduced. Nevertheless, the problem of under-application on section borders still exist.

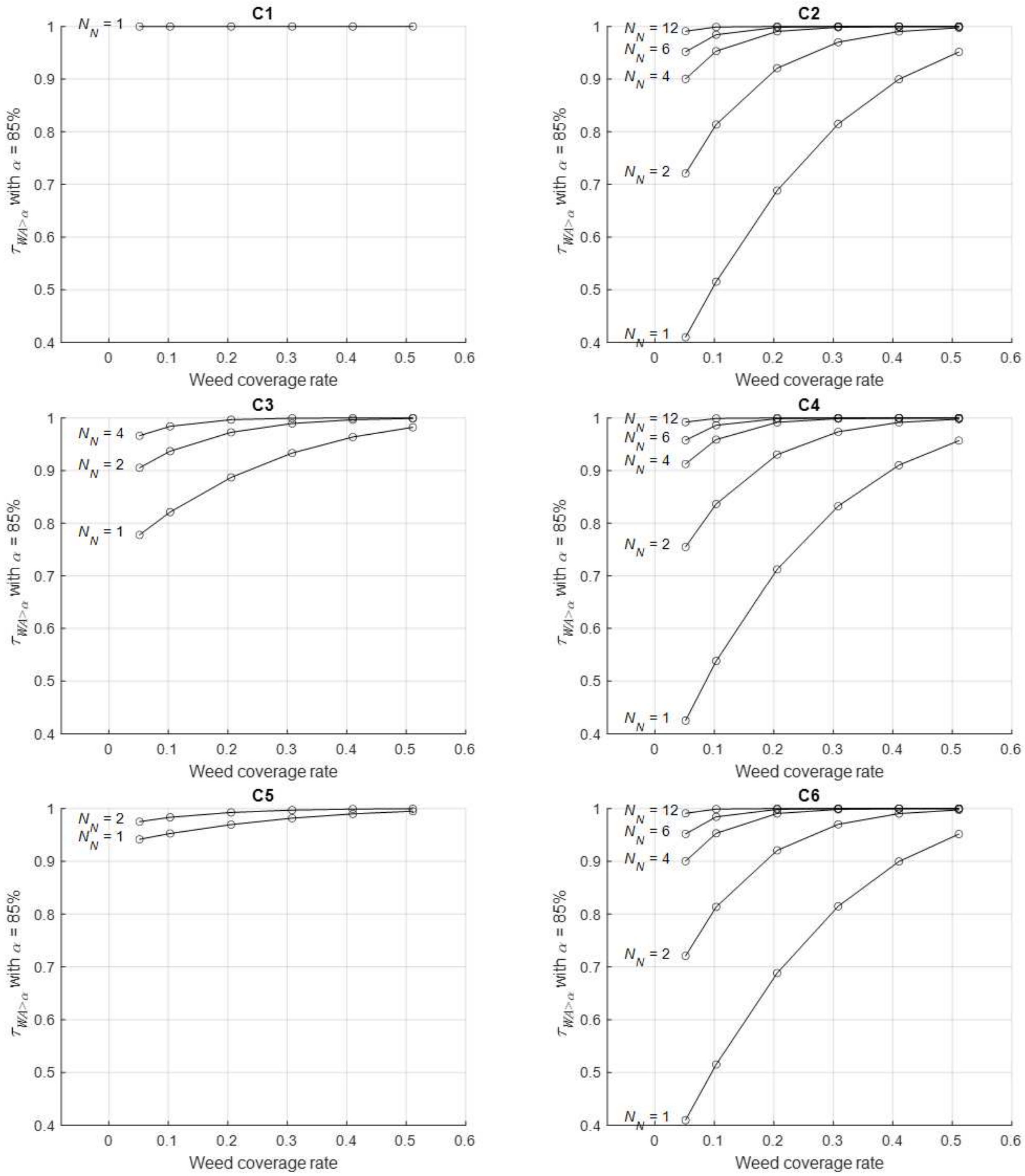


Fig. 9. Analysis of the weed area on which the application rate is higher than 85% ($\tau_{WA>85\%}$) with respect to the weed coverage rate, in the case of small patches (l_e = 1 m, w_e = 0.2 m) and different operation conditions from C1 to C6 (Table 2). The section width (expressed in number of nozzles N_N) is indicated on the left of the curves. The number of section widths presented on each graph was changed depending on the operating condition to improve readability and avoid curve overlay (for curves close to $\tau_{WA>85\%}$ = 1).

