Chapter 4
Economics of Site-Specific and Variable-Dose Herbicide Application

Jens Erik Ørum, Per Kudsk, and Peter Kryger Jensen

Abstract Site-specific application of pesticides has so far focused mainly on herbicides. The purpose of precision farming technologies in relation to herbicide use is to reduce herbicide cost and environmental impact from spraying, but at the same time to achieve acceptable weed control. Another purpose is to increase the spraying capacity, to reduce the number of sprayer refills, and finally to minimize time spent on weed monitoring. In this chapter the relevance and profitability of four precision herbicide application technologies, two weed detection technologies and a low dose decision support system (DSS) is analysed. With a low dose herbicide, cost can be reduced by 20–50%. It requires, however, proper monitoring of weeds, which can be a time-consuming task that again requires that the farmer is able to identify the dominant weed species. The current development of high-speed camera and software systems can help to detect and map individual weeds, and some systems have proved to be cost effective for certain weeds.

Keywords Weed detection • Weed control • Crop protection • Low dose DSS • Precision spraying

4.1 Introduction

Research into site-specific application of pesticides has focused mainly on herbicides, although some research has been carried out within the area of disease detection and variable application of fungicides (Pedersen 2003). Preventive and site-specific treatment with insecticides is complex because insects are difficult to

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monitor in the field. In contrast, weeds tend to have a patchy distribution in the field and some diseases also typically occur in the same areas in the field with specific micro climatic conditions, although weed distribution cannot be considered invariable. On the other hand, farmers are aware of the potential savings of chemicals through precision spraying, although they may also have reservations about the potential benefits because of technical difficulties and lack of decision support systems when using site-specific technologies (e.g. Pedersen et al. 2004).

Examples of precision technologies relevant for site-specific herbicide application are:

- High precision cell and micro spraying
- Boom section and nozzle control
- Boom section control to reduce overlap
- Direct injection
- Real time weed detection with high speed cameras
- DSS systems for low dose herbicide use recommendations

The purpose of these technologies is to determine what, where and when to control weeds efficiently preferably at a low cost. Farmers' incentives for using these technologies are to (1) increase the spraying capacity and efficiency (more acreage covered per time unit, reduce number of sprayer refills), (2) minimize time-consuming activities like manual weed monitoring and (3) have access to decision support on herbicide choice and dose to reduce herbicide cost without loss of efficacy on the weeds. The incentive of the society to support the adoption of these technologies is to reduce the unintended environmental impact from spraying and at the same time maintain effective and competitive food production.

Site-specific application is about where to spray, while variable-dose application is about how much to spray. Knowledge of weed distribution in time and space is essential for both approaches. The main difference is that understanding weed response to herbicides, crop and weed competition and weed population dynamic is a prerequisite for variable-dose application.

High precision spraying of individual weed plants with broad-spectrum herbicides like glyphosate is the ultimate example of site-specific herbicide application. The system must distinguish between crop and weed. What isn't a crop is a weed plant, or everything green outside the crop row or GPS located crop plant is a weed. Site-specific solutions focus mostly on technology and engineering and less on biology and agronomy. Depending on the weed species and density, site-specific spraying could ideally reduce herbicide use by a factor of 100 or 1000 compared to a full dose spraying of the whole field.

Assuming a density of 300 weeds per m^2, Mathiassen et al. (2016) found that glyphosate doses applied at an early growth stage could be reduced from currently recommended glyphosate dose of 560–720 g ha^{-1} to 2.5–32.0 g ha^{-1} by using a Drop on Demand inkjet printer application system (DOD). Thus, specifically targeting the weed plants with the DOD system or similar devices may lead to significant reductions (factor 20–300) in herbicide field rates.

Weed detection, planning and spraying are the three dimensions in chemical weed control with variable-doses, and in this chapter we will evaluate the development and economic potential of some of the technologies above listed relating to these three dimensions. This evaluation will first of all be based on studies in the literature. In the case of automated weed detection and DSS systems for low dose herbicide recommendations we will, however, give an example of a potential 40% herbicide use reduction with a low dose DSS system that has not been exploited because of a lack of weed monitoring capacity, lack of economic incentive and a too great efficiency of pre-emergence herbicides. Profitability of investments in precision technology and future herbicide cost reductions will be calculated with a 4% discount rate and a 5 year lifetime of the investment, resulting in a capitalization factor of 4.6.

4.2 Application Technologies

4.2.1 Site-Specific Application and Variable-Dose

Variable-dose application can be achieved in many ways, from varying the application by turning on and off the sprayer while driving, adjustment of speed and tank pressure or by advanced high precision control of individual spray boom sections and nozzles (see e.g. Grisso et al. 2011). Conventional boom sprayers are usually mounted with a water tank with chemicals that are mixed with water. Usually 2–3 different chemicals are mixed at a time for each treatment. To conduct variable-dose application, some sprayers are equipped with devices to regulate the amount of chemicals simultaneously with the spraying. A GPS receiver and a tractor computer can be installed to regulate and carry out variable-dose application of pesticides. Conventional boom sprayers can also be divided into different sections to enable site-specific application along the boom. One example is described in the Sensispray development project, in which a 27-m length boom sprayer with seven sections was equipped with sensors to control spray volume per boom section, thereby having a length of about 3–4.5 m for each section (van de Zande et al. 2009).

