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Advances in site-specific weed management in agriculture—A review

Roland Gerhards1 | Dionisio Andújar Sanchez2 | Pavel Hamouz3 | Gerassimos G. Peteinatos1 | Svend Christensen4 | Cesar Fernandez-Quintanilla5

Abstract
The developments of information and automation technologies have opened a new era for weed management to fit physical and chemical control treatments to the spatial and temporal heterogeneity of weed distributions in agricultural fields. This review describes the technologies of site-specific weed management (SSWM) systems, evaluates their ecological and economic benefits and gives a perspective for the implementation in practical farming. Sensor technologies including 3D cameras, multispectral imaging and Artificial Intelligence (AI) for weed classification and computer-based decision algorithms are described in combination with precise spraying and hoeing operations. Those treatments are targeted for patches of weeds or individual weed plants. Cameras can also guide inter-row hoes precisely in the centre between two crop rows at much higher driving speed. Camera-guided hoeing increased selectivity and weed control efficacy compared with manual steered hoeing. Robots combine those guiding systems with in-row hoeing or spot spraying systems that can selectively control individual weeds within crop rows. Results with patch spraying show at least 50% saving of herbicides in various crops without causing additional costs for weed control in the following years. A challenge with these technologies is the interoperability of sensing and controllers. Most of the current SSWM technologies use their own IT protocols that do not allow connecting different sensors and implements. Plug & play standards for linking detection, decision making and weeding would improve the adoption of new SSWM technologies and reduce operational costs. An important impact of SSWM is the potential contribution to the EU-Green Deal targets to reduce pesticide use and increase biodiversity. However, further on-farm research is needed for integrating those technologies into agricultural practice.

Keywords
Artificial Intelligence, patch spraying, precision farming, robotic weeding, sensor technologies, weed mapping
1 | INTRODUCTION

Site-specific weed management (SSWM) considers the spatial variability and temporal dynamics of weed populations in agricultural fields. Weed control methods are precisely targeted to individual weeds or patches of weeds. The economic attractiveness of this practice in a given field depends on the area of that field with weed densities below the economic threshold. However, these areas can vary substantially between fields and crops. Weed mapping and site-specific herbicide spraying have resulted in 23%-89% herbicide savings in a series of 58 field experiments in cereals, maize, sugar beet and peas without causing crop yield losses of uncontrolled weeds and additional costs for weed control in the following years (Berge et al., 2012; Christensen et al., 2009; Gerhards & Oebel, 2006). Savings were realised by turning off the boom sections at locations below the economic weed threshold and by adjusting the herbicide rate to the local weed species composition and densities. Herbicide use can be further reduced if site-specific application is supplemented with species-specific spraying (Wiles, 2009). A German study showed that SSWM only with uniform tank mixture resulted in an average of 37% of field area untreated. However, using species-specific control with a three-tank sprayer resulted in 59%-80% untreated area depending on the weed species (Gutjahr et al., 2012).

Site-specific weed management started with grid sampling and weed mapping in the late 20th century (Marshall, 1988; Wiles et al., 1992). Current advances of this concept comprise several commercial and practical applications in camera-guided weed hoeing, sensor-based patch and spot spraying, robotic weeding and weed scouting (Champ et al., 2016; Dyrman et al., 2016; Gutjahr et al., 2012; Kunz et al., 2015; Peteinatos et al., 2020; Tillett et al., 2002). Several more prototypes, such as sensor-based electrical weed control (Reiser et al., 2019), Unmanned Aerial Vehicle (UAV)-based weed mapping and patch spraying (Mink et al., 2018; Rasmussen et al., 2013) and targeted weed control with direct injection of herbicides (Pohl et al., 2019; Ruigrok et al., 2020), are currently being developed.

For successful implementation, it is important that SSWM provides economic and environmental benefits. The new sensor technologies should be combined with decision support systems (DSS) supporting farmers to apply weed control treatments at the right time, in the right intensity and at the right locations (Christensen et al., 2003). A common and standardised communication and data management platform between the weed sensing system and the actuator is a bottleneck for further development of SSWM. Moreover, SSWM systems need to be robust under variable field conditions with little input for maintenance.