4. Discussion

The use of computer simulations enables to provide a practical and simple model to study how the weed distribution characteristics and the boom section width of the sprayer may affect both the quantitative reduction of herbicide amount expected by patch spraying and qualitative distribution of herbicide with under-dosed or overdosed areas. Examples of results presented in section 3.1 as well as the general expression of the sprayed amount ratio (Eq. (4)) confirm the general trends already observed by various authors such as Wallinga et al. (1998), and Rasmussen et al. (2019) who claimed that the herbicide reduction increased when the section width of the sprayer decreased due to less spraying outside the patches. A more refined analysis can be carried out by comparing to the results obtained by Franco et al. (2017), who modeled the relative sprayed area S as the sum of the weed coverage rate γ and a power function of the "precision of spraying" (L/w) as follows:

$$S = \gamma + \alpha \left(\frac{L}{w} \right)^{\beta} \tag{7}$$

where α and β are two regression parameters, L is the total width of the boom and w is the width of each boom section.

The regression analysis led by these authors was based on simulations carried out for two cases: one in the case of scattered circular patches with a weed coverage rate of 10.9% (leading to α = 0.56 and β = -0.73) and another in the case of few significant circular patches with a coverage rate of 10% (leading to α = 0.29 and β = -1.01). Since the authors implicitly assumes a perfect rectangular spray pattern for each nozzle, the sprayed area is not affected by any overlap effect and is directly proportional to the herbicide amount. Consequently, the relative sprayed area S computed by Franco et al. (2017) can be compared to τ_Q. Moreover, setting the boom width at 40 m, the authors expressed the relative sprayed area as a function of the boom section width. Fig. 10 presents the two regression models established by Franco et al. (2017) superimposed to data computed with Eq. (4) for a weed coverage rate set at 10%. Fig. 10 shows that the results obtained by these authors in the case of significant patches are similar to those derived from Eq. (4) with w_w = 16 m. In the case of scattered patches, the results are close to those computed with w_w = 4 m. The lack of information concerning the patch diameters does not allow further interpretations or comparisons. Nevertheless, Fig. 10 shows that the expected reduction of herbicide amount (derived from Eq. (4)) is less optimistic than the results presented by Franco et al. (2017) when patch sizes are smaller. The results presented herein are also less optimistic when the weed coverage rate increases. The comparison of Eq. (7) to Eq. (4) puts the emphasis on the interest of Eq. (4) to provide an analytical expression of the sprayed amount ratio as a function of the weed coverage rate, the weed patch width and the boom section width irrespective of any other regression coefficients. Contrary to what may be inferred from Eq. (7), Eq. (4) also demonstrates that the sprayed amount ratio cannot be simply expressed as the sum of the weed coverage rate and a function independent of this weed coverage rate.