4.2.2 Micro and "Cell" Spraying

As stated in Franco et al. (2017) the ultimate site-specific weed management strategy would be to apply one drop of herbicide per weed plant. This strategy was tested by Lund et al. (2006), with micro spray tubes that open and close individually with solenoid valves. In a field with 100 weed plants per m^2 and 20 tubes per 100 mm, it was possible to obtain 84% weed control with as little as 27 g of glyphosate ha^{-1}. Lund et al. (2008) has shown that with vision based spraying techniques one can treat areas of 100 × 100 mm individually (named 'cell spraying' by the authors).

This approach could potentially reduce pesticide use by 50–70% compared to conventional boom spraying.

Compared to a full dose of conventional herbicides the micro spraying system offers a potential saving of 10–20 € ha^{-1} and the cell spraying system offers a saving of 5–14 € ha^{-1} (Franco et al. 2017). The main question is, however, whether the cost reductions can justify the investment in a system with the required remote controlled micro tubes, image or video devices for real-time detection of weeds or alternatively high precision weed maps in combination with RTK-GPS technology etc. On the other hand, the capacity of high precision systems is another challenge for their commercialization. Despite the low capacity, a small micro sprayer with a 1-m boom could be sufficient if the system is unmanned and RTK GPS guided. High precision micro tube systems are not yet available and affordable for farmers, and the video guided cell spraying systems are commercially available for row crops only (Franco et al. 2017).

4.2.3 Boom Section and Nozzle Control

A boom sprayer (Fig. 4.1) is usually supposed to apply exactly the same dose in its full length. There are, however, at lot of methods to control and adjust the dose and to open and close parts of the sprayer to produce a variable-dose or site-specific pesticide application.

The boom consists of sections (H) with several nozzles per section (I) that, on advanced sprayers, can be opened or closed by the operator or automatically according to a plan and a GPS position (F). The dose is determined by nozzle size, spray pressure and driving speed. With more advanced sprayers, the dose is controlled

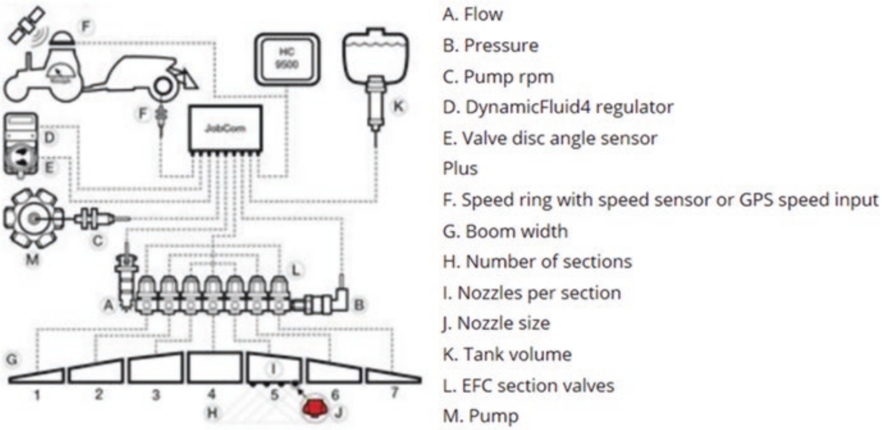

Fig. 4.1 Schematic overview of a boom sprayer (DynamicFluid4 sprayer, Hardi International A/S)

with a separate pump (M) that can be controlled by a computer that activates specific boom sections and nozzles (F). Using boom section and nozzle control units together with a crop scanner or GPS with RTK positioning, it is possible to vary the dose and do site-specific spraying applications. The challenge is, however, to identify and exploit the most profitable opportunities.

In cereal crops, high precision and reduced herbicide consumption could be achieved with traditional boom sprayers equipped with remote control of the individual nozzles or boom sections. With a traditional boom sprayer with between 2 and 4 nozzles per m boom spraying precision with remote control of every nozzle would be 250–500 mm. If we consider a weed density that varies from 25 to 200 plants per m^2 and a spraying precision (wideness of the sprayed area per nozzle) between 250 and 500 mm, then it would almost certainly result in full spraying of the field. A precision of 30–100 mm would be needed to reduce the pesticide use significantly (Franco et al. 2017). However, in that case, the cost savings of reduced herbicide would probably not be sufficient to pay for video devices, weed mapping, RTK-GPS equipment and remote controlled solenoid valves for individual nozzles or boom sections. To make a precision of 250–500 mm spraying profitable, a very patchy variation in the weed density and distribution would be required, such as for thistles and couch grass, which tend to grow in colonies, patches, spots and clusters.