The objectives of this review are (1) to summarise the different technologies and approaches for SSWM and evaluate them, (2) highlight the environmental and economic impacts of SSWM, (3) give future perspectives for the implementation of SSWM in practical farming and finally (4) describe the need for further improvements, investigations and developments in SSWM.

2 | SPATIAL VARIATION OF WEED POPULATIONS

Site-specific weed management relies upon a good understanding of the distribution of weeds in the field. Aggregation of weeds, their spatial structure, the crop rotation, weed species competition and the planned weed control tactics decide the resolutions of sensors and weeding tools. In some situations, weeds tend to form large discrete aggregated patches, whilst in others a large number of small, diffuse patches are present (Heijting et al., 2007). In a UK study (Lutman & Miller, 2007), Alopecurus myosuroides Huds. infested large portions of the fields. However, this species showed poor ability to colonise new areas in cereals if effective weed control methods were applied across the entire field. Other annual species such as Galium aparine L., Fumaria officinalis L., Matricaria chamomilla L. and perennials, such as Cirsiurn arvense L., had more aggregated distribution (Colbach et al., 2000; Gerhards et al., 1997; Lutman & Miller, 2007). Opportunities for site-specific treatments are different in both cases. In the first case, weed detection and weeding could be conducted with a coarse resolution. In the second case, a finer resolution of sensor and application technologies is needed. In the extreme case of spot spraying, patch size is not relevant since each weed plant is controlled individually (Ustumo et al., 2018).

Spatial weed distribution and aggregation of weeds in patches are the result of the biology of the species, the weed management practice and site-specific characteristics of the field like soil texture (Gerhards et al., 1997; Mortensen et al., 1998). Uncontrolled weeds and poor crop establishment may cause persistent weed infestations (Cousens & Mortimer, 1995). Tillage and harvest operations play important roles in the dispersal of numerous weed species, conditioning their spatial distribution in the field (Andújar et al., 2012; Barroso et al., 2006; Blanco-Moreno et al., 2004). All these factors should be considered in order to manage weeds site-specifically. Soil variability is also causing weed heterogeneity. Alopecurus myosuroides in cereals in Germany mostly occurred at locations in the field where the clay content was relatively high (Nordmeyer & Niemann, 1992). A long-term survey in an arable field in Germany showed that 28% of the spatial weed species variability was explained by soil texture, available water capacity and soil organic carbon (Pätzold et al., 2020). Topography is another source of weed heterogeneity. Heavy infestations of Avena sterilis L. in dry-land cereal crops in Spain tend to concentrate in flat lowland, concave landscapes and on northern slopes (Ruiz et al., 2006). In irrigated lands, Sorghum halepense (L.) Pers. infestations in maize crops are more prevalent in the lower areas close to the rivers with more prone to periodic flooding (Andújar et al., 2011a; Andújar et al., 2011b).

Farmers often hesitate to apply SSWM based on economic weed threshold because they are afraid of an exponential increase in the weed soil seedbank leading to higher infestations and higher costs for weed control in the following years. However, this risk is not supported by experimental evidence. Ritter and Gerhards (2008) reported that populations of A. myosuroides did not significantly change in density, location and size when SSWM methods were applied over...
a period of 8 years in a 3-year rotation. Similarly, Christensen et al. (2003) did not find significant changes in the occurrence or density of species in a 5-year trial with SSWM. For the species with short-lived seeds such as Apera spica-venti (L.) Pal. Beauv, the change in spatial distribution may be much faster. Such species with relatively short seed longevity, however, pose rather short-term risk for farmers and can be reduced by appropriate crop rotations (Hamouz et al., 2014).