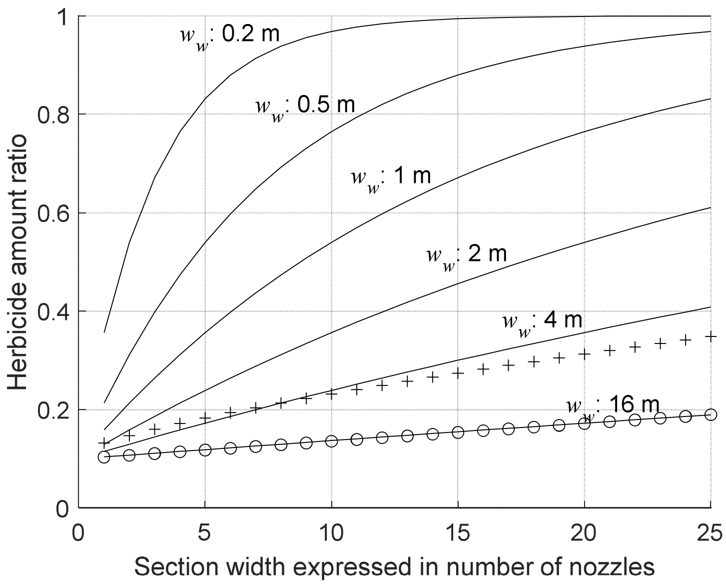


Fig. 10. Sprayed amount ratio computed for a weed coverage rate of 10% (continuous lines) and different patch width values (w_w, indicated on the curves) with respect to the section width (expressed in number of nozzles spaced 0.5 m apart). Results derived from Franco et al. (2017) in the cases of scattered patches (+) and significant patches (○) are reproduced and superimposed.

Relevant comparisons with the other results found in the literature are limited because of major differences in methodology, input parameters, scale of observation or formulation of the outcomes. For example, Wallinga et al. (1998) considered on the one hand the spatial position of a number of seedlings and not a weed coverage rate, and on the other hand they do not take into account the operating constraints of a sprayer since their virtual sprayer applied the herbicide to a circular area around each weed.

In this work, full elliptical patches at random positions on virtual field bands modeled weed populations. The assumption associated with the design of these maps is related to a weed coverage rate and not a weed density stated in plants per meter. This choice is consistent with the weed maps usually obtained with imaging systems (mounted on ground vehicle, UAV or satellite). Although the actual shape of weed patches is more complex, the elliptical shape assumption provides a model directly parameterized by the size of the patches. Thereby, this geometrical shape assumption is consistent with the objective of assessing the ability of sprayers to reduce herbicide and meet farmers' expectations. Spraying simulations could be carried out in the same way on actual weed maps, but the results would remain specific to few situations and the trends would then be difficult to generalize.

Computer simulations are of practical use for farmers or manufacturers to estimate the sprayer spatial resolution required to reach an herbicide reduction target according to the weed spatial distribution. The simulations made it possible to build charts (such as presented in Fig. 7) to help users or manufacturers in the choice of boom section widths according to the herbicide reduction target and weed infestation characteristics (*i.e.* coverage rate and patch size). For example, referring to Fig.7, the choice of 6-nozzle boom sections instead of individually controlled nozzles would reduce the sprayer cost while expecting a herbicide use reduction of 50% when infestation rates are up to 30% and when weed patches are at least 4 m wide.

In this paper, results assessed the potential reduction of the herbicide product with regard to a single weed map for the all field. This corresponds to the case where farmers apply one herbicide or a mixture of herbicide selected with regard to the dominant or most problematic weed species present in field. Nevertheless, the results of several different simulations carried out with different weed maps can also be considered to estimate the herbicide reduction when different herbicides are applied separately and specifically on different weed classes (with different spatial distribution in the field). This corresponds to the case where farmers decide to apply different herbicides with several successive sprayer passes. It also corresponds to the use of sprayers equipped of multiple tanks as proposed by Gerhards and Oebel (2006) and

Gutjahr et al. (2012). Indeed, depending on weed classes, the weeds distributions can vary and induce differences in herbicide application. Thus, applying separately different herbicides rather than a mixture helps in reducing the global amount of herbicides used and is an effective strategy to avoid the selection of herbicide-resistant weeds (Gutjahr et al., 2012).

Bearing in mind the assumptions underlying the study (*e.g.* perfect on and off switching of the nozzles, no disturbance due to travel speeds, wind effects, …), the results have to be seen as the better limits. For example, Fig. 7 presents the most favorable results in terms of herbicide reduction reached for imposed weed spatial distributions.