A study by Franco et al. (2017) showed that the profitability of increased precision in glyphosate spraying of thistle patches in cereals decreases significantly with an increasing precision. The marginal value (v) of an extra unit was found to be a power function of length of the boom (l), the length of the controlled units, either nozzles or boom sections, (w) and the cost of a full herbicide dose (H), such that:

$$v = H\alpha\beta\left(\frac{l}{w}\right)^{\beta-1}.$$

The α and β values depend on the size and distribution of the weed patches. Below is an example with a 40-m boom, many and scattered patches of weeds (α=0.56 and β=-0.73) and few and concentrated patches of weeds (α=0.29 and β=−1.01). Figure 4.2 shows how the reduction in marginal costs decreases rapidly with an increased precision from an increased number of remotely controlled units (RC).

Figure 4.2 shows that the first step from broadcast spraying to a simple (1 unit) open and closing of the whole sprayer reduces the herbicide cost by 6–9 € ha^{-1}. With an extra control unit, the 40-m sprayer is divided into two 20-m sections, reducing the herbicide cost by an extra 2–3 € ha^{-1}. With 5–6 units corresponding to 5–10-m sections the extra herbicide cost reduction is marginal. In this case a five- or 10-m precision is cost efficient, but this knowledge could be derived only by using a very detailed weed map that shows the thistle patches.

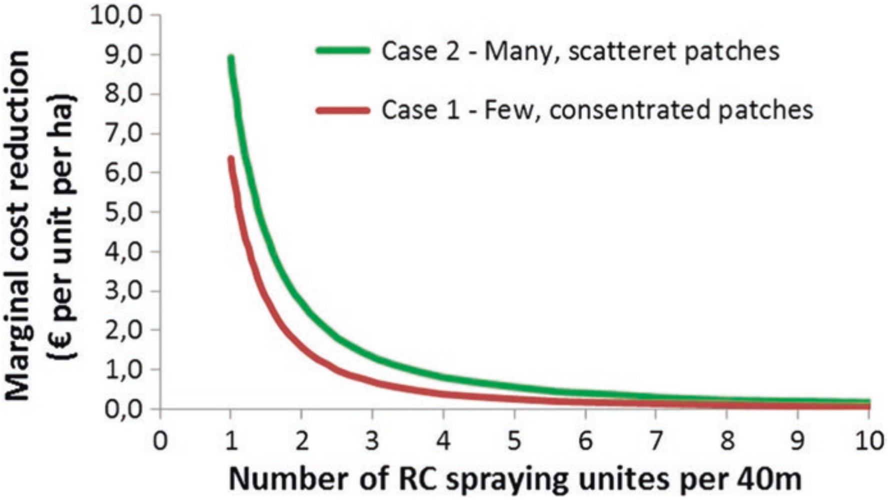

Fig. 4.2 Marginal cost reduction (€ha^{-1})per an extra controlled unit (Franco et al. 2017)

4.2.4 Boom Section Control and Reduced Overlap

Reducing overlap when spraying is a potential source for cost reduction. A rough estimate of a 5% reduction in pesticide use could be achieved by reducing overlapping when spraying along field edges (Petersen et al. 2017). It takes automated boom section control, GPS and software to realize this reduction. Most new sprayers are manufactured with electronic on/off switches for individual boom sections. To control the individual sections computer and software such as Rinex AS 7500 (by Leica Geosystems), GPSswitch (by Amazone), Swath Control Pro (by John Deere), AgGPS FieldManager (by Trimble) etc. are needed.

According to a Danish sprayer retailer (Mertz, 2017), 80% of all new sprayers are equipped with automated section control. Computer software and installation may sum to around 3000 €. If not already installed, a GPS unit is available at a cost of around 2000 €.

Given a 4% discount rate and a 5-year lifetime, a 3000 € investment in sprayer section control or GPS equipment must produce a yearly cost reduction that is equivalent to 649 €.

Table 4.1 provides the pesticide costs for Danish arable crops 2015 and the required area (ha) needed to make a cost reduction of pesticides.

Table 4.1 shows that a 5% pesticide cost reduction on 90 ha of winter wheat is sufficient to balance the 3000€ automated section control investment. A GPS is a requirement for automated section control and RTK may be a prerequisite for even finer control of individual nozzles (1 cm accuracy). If a 5% reduction in pesticide costs alone is needed to pay for these additional investments, an extra area of

Table 4.1 Pesticide costs (€ ha^{-1}) for Danish arable crops 2015* and required area (ha) to make a 5% cost reduction of pesticides

Crop			Costs		Technology			
	1.000 ha	Weight	Pesticides	5% reduction	Section control	GPS	RTK	Total
					Investment (€)			
					3000	2000	13,000	18,000
			Costs (€ ha^{-1})		Break even area (ha)			
Winter wheat	570	31%	145	7.3	90	60	388	538
Winter barley	110	6%	104	5.2	125	83	542	750
Spring barley	490	27%	60	3.0	215	143	933	1291
Canola	190	10%	250	12.5	52	35	225	312
Seed grass	27	2%	96	4.8	135	90	584	809
Beets	25	1%	284	14.2	46	31	198	275
Starch pot.	27	1%	430	21.5	30	20	131	181
Maize	180	10%	83	4.1	157	105	682	944
Fodder grass	200	11%	0	0.0	–	–	–	–
Weighted avg.	1800	100%	114	6	114	76	495	685

Source: Statistics Denmark (DST 2016) and MST (2017)
Note: Assumption: 5 year lifetime and a 4% discount rate

60–388 ha of winter wheat or an extra area of 76–495 ha of a standard crop rotation is needed to achieve a breakeven of these investments.