A good understanding of spatial distribution and temporal stability of weed populations may contribute to simplify the monitoring process. Precise weed maps provide several benefits to farmers and consultants. The knowledge of the association of a noxious weed species and various topographic or soil factors would allow to focus weed monitoring in high-risk areas. Early-season weed maps can be used to calculate the potential herbicide savings and plan site-specific weed control application. Weed maps generated from aerial images close to harvest can be used to control patches of C. arvense L. in the following years (Rasmussen et al., 2021).

Pre-harvest weed maps can also be used for studying spatial and temporal dynamics of weed species. Overlaid with yield maps, pre-harvest weed maps provide knowledge about yield losses associated with different weed densities and species. Pre-harvest weed maps of fields that have been sprayed with herbicides may show surviving or resistant weeds. If weed patches are persistent in density and location over years, maps from previous years could be used for planning spatial weed control applications over several years. However, if weed emergence varies from year to year due to, for example, varying weed competition and weed seed production, patches grow or shrink in both distribution and density from year to year. Therefore, weed sensing and mapping is necessary every year. Weed species with high seed production may rapidly disperse from small patches of minor economic importance to larger infestation of the whole field. Therefore, the species population dynamics should be part of SSWM decisions to avoid that these patches expand and create a significant hazard in the following years.

3 | SENSOR TECHNOLOGIES FOR SITE-SPECIFIC WEED MANAGEMENT

3.1 | Sensor systems and sensor platforms

Advances in sensor technologies for identifying weed patches and single weeds had a great impact on the development of SSWM. Weed sensing can be performed from ground or from the air. Ground sensing allows a higher level of resolution and real-time treatment. On the contrary, aerial systems are able to cover a larger area of land in less time for the creation of weed and treatment maps. However, the spatial resolution achieved with remote sensing may not be sufficient for weed species detection in early growth stages. In the specific case of perennial weed species and high-density weed patches, weed distribution maps have been generated shortly before weed treatment by using UAVs (Rasmussen et al., 2013; Torres-Sánchez et al., 2013). In wide row crops, post-processing of UAV images can remove pixels from the crop line. All the remaining green pixels will then be classified as weeds (Mink et al., 2018). Latest UAV camera systems provide remote images of less than one-centimetre spatial resolution per pixel, which would be sufficient also for mapping weed seedlings (Mink et al., 2018).

Stereo and 3D imaging is a new technique for modelling of morphological differences between crop and weed species (Andújar et al., 2018). The extraction of 3D plant parameters can be achieved based on RGB images (Arvidsson et al., 2011), LiDAR (Guo et al., 2018), structured light (Nguyen et al., 2015), spectroscopy (Shapira et al., 2013), thermal images (Ortiz-Bustos et al., 2017) and ultrasound (Andújar et al., 2011a; Andújar et al., 2011b). Depth cameras and laser scanners located at a known position with variable distance and angle in relation to the target allow acquiring positioned data for 3D reconstruction. Three-dimensional imaging has increased the precision of weed classification and automatic row detection in camera-guided hoeing systems compared with conventional RGB cameras mainly when plants overlapped (Gerhards et al., 2020). Integration of size and plant height also provides more accurate estimates of weed competition in decision models (Andújar et al., 2018).

Advances in crop-weed discrimination were also achieved with multispectral and hyperspectral cameras combined with machine learning algorithms (Zhang & Slaughter, 2011). Images of multispectral and hyperspectral cameras allowed better segmentation of plants in digital images compared with RGB images. Soil, mulch and stones can be removed from the images by subtracting the red spectrum from the infrared spectrum of the images (Gerhards & Oebel, 2006). In RGB images, they might lead to misclassifications. However, considering that RGB cameras are still the most widely used sensors, new classification algorithms based on Artificial Intelligence (AI) have been programmed for RGB images (Peteinatos et al., 2014; Utstumo et al., 2018; Wu et al., 2020) (Figure 1).