The computer simulations demonstrated that decreasing the weed patch size increases the sensitivity of herbicide reduction to the boom section width. Thus, in the case of small patches, narrow section widths (less than four nozzles) or nozzles controlled individually are required to reach the herbicide reduction objective. In these situations, a substantial proportion of weed areas can be exposed to a sublethal application rate because the spray deposit under a single nozzle is not constant and it is not possible to obtain a uniform application rate on the whole transverse spraying distance without overlapping of several sprays. On some areas, these situations can lead to weed-control failures, yield losses (for the crop) and an increase of weed seedbanks. It can also promote survival and multiplication of herbicide-resistant weed specimens, since the application of reduced herbicide rates (*i.e.* sublethal doses) on weeds is known, in particular, to select non-target-site herbicide-resistant weed populations (Neve and Powles, 2005). Taking into account the results presented in section 3.2, the use of even nozzles (C5) or low angle flat nozzles (C3) could be a way to reduce the risk of local under-applications as long as the boom height is accurately controlled (especially in the case of even nozzles). Overall, finding an actual nozzle that would provide a uniform application rate when it is used with or without overlap and with a transverse spray pattern insensitive to the boom height is not possible. Technical solutions to maintain the application rate at the prescribed value on all the detection area could be set up by increasing the flow rate when very narrow sections or individual nozzles are switched on, or by widening the spray section on both sides of the weed detection width. However, both of these approaches would increase the herbicide amount required for the application.

Thus, future works will focus on the use of complementary computer simulations to help in designing more flexible nozzle control in order to avoid under-applications on weeds while reaching a significant reduction of herbicide use. Future works will also seek out and consider the effect of wind and travel speed conditions on the deformation of the spray deposits and assess consequences of potential mistargeted applications.

4. Conclusion

The use of computer simulations appears as a relevant way to study weed patch spraying, especially concerning the interaction of parameters that affect the global reduction of herbicide amount and potential under-application occurrences. Based on a simplified representation of weed patches, simulations of patch spraying have enabled to establish a model to estimate herbicide use reduction as a function of the boom section width and the spatial weed distribution defined by patch size and coverage rate. The model is of practical use to study the combined effects of sprayer features and weed spatial distribution characteristics on herbicide use reduction. It provides users and manufacturers with simple tools to build charts and estimate the sprayer spatial resolution required to reach a given herbicide reduction target according to the weed distribution. In the case of small patches dispersed in the field, computer simulations have demonstrated that individual nozzles controlled independently or at least narrow boom sections are required to reach a significant herbicide reduction. In these situations, numerical simulations have also estimated the proportion of weed area exposed to herbicide under-application because of the the lack of spray overlap. They related this proportion to the section width and the nozzle spray pattern. This finding encourages using simulations to help in developing more flexible nozzle control in order to avoid any risk of weed control failure and selection of herbicide-resistant weeds while reaching a significant reduction of herbicide use. Although the work has been devoted to weed control, it retains its interest in any patch spraying context with the objective of reducing the amount of chemical inputs by switching on or off boom sections or individual nozzles preventing from chemicals areas that do not require treatment.

5. Acknowledgements

The work was supported by the national superior institute of agronomic sciences, food and environment (AgroSup Dijon), the French institute for research and innovation in agriculture, food, and the environment

(INRAE). The authors gratefully acknowledge Dr. A. Herbst, Julius Kühn-Institute (JKI) for providing experimental data on transverse spray patterns.

6. References

Barroso, J., Navarrete, L., Sanchez Del Arco, M.J., Fernandez-Quintanilla, C., Lutman, P.J.W., Perry, N.H., hull, R.I., 2006. Dispersal of *Avena fatua* and *Avena sterilis* patches by natural dissemination, soil tillage and combine harvesters. Weed Research 46, 118-128.

Carroll, J.P., Holden, N.M., 2009. Modeling the relationship between patch sprayer performance and weed distribution. Transactions of the ASABE 52, 1051-1056.

Castaldi, F., Pelosi, F., Pascucci, S., Casa, R., 2017. Assessing the potential of images from unmanned aerial vehicles (UAV) to support herbicide patch spraying in maize. Precision Agriculture 18, 76-94.