Overlapping, however, does not just occur at field edges, but also between the spray tramlines. This kind of overlapping is possibly responsible for another 5% overlap (Petersen et al. 2017). However, to reduce this overlap, opening and closing of full sections is not enough. In this case, individual control of nozzles is needed to reduce the overlap. A solution with an additional control of the outermost two nozzles and the next two nozzles is available. It also takes a higher precision to exploit this overlap. If this is not installed, the investment in RTK may increase by approximately 13,000 € per unit. Instead of very precise spraying, it may be more cost efficient to invest in more precise seeding. The RTK may still be needed but the investments in the control of individual nozzles are saved and seeds (and fertilizers) can be saved.

The benefits of auto guidance and site-specific management are further described in an IPNI guideline (IPNI 2017).

4.2.5 Direct Injection

Farmers' spraying strategies usually require the mixing of herbicides into an exact amount of water prior to spraying. Hence, they need to estimate the precise amount for each herbicide required for a particular field to avoid having to empty the tank after each operation in the field and potentially waste herbicide. This approach conflicts with the idea of precision spraying (Pedersen 2003). It is therefore vital that site-specific spraying systems (1) separate herbicides and water and (2) use efficiently the knowledge of weed susceptibility to herbicides and weed distribution for estimating the optimum herbicide mixture.

Injection sprayers provide these attributes as the various undiluted herbicides are kept in a container, separated from the water tank. Water is pumped through the nozzles and herbicides are injected into the water (Walter and Heisel 2001). Commercial injection systems usually have around five containers for different herbicides (Fig. 4.3). With the injection system there are no leftovers after spraying and there are no herbicides in the water tank. An injection system can, in principle, be mounted on any hydraulic sprayer. Although several injection systems are commercially available they need further improvement in regard to reaction time and cleaning of containers and costs are still very high (Anglund and Ayers 2003).

Fig. 4.3 Example of pesticide containers on injection sprayer (Photo: Kyndestoft Maskinfabrik ApS)

4.3 Planning and Low Dose DSS

4.3.1 CPO-Weeds

Weed detection, planning and spraying are the three dimensions in variable-dose chemical weed control. As indicated above, different spraying and application methods and strategies have different implications. The subsequent question related to the planning is which herbicides and doses to apply?

In most fields, the farmers face the challenge to control weed flora consisting of several weed species rather than just one or two species, and he/she can choose among a wide range of herbicides. Most herbicides control more than just one weed species, some weed species must be controlled more effectively than others. The effect of two or more herbicides is to some extent additive, but some herbicides cannot be applied together, and efficacy of the herbicides often depends on climatic conditions, crop density and weed growth stage. For that reason the optimal herbicide recommendation will often be a combination of smaller than recommended doses of different herbicides. A few days later, the optimal recipe may be different, e.g. due to weeds growing larger or changing climatic conditions. Many active ingredients of herbicides are sold as premixes, but often farmers are able to make up their own herbicide mixes, tailor-made for their specific weed problems and these mixtures are often cheaper. The problem is, however, to find the optimal ‘recipe’. Here a decision support system like CPO-weed is relevant.

Crop Protection Online-Weeds (CPO-Weeds) is a decision support system for chemical weed control developed in Denmark and subsequently adjusted to conditions in other countries. Several trade names have been used including PC Plant Protection (Denmark), Crop Protection Online (Denmark), VIPS-Ugras (Norway), CPOWeeds (Spain) and DSSHerbicide (Poland, Germany). In each country, the CPO-versions are adjusted according to herbicide availability and parameterized accordingly, whereas the algorithms and calculations follow the same concept (Sønderskov et al. 2016).

Herbicide recommendations in CPO-Weeds are calculated through a three step process following the user’s input on weed species as well as growth stage and density of each weed species in the field. The first and second step is to determine the need for control and the level of control required for each of the reported weed species, respectively. The threshold for each weed species depends on the crop, crop growth stage and crop density as well as the growth stage and density of the weed species. The most competitive and problematic weed species will be controlled effectively, whereas less competitive weed species at low densities are either tolerated or partly controlled. The assessment of need for control and required level of control is based solely on expert knowledge. The third step of the decision process is the selection of herbicide solutions including herbicide mixtures that can provide the required control of each of the weed species. Potential herbicide tank mixtures combining up to four different herbicides at specified doses are identified using the additive dose model (ADM). Finally, herbicide solutions are ranked according to either the costs, the TFI or the pesticide load using a linear programming (LP) method. The concept behind the three steps is explained in more detail in Sønderskov et al. (2016).