3.2 | Artificial Intelligence for plant species classification

Convolution neural networks (CNNs)—first implemented by LeCun et al. (1989)—can be used as a very precise tool for weed classification and object detection. Although the use of CNNs is relatively new, these tools have mostly replaced previous methods of AI for weed identification (Kamilaris & Prenafeta-Boldú, 2018). The homogeneous distribution of the crops in rows was included in the classifiers for crops and weeds (Strothmann et al., 2017). Classification accuracies ranged between 94% and 99.5% depending on the neural network selected, the number of species trained and the quality of training (dos Santos Ferreira et al., 2017; Olsen et al., 2019; Peteinatos et al., 2020; Potena et al., 2017). Besides accuracy, the advantage of CNNs is their ability to create correlations, extrapolate and weigh new features independently (Lee et al., 2017; Milioto et al., 2017). The causality of features and their weight on the classification are sometimes not completely
understood in the CNNs, because they surpass the human-brain capacity to understand complex data (Rawat & Wang, 2017). Yet, two main limitations for CNNs in weed identification still exist. Advanced hardware and intense computation time at training stage hinders their adoption, especially for online systems (Peteinatos et al., 2020; Rawat & Wang, 2017). The effort for training CNNs with plant species in different growth stages, under different environment and in different plant communities, is immense and may require joint actions of several working groups (Dyrmann et al., 2016; Peteinatos et al., 2020). Hall et al. (2018) reduced the time for training a CNN by unsupervised clustering and selective labelling weed species in cotton without significantly reducing classification accuracy. In simple spraying and hoeing operations, when only crop and weed need to be separated in digital images or weed species can be grouped into classes of grass weeds and dicotyledonous weeds, it might be faster and more efficient to use less complicated machine learning systems such as described by Gerhards and Oebel (2006).
4 | PRECISION APPLICATION TECHNOLOGIES

4.1 | Patch spraying

In the early 90ies of last century, simple map-based GPS-controlled patch spraying was applied turning on and off each boom section separately, where the economic weed threshold was exceeded (Gerhards & Christensen, 2003). Little progress has been made in precise spraying technologies within the past 15 years. Therefore, the potential of improved weed detection systems cannot fully be exploited. Adjusting the herbicide mixture to the actual weed species distribution in the field would double the potential for herbicide savings compared with patch spraying system with conventional one-tank boom sprayers (Gutjahr et al., 2012). Therefore, real-time adjustment of herbicide mixture to the actual weed species infestation would be an important technology for SSSWM. So far, only prototypes of direct injection of up to three different herbicides into the pressure system of a boom sprayer have been developed by Danfoil in Denmark and by Dammann with Julius Kühn Institut in Germany (Pohl et al., 2019). A different solution for varying herbicide mixture is a three-tank sprayer by Kverneland with the University of Bonn (Gerhards & Oebel, 2006). However, all these developments require previously created digital spray maps.

Simple systems for real-time site-specific herbicide application, which are able to discriminate between green vegetation and soil based on their spectral properties, were developed decades ago (Felton & McCloy, 1992) and are commonly available as commercial products (e.g. WeedSeeker (Trimble)). Use of such systems is, however, limited for fallows or other situations where the living biomass from weeds and crops does not need to be distinguished. Cameras combined with AI can distinguish between crops and weeds and identify weed species in real time (Fernandez-Quintanilla et al., 2018). Those smart camera systems have mostly been included in prototypes of spraying robots for specific applications in individual crops. In some cases, these cameras have been incorporated in self-propelled robots (Kilter AX-1, Kilter AS) and field boom sprayers (H-Sensor, AgriCon; Smart spraying, Bosch/BASF; DAT Ecopath, Dimensions, Agri Technologies AS; Robocrop Spot Sprayer, Garford Farm Machinery Ltd.) to control weed patches in maize, soyabean, winter wheat and cotton. Sensor-based control of single nozzles would increase the savings of herbicides and facilitate the application of economic weed thresholds (Blue River).

