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TAILORED WEED MANAGEMENT STRATEGIES FOR SPECIFIC AGRICULTURAL SITES

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Site-Specific Weed Management (SSWM) offers significant economic and environmental benefits by targeting herbicide application only to weed-infested patches, reducing overall herbicide use and minimizing environmental impact. This approach is enhanced by GPS technology, enabling precise control measures. Recent advancements in SSWM technologies, including automated weed detection and robotic systems, have shown promising results in reducing herbicide use by up to 80% and increasing crop yields. However, challenges remain in mapping accuracy, costs, and long-term ecosystem impacts. Continued research and development are essential for widespread adoption and further optimization of SSWM practices.

Site-specific weed management is particularly effective when weeds are concentrated in patches rather than uniformly distributed across a field. By targeting only those areas, farmers can significantly reduce herbicide use, minimizing the environmental impact and cost. This approach also helps manage long-term herbicide use by addressing new or difficult-to-control weeds early, preventing their spread. Historically, before herbicides were common, farmers removed these patches before seeds matured to control the spread. Effective patch management requires detailed knowledge of weed locations, which can be obtained through field scouting, remote sensing, or aerial photographs that differentiate crops from weeds. In Alberta, weed-sensing sprayers have been used to detect and treat weed patches without prior mapping, proving effective in fallow systems with a 19-60% reduction in herbicide use. While this technology is limited to large or dense patches and not suitable for in-crop use, other site-specific sprayer technologies are becoming more widespread as GPS and variable rate sprayers become increasingly accessible.

The fundamental components of site-specific weed control technologies consist of three key elements:

1. **Weed Sensing System:** This system is responsible for identifying, localizing, and measuring crop and weed parameters.
2. **Weed Management Model:** It utilizes knowledge and information on crop–weed competition, population dynamics, the biological efficacy of control methods, and decision-making algorithms to optimize treatments based on weed species density and composition, as well as economic and environmental considerations.
3. **Precision Weed Control Implement:** Examples include sprayers with individually controllable boom sections or nozzles that allow for spatially variable herbicide applications.

SSWM Considerations: Pre-emergence herbicides should be selected based on soil properties for effective control of annual weeds. Spot spraying is recommended for fields with low weed density, while patch outlining or combine mapping can help record areas where weeds have escaped treatment (Blasco *et al.*, 2002). It's crucial to spray not only the known weed patches but also the surrounding boundary areas to ensure comprehensive control. Post-emergence foliar herbicides should be used in conjunction with reflectance sensors for precise application. Economically, the use of high-cost herbicides is most feasible when targeting highly aggregated problem weeds.

Recommendations: To prevent the spread of new or hard-to-control weeds across the entire field, it is important to manage patches early. Farmers can locate these weed patches through field scouting, remote sensing, or aerial photography. Once identified, patches can be managed through localized spraying, using weed-sensing sprayers in fallow fields, or GPS-guided systems. Non-chemical methods, such as mowing, tillage, silage cutting, or grazing, can also be effective in controlling these weed patches.

SSWM Spraying Systems Aim: The goal of Site-Specific Weed Management (SSWM) spraying systems is to deliver the right dose of the right herbicide precisely where it is needed. However, there are several technical challenges to overcome, leading to various research approaches with differing levels of complexity.

Automatic Weed Detection

Automatic weed detection is essential for the widespread adoption of site-specific weed management (SSWM) since manual weed sampling is labor-intensive and costly. Two main approaches for weed sensing and herbicide application exist: offline and online. In the offline approach, weeds are first detected and mapped, and then herbicides are applied based on this weed infestation map. For instance, a study at the University of Hohenheim used this method to target *Cirsium arvense* in a maize field, where only 30% of the field was treated, resulting in a 70% reduction in herbicide use. The online approach, on the other hand, integrates weed sensing, decision-making, and herbicide application in a single pass. This method employs smart sensors combined with a control system on the tractor, allowing real-time, efficient weed management. These online systems are currently under development and have the potential for large-scale commercial use, promising more sustainable agricultural practices.

Components of Site-Specific Weed Management (SSWM)

1. **Weed Mapping/Sensing:** This involves detecting and mapping weed infestations, either prior to treatment or in real-time.
2. **Treatment Decision:** Decisions range from simple ON/OFF applications to more complex systems that account for spatial variation in weed species and density, sometimes applying multiple herbicides at varying rates.
3. **Treatment Application:** This can involve manual mapping, digital imagery, or advanced sensors like WeedSeeker, which uses red and near-infrared (NIR) reflectance to detect green plant biomass and control spray applications. Other systems, such as CropCircle and GreenSeeker, also map biomass using red/NIR reflectance. More advanced systems in development combine reflectance with image shape analysis for precise weed identification.
4. **Documentation:** Most SSWM systems log the herbicide application map as a record, aiding future management decisions.

Prior Mapping vs. Real-Time Detection

Mapping weeds before spraying is simpler but may require an extra pass over the field. Real-time detection, however, integrates sensing and application in one step, requiring sensors and onboard computers to process imagery and control nozzles. While simple reflectance systems measure total plant biomass (including both crops and weeds), more complex systems use reflectance and image shape analysis to differentiate between crops and weeds, with advanced research systems capable of identifying up to 25 weed species.

Treatment Decision

Treatment decisions can vary in complexity. The simplest method is an ON/OFF approach, which is easy to implement but may miss isolated weeds outside of identified patches. Alternatively, a uniform basal treatment can be applied, with additional treatment only for specific patches. More advanced systems consider spatial variation in weed species and density, potentially applying up to three herbicides at varying rates using sophisticated computerized expert systems like Plant Protection On-Line.