Cousens, R., Croft, A.M., 2000. Weed populations and pathogens. Weed Research 40, 63-82.

Dieleman, J., Mortensen, D., 1999. Characterizing the spatial pattern of *Abutilon theophrasti* seedling patches. Weed Research 39, 455-467.

Esau, T., Zaman, Q., Groulx, D., Farooque, A., Schumann, A., Chang, Y., 2018. Machine vision smart sprayer for spot-application of agrochemical in wild blueberry fields. Precision Agriculture 19, 770-788.

Faqiri, N.L., Krishnan, P., 2005. Effect of nozzle pressure and wind condition on spray pattern displacement of RF5 and 110-5R nozzles. Applied Engineering in Agriculture 21, 747-750.

Franco, C., Pedersen, S.M., Papaharalampos, H., Ørum, J.E., 2017. The value of precision for image-based decision support in weed management. Precision Agriculture 18, 366-382.

Gao, J., Liao, W., Nuyttens, D., Lootens, P., Vangeyte, J., Pižurica, A., He, Y., Pieters, J.G., 2018. Fusion of pixel and object-based features for weed mapping using unmanned aerial vehicle imagery. International Journal of Applied Earth Observation and Geoinformation 67, 43-53.

Gerhards, R., Oebel, H., 2006. Practical experiences with a system for site-specific weed control in arable crops using real-time image analysis and GPS-controlled patch spraying. Weed Research 46, 185-193.

Gonzalez-de-Soto, M., Emmi, L., Perez-Ruiz, M., Aguera, J., Gonzalez-de-Santos, P., 2016. Autonomous systems for precise spraying – Evaluation of a robotised patch sprayer. Biosystems Engineering 146, 165-182.

Gutjahr, C., Sokefeld, M., Gerhards, R., 2012. Evaluation of two patch spraying systems in winter wheat and maize. Weed Research 52, 510-519.

Hassen, N.S., Sidik, N.A.C., Sheriff, J.M., 2013. Effect of nozzle type, angle and pressure on spray volumetric distribution of broadcasting and banding application. Journal of Mechanical Engineering Research 5, 76-81.

Herbst, A., 2019. Personnal communication: Results of the spray pattern measurements, Julius-Kühn-Institut (JKI), Braunschweig, Germany.

Humston, R., Mortensen, D.A., Bjornstad, O.N., 2005. Anthropogenic forcing on the spatial dynamics of an agricultural weed: the case of the common sunflower. British Ecological Society 42, 863-872.

ISO 5682-3, 2017. Equipment for crop protection — Spraying equipment — Part 3: Test method to assess the performance of volume/area adjustment systems, International Organization for Standardization, Geneva, Switzerland.

ISO 16119-2, 2013. Agricultural and forestry machinery — Environmental requirements for sprayers — Part 2: Horizontal boom sprayers, International Organization for Standardization, Geneva, Switzerland.

Krishnan, P., Gal, I., J. Kemble, L., L. Gottfried, S., 1993. Effect of Sprayer Bounce and Wind Condition on Spray Pattern Displacement of TJ60-8004 Fan Nozzles. Transactions of the ASAE 36, 997-1000.

Langenakens, J.J., Clijmans, L., Ramon, H., De Baerdemaeker, J., 1999. The Effects of Vertical Sprayer Boom Movements on the Uniformity of Spray Distribution. Journal of Agricultural Engineering Research 74, 281-291.

Lebeau, F., 2004. Modelling the dynamic distribution of spray deposits. Biosystems engineering 89, 255-265.

Mahalinga Iyer, R., Wills, B.M.D., 1978. Factors determining the design of tractor-mounted sprayer booms—sprayer nozzle characteristics. Journal of Agricultural Engineering Research 23, 37-43.

Matlab, 2019. Version 9.7. The MathWorks, Inc., Natick, Massachusetts, United States., The MathWorks, Inc., Natick, Massachusetts, United States.