Apart from regular spray volume regulation by hydraulic pressure control, variable rate technology is also applied for site-specific weed control. Herbicide rate can be adjusted in a wide range to weed species composition and growth stage using pulse-width modulation (PWM). Some agricultural machinery companies offer this technology (e.g. AIM Command FLEX®, ExactApply) (Butts et al., 2019). More importantly, it can be used for site-specific herbicide application of single nozzles. Further investigation is required to determine the herbicide rate needed for different weed species and herbicides similarly to the decision algorithm for patch spraying (Christensen et al., 2003).

4.2 | Camera-guided physical weeding

Restrictions in herbicide use, their negative side effects on the environments, herbicide residues in the food chain and the spread of herbicide-resistant weed populations were the driving forces for precision application technologies in physical weed control (Gerhards et al., 2020, 2021). Camera-guided inter-row hoeing with automatic side-shift control using Garford Robocrop Guided Hoes®, UK, and an OEM Claas stereo camera®, Germany, in combination with an Einböck Row-Guard® hoe, Austria, has increased total weed control efficacy (inter-row and intra-row) in sugar beet and soyabean to 85% compared to 70% for machine hoeing with manual guidance (Kunz et al., 2015). Higher weed control efficacy was obtained by guiding ducks-foot blades closer along crop rows. With increasing driving speed, stronger burial of intra-row weeds with soil was observed. The RGB-Vision Control System® from K.U.L.T., Germany, facing diagonally forward and scanning 4–6 crop rows, provides a robust row detection even in partly overlapping crop rows such as cereals at 12.5–15 cm row distance (Gerhards et al., 2020). Regions of highest green pixel densities are identified and connected to a line for tracking of crop rows (Tillett et al., 2002). This allows precision hoeing in conventionally grown cereals, legumes and oil-seed rape. Artificial light improved the quality of row detection. Several manufacturers offer

| TABLE 1 | Inter-row camera guidance systems for mechanical hoes |
|---------------------------------------------|
| **Commercial products** | **Accuracy (cm)** | **Minimum inter-row spacing (cm)** | **Camera technology** | **Maximum speed (km/h)** |
| K.U.L.T. Vision Control® | ±2 | 12.5 | 1D Bi-spectral (NIR + Red) | 15 |
| Garford Robocrop Guided Hoes® | ±4 | <10 | 3D visible spectrum | 14 |
| Horsch Transformer VF | ±4 | 20 | Several cameras using ISOBUS-connection, Section control | 12 |
| Stekete IC® | ±4 | 25 | 2D bi-spectral (NIR + Red) | 10 |
| OEM Claas Row-Guard®, Einböck, Hatzenbihler, Schmotzer | ±4 | 25 | 3D stereo | 14 |

Note: Accuracy describes the maximum offset of the hoeing guidance from the line in the centre of two crop rows.
camera-based automatic side-shift control systems with working width of 3–9 m (Table 1). Even if camera-guided physical weeding systems will be able to remove 80%–90% of the weeds, it may still be necessary to combine them with other weed control tactics, such as band-spraying, selective in-row hoeing, stale seeded or pre-emergence harrowing to avoid yield losses and prevent an increase in weed populations. Cross-hoeing along crop rows and vertically to the crop rows is a special form of camera-based inter-row hoeing. It requires that crop seed as placed in a square grid pattern using special seeders.

Camera-based in-row hoeing has so far been developed for transplanted vegetables (K.U.L.T. Robovator, Garford Robocrop InRow Weeder®, and Stekete Ic®) (Lati et al., 2016). The systems work precisely if weeds are relatively small compared with the crop. In addition, they are able to control a high proportion of the intra-row weeds. However, working speed is low with a maximum of 1.8 km/h (Tillett et al., 2002, 2008). Camera-based intra-row weeding, band-spraying and other selective physical in-row weed control benefit from camera-guided inter-row hoeing, because they are precisely guided along crop rows (Gerhards et al., 2020).