Treatment Application

The most sophisticated sensor available is still the human eye, but manual mapping is time-consuming, and real-time manual control is prone to human error. Digital imagery from the ground or remote sources (satellite or aircraft) can be used, but these methods may lack the spatial resolution needed for smaller patches. WeedSeeker is currently the only commercialized system that directly links sensors to spray control, utilizing a red/NIR reflectance ratio to detect green plant biomass. Other sensors, like CropCircle and GreenSeeker, also map biomass using red/NIR, while more advanced systems under development in Denmark and Germany combine red/NIR imagery with image shape analysis to identify specific weed species.

Documentation

Most SSWM systems under development include features to log the "as applied" herbicide application map, providing a valuable record for future reference and management.

Weed Detection for SSWM: Mapping and Real-Time Approaches

This overview examines the current state of remote and proximal (on-ground) weed detection systems for site-specific weed management (SSWM), highlighting both the limitations and opportunities of these technologies. Remote sensing, particularly using multispectral aerial imagery, can generate accurate weed maps, especially at later weed phenological stages. However, high spatial resolution images from satellites and unmanned aerial vehicles (UAVs) still require further analysis to be fully effective. Hyperspectral imaging offers highly accurate mapping at both early and late stages across medium to farm scales, but its high operating costs make it economically unviable. On-ground detection systems can yield accurate results at a medium farm scale, but the challenge remains to develop a robust classifier that can distinguish between soil, weeds, and crops across various conditions.

The main limitations of remote and proximal sensing technologies are twofold: the time and expertise required to apply these advanced technologies, and the high costs and lack of compatibility with existing machinery. Potential solutions include offering advisory services that provide technical support and training, and the development of standardized, more affordable technologies.

Current State of SSWM

The state-of-the-art in weed monitoring is evolving, but is it ready for effective site-specific weed management in arable crops? Weed monitoring is crucial as the initial step in any SSWM program. A wide array of platforms, cameras, sensors, and image analysis techniques are available for detecting and mapping weed presence and abundance at various stages and spatial scales. Remote sensing from satellites or aircraft provides accurate weed maps when images are captured at late phenological stages. UAV-mounted cameras have proven effective for early-season weed detection in wide-row crops, offering relatively high spatial resolution. Ground-based platforms, using both imaging and non-imaging technologies, can achieve even higher resolution and are suitable for real-time SSWM in certain scenarios.

Practical Experiences and Challenges in Site-Specific Weed Management (SSWM)

Site-specific weed management using real-time image analysis and GPS-controlled patch spraying has demonstrated significant potential in reducing herbicide use. By utilizing spatial information on weed seedling populations, herbicide application can be targeted to areas with high infestation. In a two-year study, this approach reduced herbicide use in winter cereals by 6–81% for broadleaf weeds and 20–79% for grass weeds, with control efficacy ranging from 85% to 98%. These results show that SSWM can effectively manage weeds without increasing future infestations.

However, the main challenges for SSWM include developing accurate mapping and scanning systems and improving direct injection systems for herbicides. Recent European advances suggest these issues may be resolved, with prototypes now capable of identifying up to 25 weed species in real-time.

SSWM offers substantial benefits, potentially reducing herbicide use by 10–80% and increasing crop yields by 5–10% in untreated areas. Additionally, there is strong interest in SSWM for its environmental benefits, such as reducing chemical runoff. However, limitations include the high cost of mapping, difficulties in assessing weeds at the seedling stage, and limited knowledge of the long-term effects of spot spraying on weed ecosystems.

Precision Weed Control Implements

Precision weed control implements range from simple systems to advanced technologies. At its most basic, a precision weed control implement consists of an automated weed detection system mounted on the front of a tractor or self-propelled sprayer. This system identifies weeds and sends the information to a decision algorithm, which controls the spraying system (Paice *et al.*, 1995). Research in this area includes weed control in stubbles and pavements, with several sprayers developed for targeted treatment of weed patches or subfields.

One such system is the patch sprayer developed by Gerhards and Oebel (2006), which uses a GIS containing three treatment maps based on weed species composition. The sprayer, with a 21-meter boom divided into seven sections, delivers herbicides from three separate tanks, each containing different treatments. Another example is the commercially available WeedSeeker® sprayer, which uses advanced optics and computer circuitry to detect weeds and apply precise amounts of herbicide.

Robotic Weeding

Robotic weeding is emerging as a significant innovation in precision agriculture. Robots, capable of sensing their environment and making decisions, are increasingly being integrated into agricultural machinery. These robots can perform tasks such as micro-spraying or hoeing at the individual plant level, offering a precise and efficient alternative to traditional methods (Blackmore *et al.*, 2007). Although swarm robotics, where multiple small robots work together, holds promise for large-scale agricultural applications, it remains largely experimental. The SAGA project, part of the ECHORD++ initiative, is pioneering the use of swarm robotics for weed detection and mapping, using small unmanned aerial vehicles (UAVs) in agricultural settings.

Conclusion

Site-Specific Weed Management (SSWM) using variable herbicide application offers significant economic and environmental benefits, with promising advancements from overseas research. In Australia, an effective approach could involve a cost-effective basal herbicide applied across the field, complemented by a more targeted and variable application of a potent but more expensive herbicide to weed-infested patches. Traditionally, entire paddocks are sprayed, even though weeds often grow in specific patches. By spraying only where weeds are present, SSWM not only reduces herbicide use but also minimizes environmental impact. The integration of GPS technology has made it feasible to implement SSWM, allowing for precise control measures targeted only where necessary.

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