The development of CPO-Weeds was initiated following a political decision in Denmark to reduce pesticide use, and CPO-Weeds and field experiments in various countries have revealed the potential for reduction of between 20 and 40% compared to labelled rates or standard recommendations (Sønderskov et al. 2016).

Even though CPO-Weeds are considered robust and trustworthy by both farmers and advisors, the number of farmers subscribing to the system is relatively small. A survey (Jørgensen et al. 2007) revealed that even though most farmers expressed considerable confidence in the recommendations provided by CPO-Weeds, the DSS did not fit into their way of decision-making. The advisory service in Denmark, however, makes use of CPO-Weeds, and as many farmers receive their advice on herbicide use from the advisors, they are indirectly end users benefitting from CPO-Weeds. The survey also revealed that a limiting factor for an increased uptake of CPO-Weeds is the need for field monitoring of weeds, which can be a time-consuming task and requires high level of knowledge on weed identification that farmers often do not possess. Another limiting factor was a general lack of economic incentives for reducing herbicide doses.

4.3.2 CPO-Weed Scenarios

In CPO-Weeds all weeds are reported by name, density and growth stage, but some weeds are more important than others, in the sense that their presence will prompt higher doses or the need for more expensive herbicide. In theory, there is an unlimited number of weed scenarios in CPO-weed, but 24 typical weed scenarios related to five crops are available for batch calculations and demonstration purpose.

To give an impression of the functionality and input needed for CPO-weed recommendations and to stress that intelligent and cost effective weed control requires knowledge, we will go into some detail with the 24 weed scenarios and the corresponding CPO-weed herbicide recommendations. For simplicity, however, density thresholds and growth stages are not shown or discussed, but all weed species are treated either as pre-emergence or early post-emergence under 'normal' weather conditions.

Table 4.2 shows 23 key weed species found in the 24 weed scenarios and Table 4.3 shows the 24 weed scenarios and the required level of control for each of the key weed species.

4.3.3 Field Inspection and Weed Sampling

Weed scouting takes time and requires expertise on weed species identification at early growth stages.

Table 4.2 EPPO codes, scientific name, and English names for 23 key weed species used in the CPO-weed calculations

EPPO code	Latin name	English name
ALOMY	*Alopecurus myosuroides*	Black grass
APESV	*Apera spica-venti*	Loose silky-bent
AVEFA	*Avena fatua*	Wild oat
BRSNN	*Brassica napus L.*	Oil-seed rape (voluntieer plants)
CAPBP	*Capsella bursa-pastoris*	Shepherd's purse
CHEAL	*Chenopodium album L.*	Fat hen
CIRAR	*Cirsium arvense*	Canada thistle
AGRRE	*Elytrigia repens*	Couch-grass
CONAR	*Fallopia convolvulus*	Field bindweed
GAESS	*Galeopsis spp.*	Hemp-nettle
GALAP	*Galium aparine*	Cleavers
GERdi	*Geranium spp.*	Cranes-bill
LAMSS	*Lamium spp.*	Dead-nettle
POAAN	*Poa annua*	Annual meadow grass
POLAV	*Polygonum aviculare*	Knotgrass
POLPE	*Polygonum persicaria L.*	Redshank
SOLNI	*Solanum nigrum*	Black nightshade
STEME	*Stellaria media*	Common chickweed
TRIAE	*Tricicum aestivum L.*	Wheat (voluntieer plants)
MATIN	*Tripleurospermum perforatum*	Scentless mayweed
VERAR	*Veronica arvensis L.*	Wall speedwell
VERPE	*Veronica persica*	Common field-speedwell
VIOAR	*Viola arvensis*	Field pansy

The CPO-weed holds a manual for weed scouting. It is recommends that five representative samples (50 × 50 cm) are taken per field to calculate the average weed density. In the case of large patches with a significantly higher weed density, it is recommended the field is divided into sections. It can be difficult to make a perfect inspection as is illustrated in Fig. 4.4, which shows a detailed registration in 10 × 10 m grids of three weed species.

International Plant Nutrition Institute (IPNI) (2017, point 15) has some nice thoughts and comments about the requirements and complexity of weed scouting:

> The concept behind scouting for weeds is to provide accurate and timely information needed to make intelligent, cost effective decisions. Moreover, scouting is a key component in the design of effective weed management strategies that help to manage risks by providing information needed to optimize the correct timing of herbicides and accurately monitor weed management successes and failures (Wallace 1994).
>
> This requires one to carefully think about the dynamic and flexible weed management systems to meet challenging demands. Adaptive sampling strategies (rather than fixed strategies such as grid sampling) are flexible and build on previous information and experience (…) However, we must recognize that here is no single scouting strategy that is best in all situations and that each strategy has advantages and disadvantages (IPNI 2017 point 15).