4.3 | Robotic weeding

The complete robotization of the agricultural ecosystem has been investigated for years with the incorporation of fleets of autonomous robots capable of carrying out various agricultural operations (Gonzalez-de-Santos et al., 2017). The availability of information that improves detection and action processes complemented by meteorological and historical data is increasing day by day. The handling of large amounts of data together with the automation and robotization of agricultural tasks is the starting point of a technological revolution in which robots and information are the keys to smart agriculture. Swarms of small, low-cost robots can be effectively and economically used preferentially in high-value row crops with a low weed control threshold and in organic farming. Various prototypes of spraying robots for precise spot spraying in individual crops have been developed and analysed (Ruigrok et al., 2020; Utstumo et al., 2018; Wu et al., 2020). They achieved more than 80% correct image classification and up to 96% weed control while <10% crop damage. Those technologies include imaging technologies to differentiate between crop and weed and spraying systems targeting on individual weeds.

Robotti by Agrointelli in Denmark, Bilberry in France, and ecoRobotix in Switzerland, H-Sensor by Agricon in Germany are examples for commercial spraying robots in Europe. Apart from these spraying robots, several robots have been developed for physical weed control using hoeing blades, high voltage, laser and flaming. They target individual weeds and differentiate between crop and weeds in the intra-row space (Rasmussen et al., 2012). Naio Technologies in France, Farming Revolution in Germany, Odd. Bot in the Netherlands and Remoweed (Ferrari Costruzioni) in Italy developed commercial sensor-based hoeing robots (e.g. Naio OZ and DINO). Several studies were conducted to record the position of crop seeds during seeding using RTK-GNSS. Pre- and post-emergent hoeing was later directed around the crop plants using an RTK-GNSS-controlled guidance system (Nørremark et al., 2012). However, RTK-GNSS has a lower accuracy than cameras mounted on the machines. Therefore, a larger safety circle around a crop needs to be left untreated for RTK-GNSS guidance systems (Figure 1).

5 | COMMUNICATION BETWEEN SENSOR, TERMINAL AND APPLICATION TECHNOLOGY

Most of the above-mentioned sensor and application systems use their own protocols that do not allow the separation of the sensor from the weeding implement nor a combination of different sensors, terminals and controllers (Paraforos et al., 2019). This fact discourages farmers from using these technologies as they do not have time or competences to handle IT problems and often do not want to be tied to the technology of one company. Standard protocols for linking detection and weed treatment systems would improve the adoption of new SSWM technologies and greatly reduce operational costs. Ideally, any sensor should be interoperable with any terminal, controller and application technology as plug & play solution (Figure 1).

In most current solutions, the connection of different implements to the tractor requires as many control devices as tools to be fitted to the vehicle along with the cable connections that each device has. With the introduction of any new device, the number of control devices on the tractor increases. ISOBUS is the standard protocol for managing communication between tractors, decision support system and actuator from all manufacturers. Data and information can be exchanged in a universal language through a single control console in the tractor cab. Most commercial tractors are equipped with the ISOBUS communication system that would allow interoperability of sensing and controllers. However, until now, only the Agrointelli robot uses ISOBUS to connect its cameras with the actuator. Similar endeavours are currently developed, for example, in the EU–EIT Food project Dacweed but have still to overpass a lot of challenges. The use of a communication standard limits the amount of information to be transferred using a standard protocol. The processing and transfer of information must be fast, and this means that less data can be channelled from the sensor to the actuator via a controller. Thus, sensor data need to be condensed for ISOBUS communication systems. This can be realised in three ways:

1. external map-based information processing or real-time processing using 5G technology.
2. machine learning and use of a GPU processor that can process large amounts of information in real time for weed detection.
3. match detection and actuation resolution.
Decision support system (DSS) is an integral part of SSWM estimating the need for weed control and selecting the right type and intensity of weed management. Different types of DSSs exist. The most common versions are based on simple threshold values (Cousens, 1985). These models use empirical data to predict yield loss without weed control due to weed densities at the time, when weed control decisions are taken. Some experiments have shown that yield loss models fitted better for relative weed coverage than for weed density (Ali et al., 2013), because relative weed coverage accounts for the size of crop and weeds and relative time of emergence. Both weed density and weed cover can be measured with sensors described in the previous sections. Longchamps et al. (2014) achieved a 30% herbicides reduction with a simple threshold algorithm based on weed coverage measurement. Patches of 2 m by 3 m were treated site-specifically with post-emergence herbicides using a real-time patch sprayer when the threshold of 0.12% weed coverage was exceeded. The use of sensor and AI technologies described above would allow to determine and apply weed species-specific weed thresholds, for example, thresholds already existing for more than 70 weed species in soyabean (Hock et al., 2009. Very competitive species, such as Xanthium strumarium L., can then be treated with a lower threshold and less competitive species, such as Veronica persica Poir. with a higher threshold. That will further increase herbicide savings.

Another type of DSS integrates several expert models and algorithms into decision rule trees (Gutjahr & Gerhards, 2010; Rydahl, 2004) shown in Figure 2. In the first part of the decision rule tree, the economic weed threshold is determined from a yield loss model. If the yield loss is higher than the gain from the treatment, the economic weed threshold is exceeded. Then, a suitable herbicide is selected based on the weed species present, their growth stages and the environmental conditions. The optimum herbicide rate is determined based on dose–response studies for individual herbicides and weed species (Christensen et al., 2003). Those studies are time-consuming and expensive. However, data exist for all herbicides since they are part of the companies screening and testing new herbicides for documented optimal treatments.

Weed population dynamic models are employed to estimate variations in the soil seedbank. This part of the decision tree should support the user to prevent additional costs for weed control in the following years if they were not controlled in one year (Gutjahr & Gerhards, 2010). The three model outputs are then integrated into a site-specific decision that finds the optimal combination of herbicide and dosage that fit to the management of the site-specific weed population. Jones and Medd (2000) suggested that depleting weed seedbank using low weed thresholds in the first years substantially reduced herbicide input in the following years. This strategy had the best economic return.

There is definitely a need to adjust DSS to the capacities of new sensor-based weeding robots. Decisions can target on single plants differentiating between problematic and beneficial weeds.

### 7 | ECONOMIC ASPECTS, COMMERCIAL ADAPTATION AND ECOCLOGICAL BENEFITS

Acceptance of chemical crop protection is decreasing in the society. Pesticides are often considered as contaminants, which may affect food safety and hurt the ecosystems. This concern is reflected in political steps and legislative regulations. The use of herbicides was been restricted and probably will be more restricted due to their unfavourable ecotoxicological profiles or other environmental concerns (European Commission, 2019). The Commission targets set by the Green Deal and Farm to Fork strategies are to reduce the overall use and risk of chemical pesticides by 50% until 2030, promoting greater use of safe alternative...
ways of pest management (European Commission, 2020). To comply with these targets and to keep up with future environmental policy measures, farmers will be forced to adopt new technologies including SSWM.

Another factor, which is likely to increase the demand for environmental-friendly weed management methods, is the growing area of organically produced foods. The total organic area in the EU-27 was nearly 14 million hectares in 2019, which corresponds to 8.5% of the total utilised agricultural area of those countries. The increase in organic area between 2012 and 2019 was 46% (Eurostat, 2021). The new Action Plan for the development of organic production in the EU sets a target of 25% area of organic farming until 2030 (European Commission, 2020).

Although the precision agriculture technologies (including robotics) are generally considered to have a potential for improving farm productivity and profits (Bongiovanni & Lowenberg-DeBoer, 2004), adoption of SSWM is more complex. Application of SSWM technologies may be diverse and may be realised under various environmental and economic conditions. A key question is what operations have to be substituted by the new technologies. Replacing manual weeding by robotic weeding platforms will certainly increase productivity (Pérez-Ruíz et al., 2014; Sørensen et al., 2005). Although these manual operations are so far rather infrequent in developed countries, the increase in organic farming creates a significant potential for this technology. The farmers, however, still hesitate to invest in precision weed control technologies as the calculation of the profitability is not straightforward. By implementing robotics, many factors such as the purchase price, annual utilisation, area capacity and weeding efficiency have to be considered. Some parameters such as overall life-time and maintenance costs of SSWM have to be first proven by their long-term operation. The barriers for adoption of SSWM technologies may not be just economic. The farmers are justifiably concerned about additional works, which will place more demands on their technical and IT literacy (Balafoutis et al., 2020).