Neve, P., Powles, S., 2005. High survival frequencies at low herbicide use rates in populations of *Lolium rigidum* result in rapid evolution of herbicide resistance. Heredity 95, 485-492.

Oerke, E.C., 2006. Crop losses to pests. The Journal of Agricultural Science 144, 31-43.

Paice, M.E.R., Day, W., Rew, L.J., Howard, A., 1998. A stochastic simulation model for evaluating the concept of patch spraying. Weed Research 38, 373-388.

Paice, M.E.R., Miller, P.C.H., Bodle, J.D., 1995. An experimental sprayer for the spatially selective application of herbicides. Journal of Agricultural Engineering Research 60, 107-116.

Ramon, H., De Baerdemaeker, J., 1997. Spray Boom Motions and Spray Distribution: Part 1, Derivation of a Mathematical Relation. Journal of Agricultural Engineering Research 66, 23-29.

Rasmussen, J., Azim, S., Nielsen, J., Mikkelsen, B.F., Hørfarter, R., Christensen, S., 2019. A new method to estimate the spatial correlation between planned and actual patch spraying of herbicides. Precision Agriculture.

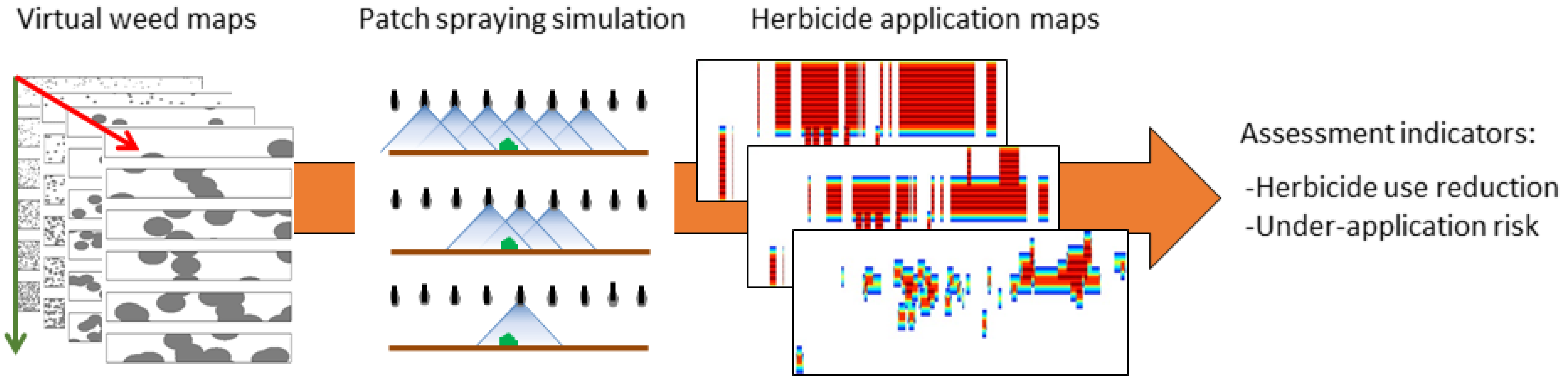
Shearer, S., Jones, P., 1991. Selective application of post-emergence herbicides using photoelectrics. Transactions of the ASAE 34, 1661-1666.

Stafford, J., Miller, P., 1993. Spatially selective application of herbicide to cereal crops. Computers and Electronics in Agriculture 9, 217-229.

Thorp, K.R., Tian, L.F., 2004. A review on remote sensing of weeds in agriculture. Precision Agriculture 5, 477-508.

Wallinga, Groeneveld, Lotz, 1998. Measures that describe weed spatial patterns at different levels of resolution and their applications for patch spraying of weeds. Weed Research 38, 351-359.

Wang, A., Zhang, W., Wei, X., 2019. A review on weed detection using ground-based machine vision and image processing techniques. Computers and electronics in agriculture 158, 226-240.


Virtual weed maps
Patch spraying simulation
Herbicide application maps
Assessment indicators:
-Herbicide use reduction
-Under-application risk