Table 4.3 Weed scenarios (EPPO codes), their frequency in each of the five crops and required level of control for each of the weed species

Crop	W sc.	Area	total	weeds	Target effecacy (%)
Winter wheat	1	11%		STEME CAPBP MATIN VERPE (basic)	75 50 85 65
	2	21%		Basic + VIOAR	80
	3	32%		Basic + POAAN	85
	4	32%		Basic + APESV	95
	5	5%	100%	Basic + ALOMY	98
	6	25%		GALAPCONAR	85 75
	7	25%		MATIN VIOAR APESV	85 75 85
Spring barley	8	56%		STEME CHEAL GAESS BRSNN LAMSS VERPE (Basic)	80 80 85 80 65 65
	9	33%	89%	Basic + CHEAL	80
	10	22%		AVEFA	95
	11	22%		CIRAR	80
	12	22%		AGRRE	85
Maize for silage	13	56%		STEME CHEAL MATIN POLPE CONAR VERPE (Basic)	85 85 85 85 90 80
	14	28%		Basic + SOLNI	85
	15	28%		Basic + AGRRE	85
	16	14%	125%	Basic + GERdi	80
Winter oilseed rape	17	60%		STEME CAPBP POAAN LAMSS VERPE (Basic)	95 85 90 85 90
	18	10%	70%	Basic + GALAP	95
	19	70%		TRIAE	90
	20	20%		MATIN	95
Sugar beets	21	203%		STEME CHEAL POLPE LAMSS VERPE (Basic)	92 96 96 92 92
	22	34%		Basic + POLAV	96
	23	34%	270%	Basic + SOLNI	96
	24	22%		AGRRE	94

4.3.4 Herbicides

Herbicides may consist of more than one active ingredient, because herbicide products sold to farmers are formulated to optimize their use. The same product may be sold under different trade names and brands in different countries. The CPO-weed calculates recommendations in various units (e.g. litres, kgs, grams and tablets) using local product names. To communicate the CPO recommendations internationally, the product recommendations are transformed to gram active ingredients and the so-called treatment frequency index (TFI). A TFI of 1 is equivalent to one standard dose per ha.

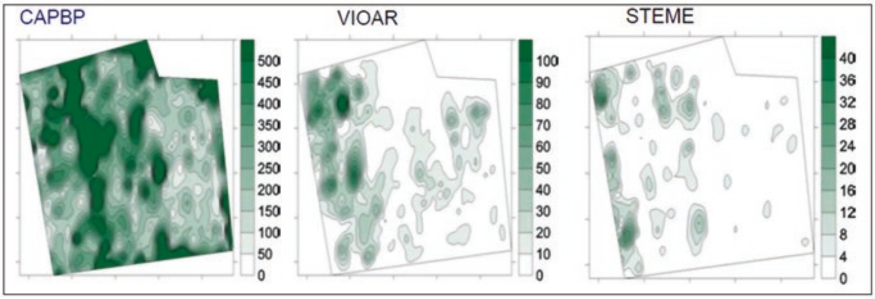

Fig. 4.4 Weed density for six weed species based on 10 m × 10 m grid. CAPBP = *Capsella bursa-pastoris*/Shepherd's Purse, VIOAR = *Viola arvensis*/Field pansy, STEME = *Stellaria media*/Common Starwort (Origin M. Walter/T. Heisel, DJF) (http://pvo.planteinfo.dk/cp/documents/InfoMarkInsp.pdf)

Table 4.4 shows CPO-weed (batch version) recommendations for the 24 weed scenarios.

Table 4.5 shows herbicide use (TFI) and costs (€ha^{-1}) in winter wheat reported by Danish farmers 2015 and calculated with CPO-weed (batch version).

CPO-weed recommendations reduce herbicide use and cost by around 45% and 52% respectively compared to the average herbicide use and estimated costs reported by Danish farmers 2015. It requires, however, 2–3 weed scoutings and planning with a DSS to obtain the potential 33 € ha^{-1} saving.

Some pre-emergence herbicides, like pendimethalin and prosulfocarb, control a broad spectrum of weeds. These herbicides are applied before the actual weed composition in a field can be determined, and selection of the dose will depend on knowledge of previous years' weed infestations. For post-emergence herbicides, on the other hand, more information will be available and generally the potential for reductions in herbicide use is greater. Herbicide reductions are, however, only possible with due consideration of the actual weed flora combined with information on the competitiveness of the crop and climatic factors such as temperature or drought. This information is pivotal because of the very variable susceptibility of weed species to the various herbicides (Sønderskov et al. 2016).

4.4 Weed Detection

4.4.1 Real-Time Weed Scouting

Weed scouting is a prerequisite for using low dose DSS systems, but it takes time and skills to do it manually. Automated, real-time weed scouting and spraying systems that integrate a video devise or camera with weed detection software and algorithms for variable-dose application could solve the scouting and planning problem (Fig. 4.5).