For site-specific herbicide application, Gerhards and Oebel (2006) reported a 50% decrease in herbicide costs. However, this figure will depend on the actual density and aggregation of weed populations. Nevertheless, this technology may only be profitable if weed infestation is low and if the equipment and time needed for weed detection and variable herbicide application will not introduce a substantial increase in treatment costs (Swinton, 2005). Andújar et al. (2013) simulated control strategies for *S. halepense* in maize crops. Site-specific weed management was the most profitable strategy when <19% of the field was infested. Robotic weeding in organic farming can reduce labour costs and allow farmers to extend the production of labour-intensive crops or even practice more profitable crop rotations. Conventional farms using SSWM might realise higher selling prices for their agricultural products (Lowenberg-DeBoer et al., 2020).

The integration of SSWM technologies in conventional farms will probably be driven by their environmental benefits, mainly the significant reduction in herbicide use. Economic aspects, such as reducing yield losses by herbicide-resistant weed populations and reducing herbicide costs, will also favour this technology. However, high efficiency and relatively low costs let farmers often decide for chemical weed control (Swinton, 2005). To make SSWM technologies more attractive for farmers, they have to provide more significant competitive advantages, such as higher selling prices for low-residue production or direct and indirect subsidies for the purchase and operation of precision farming technologies. Agro-environmental policies can be applied to push the farmers towards the adoption of more environmentally friendly weed management methods. Currently, however, there are no direct regulatory measures to adopt precision agriculture technologies in the EU (Barnes et al., 2019).

A second benefit may be the enhancement of weed biodiversity through a more selective weed control, focussing only on undesirable weed species. Rare, beneficial or endangered species can be identified, located and excluded from treatments. On the contrary, newly introduced invasive species can be eliminated before they create a persistent seedbed. The use of SSWM can promote diverse crop rotations. Various crops that are currently discarded by growers because of the limited options available for weed control can gain in attractiveness for growers. An additional environmental benefit of robotic weeding machines is the reduction in fuel and carbon consumption and less soil compaction associated with the use of small robotic weeding units.

8 | CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Site-specific weed management has the potential to contribute to reduce pesticide use and increase biodiversity in agriculture. Both targets can be reached without causing crop yield losses and additional weeding costs in the following years. Therefore, SSWM can be considered as an economical and environmentally friendly approach to meet the EU-Green Deal targets. Transferring this technology into practical farming requires that these systems become more robust under practical conditions. Farmers need support to get acquainted with the new technologies in the first years of operation through on-farm research.

Four obstacles for adoption of SSWM in agriculture have been identified in this review:

1. More effort is needed for new spraying technologies that can vary herbicide mixture in real time according to weed species distribution.
2. There is a strong need for establishing open-access image database with annotated weed species in all relevant growth stages for weed control. The set-up, structuring and maintenance of this image database could be an important objective of the European Weed Research Society working group ‘site-specific weed management’.
3. Improvements are needed to increase in-row mechanical weed control efficacy.
4. There is a strong need to implement standardised communication platforms, such as ISOBUS, to secure optimal data exchange between different sensors, decision support systems and weeding tools.

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DATA AVAILABILITY STATEMENT
Any data that support the findings of this study are included within the article.

ORCID
Roland Gerhards https://orcid.org/0000-0002-6720-5938
Pavel Hamouz https://orcid.org/0000-0003-1318-8869
Svend Christensen https://orcid.org/0000-0002-1112-1954

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