Table 4.4 Herbicide solutions (gram active ingredient per ha) recommended by CPO-weed decision support for five crops and 24 weed scenarios (w). The basic weed compositions are explained in a previous table

w	Crop and weeds	Recommended herbicides and doses (gram per ha)
Winter wheat		
1	Basic	21 g diflufenican +400 g prosulfocarb +0.9 g tribenuron-methyl
2	Basic + VIOAR	21 g diflufenican +400 g prosulfocarb +0.9 g tribenuron-methyl
3	Basic + POAAN	34 g diflufenican +540 g prosulfocarb +0.83 g mesosulfuron +0.27 g iodosulfuron- methyl-natrium
4	Basic + APESV	18 g fenoxaprop-p-ethyl +1.2 g tribenuron-methyl +15 g diflufenican +280 g prosulfocarb
S	Basic + ALOMY	26 g fenoxaprop-p-ethyl +1.4 g tribenuron-methyl +12 g diflufenican +230 g prosulfocarb
6	GALAP CONAR	1.4 g florasulam +2.9 g aminopyralid +52 g 2,4-d
7	MATIN VIOAR APESV	1.2 g metsulfuron-methyl +0.79 g florasulam +2.3 g pyroxsulam +1.3 g sulfosulfuron
Spring barley		
8	Basic	20 g diflufenican +0.65 g tribenuron-methyl
9	Basic + CHEAL	31 g fluroxypyr +0.53 g iodosulfuron-methyl-natrium +0.13 g florasulam +1.4 g diflufenican +0.26 g aminopyralid +4.7 g 2,4-d
10	AVEFA	47 g fenoxaprop-p-ethyl
11	CIRAR	99 g fluroxypyr +2,4 g florasulam
12	AGRRE	840 g glyphosat
Maize for silage		
13	Basic	110 g mesotrion
14	Basic + SOLNI	110 g mesotrion
15	Basic + AGRRE	91 g mesotrion +24 g foramsulfuron +0.81 g iodosulfuron-methyl-natrium
16	Basic + GERdi	370 g bentazon +74 g mesotrion
Winter oilseed rape		
17	Basic	100 g clomazon
18	Basic + GALAP	110 g clomazon
19	TRIAE	24 g propaquizafop
20	MATIN	100 g clopyralid
Sugar beets		
21	Basic	360 g phenmedipham +140 g ethofumesat +96 g desmedipham
22	Basic + POLAV	140 g ethofumesat +140 g phenmedipham +380 g metamitron +96 g desmedipham +5 g triflusulfuron-methyl
23	Basic + SOLNI	260 g ethofumesat +420 g metamitron +84 g phenmedipham +5 g triflusulfuron- methyl
24	AGRRE	87 g propaquizafop

Table 4.5 Herbicide use (TFI) and costs (€ha^{-1}) in winter wheat reported by Danish farmers 2015 and calculated with CPO-weed. HRAC is EPPO herbicide resistance classification

Herbicides		Herbicide use (TFI)		Costs (€ per ha)	
HRAC	Active ingredient	2015	CPO	2015	CPO
A	Clodinafop-propargyl	0.01	0.00	0.5	0.0
A	Fenoxaprop-P-ethyl	0.01	0.11	0.4	3.3
B	Tribenuron-methyl	0.07	0.10	0.6	0.8
B	Sulfosulfuron	0.02	0.02	0.5	0.6
B	Iodosulfuron-methyl-natrium	0.10	0.01	3.2	0.3
B	Flupyrsulfuron-methyl	0.04	0.00	0.7	0.0
B	Florasulam	0.29	0.11	6.9	2.6
B	Mesosulfuron	0.10	0.03	3.7	1.0
B	Pyroxsulam	0.14	0.03	2.3	0.5
B	Metsulfuron-methyl	0.07	0.05	0.9	0.6
C3	Ioxynil	0.05	0.00	1.5	0.0
C3	Bromoxynil	0.05	0.00	1.7	0.0
F1	Picolinafen	0.00	0.00	0.0	0.0
F1	Diflufenican	0.25	0.23	3.1	2.9
K1	Pendimethalin	0.05	0.00	4.8	0.0
N	Prosulfocarb	0.28	0.14	23.0	12.0
O	Fluroxypyr	0.13	0.00	2.3	0.0
O	MCPA	0.02	0.00	0.9	0.0
O	2,4-D	0.01	0.01	0.2	0.2
Z	Aminopyralid	0.01	0.01	0.0	0.0
	Total	1.70	0.86	57.1	24.7
	Reduction med CPO		0.83		32.4
	Relative reduction		49%		57%

It has now become possible to scout for weeds with high-speed cameras like H-sensor (AgriCon, Figs. 4.6 and 4.7) and DAT (Dimensions Agri Technologies AS, Figs. 4.5 and 4.8) mounted on the sprayer. According to Dimensions Agri Technologies AS (DAT) their DAT–sensor will reduce the use of herbicides by an average of 50% — by enabling simultaneous detection and spraying of weeds.

The DAT-Sensor Software image analysis software estimates coverage of broad-leaved weeds and cereals in near-ground RGB images. The algorithm identifies weeds by shape, size, colour and texture. Dicot weeds highlighted in red (Fig. 4.5).

4.4.2 *Weed Mapping with a Camera Mounted on an ATV*

As already mentioned, weed detection (monitoring and scouting), planning and spraying are the three dimensions in chemical weed control with variable doses. Weed detection, planning and spraying, however, do not have to take place

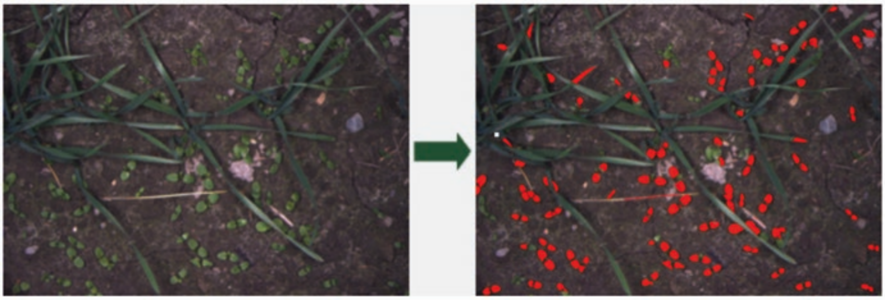

Fig. 4.5 DAT-Sensor Software weed detection (in red: weed identified as dicot weed) (Photos: Dimensions Agri Technologies AS)

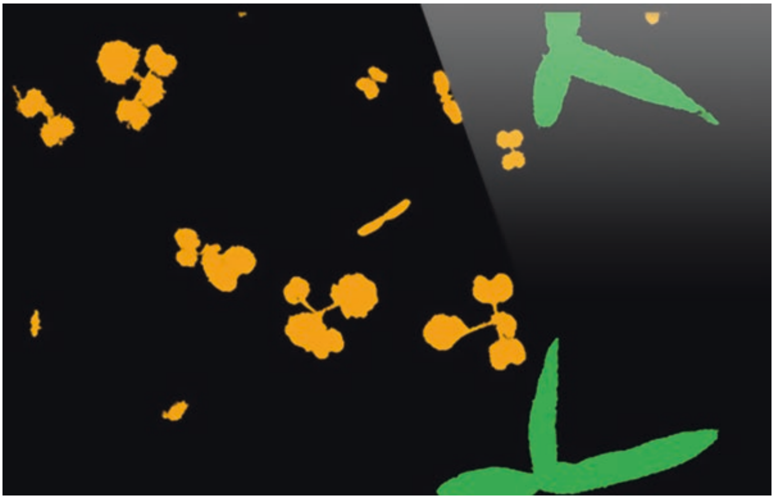

Fig. 4.6 H-Sensor weed detection. (in yellow: weed detected as dicot weed) (Photo: AgriCon GmbH)

Fig. 4.7 H-Sensors mounted on a boom sprayer. "Different treatment for grass and dicot weed" (Photo: AgriCon GmbH)

Fig. 4.8 DAT–sensors mounted on a sprayer (Photo: Dimensions Agri Technologies AS)

simultaneously. A weed map produced with automated weed scouting could be a cost efficient alternative to manual weed scouting, and an ideal basis for planning with a DSS like CPO-weed.

The Danish RoboWeedSupport project (Laursen et al. 2017) intends to bridge the gap between the potential herbicide savings using a decision support system like CPO-weed and the required weed monitoring. Their project has examined the cost of performing data collection based on a camera system with three cameras on a 24-m boom mounted on an all-terrain vehicle (ATV) able to drive and record data at up to 50 km h^{-1} with an image quality sufficient for identifying newly emerged grass weeds. Their economic estimates are based on approximately 100 hectares recorded at three different locations in Denmark. With an average image density of 99 images per hectare, the ATV had a capacity of 28 ha per hour, which is estimated to cost 6.6 € ha^{-1}. Alternatively, relying on a boom mounted solution on a tractor, while applying fungicides or fertilizer before the last follow up herbicide application, it was estimated that a cost of 2.4 € per ha is obtainable under equal conditions.

4.5 Conclusion

Site-specific application of pesticides has so far focused mainly on herbicides. The purpose of precision farming technologies in relation to herbicide use is to reduce herbicide cost and environmental impact from spraying, but at the same time to maintain a satisfactory level of weed control. Another purpose is to increase spraying capacity, to reduce the number of sprayer refills and to minimize time spent on weed monitoring. In this chapter, the relevance and profitability of four precision herbicide application technologies, two weed detection technologies and a low dose decision support system (DSS) are analysed. Crop Protection Online-weeds (CPO-Weed) is a decision support system for chemical weed control developed in Denmark and subsequently adjusted to the conditions in several other countries. With lower than recommended herbicide doses provided by CPO-weed, herbicide cost can be reduced by 20–50%. It requires, however, a proper monitoring of weeds, which can be a time-consuming task that, furthermore, requires that the farmer is able to identify the weed species correctly. The current development of high-speed camera and software systems can take over the task of detecting and mapping weeds. However, at the moment no system is available that is able to distinguish and classify all common weed species correctly.

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