Session 18

Economics of Precision Agriculture

136. Economics of site-specific weed management: a review

V. Pitsyk*, J. Pfrombeck and M. Gandorfer
Institute for Agricultural Engineering and Animal Husbandry, Bavarian State Research Center for Agriculture (LfL), Hans-Loher-Straße 32, 94099 Ruhstorf a.d. Rott, Germany;
** vladyslav.pitsyk@lfl.bayern.de*

Abstract

This review evaluates research between 1995 and 2024 on the economics of site-specific weed management, analysing 25 studies with a focus on methodologies, reported benefits and cost considerations. Although many early studies reported the economic potential, technology or management costs were often omitted or underestimated. Recent research, considering advancements in site-specific weeding, has shown the ability to further increase the economic benefits, yet they remain limited when all the costs are factored in. Although still largely hypothetical, environmental benefits could come to the fore as the primary driver for the competitiveness of this technology over broadcast applications.

Keywords: crop protection, economic benefits, profit, site-specific, weed management

Introduction

The growing interest in site-specific weed management (SSWM) is driven by environmental concerns and economic prospects. Cussans (1992) defined SSWM as a concept that matches weed control strategies to the spatial variability and composition of weeds within a field. Early studies relied on simulated weed distributions or estimated weed cover from manual random sampling using interpolation methods. Bioeconomic models or decision support systems (DSS) were then applied to establish economic thresholds for weed control. Swinton's (2005) review summarized well the methodology and results available at that time. Since then, more sophisticated technologies have emerged, including camera-based mechanical weeding, sensor- or camera-based spot spraying, sensor-based electric weeding, unmanned aerial vehicle (UAV) -based weed mapping and improvement of direct injection systems. Several commercial solutions have been introduced to the market, reflecting the rapid evolution of SSWM technologies.
This study addresses the gap in a comprehensive review of economic evaluations of SSWM, considering also recent technological advancements. This review builds on Swinton's (2005) work and summarizes findings from the last three decades, analysing trends in profitability and wider economic impacts.

Materials and methods

A systematic literature review was conducted to identify research on the economics of SSWM in crop production. The searches were restricted to studies published in English and German between January 1995 and August 2024. The 30-year time span was chosen to provide a comprehensive understanding of changes in economic outcomes over time, starting from the very inception of research on SSWM. The primary database used was Scopus, with additional searches conducted in Wiley Online, CAB Abstracts, and AgEcon Search. The search strategy was adapted to the syntax of each database, employing Boolean operators (AND, OR) and wildcards (*) where applicable. The search string, adapted from Lowenberg-DeBoer *et al.* (2019), consisted of four components combined using AND: (i) (economic* OR profit* OR finance* OR cost* OR net return*) AND (ii) (wheat OR barley OR oat OR triticale OR maize OR corn OR canola OR oil* OR sunflower OR sugar* OR potato OR crop* OR plant* OR field*) AND (iii) (site-specific* OR precision OR target*) AND (iv) (weed management OR weed control OR weed detection OR weed scouting). This search initially yielded 1639 articles. An additional 13 articles were identified through conference proceedings, resulting in a total of 1,652 titles for the initial screening. Manual screening focused on identifying studies with advanced economic evaluations, excluding those using herbicide savings percentages as the sole economic metric. After screening, 25 articles were selected for full-text review. The final full-text assessment considered the type of economic analysis conducted, the economic benefits reported, and the costs considered.

Results

Studies overview

Of the 25 studies reviewed, 11 were from the US, 6 from Germany, and 8 from the UK, Hungary, Australia, and Spain. Five studies simulated initial weed distribution, thirteen used random grid sampling and interpolation to estimate whole field weed coverage, four utilized sensor or drone data, two relied on "manually recorded" data, and one did not specify the sampling method. Nineteen studies simulated site-specific herbicide application while six of the studies were based on field experiments. All studies used partial budgeting to estimate economic benefits but varied in the factors considered. Additionally, five studies applied stochastic modelling to identify key factors influencing profitability. Notably, 14 different terms were used across 25 studies to describe the results of economic analysis; thus, to ensure clarity, the exact terminology from each paper was used in this review. Most studies focused on arable crops such as cereals, soybeans, and sugar beets, with two examining peanuts and blueberries. Figure 1 provides a general trend of the results of the studies examined. Mixed results indicate that studies reported both positive and negative outcomes, depending on the factors considered.

Early attempts – simulation studies

As Takács-György and Takács (2011) noted, simulations are a cost-effective method for evaluating the economic and environmental benefits of SSWM. Early studies in the late 20th century used basic bioeconomic models to determine pest thresholds for control; however, Oriade *et al.* (1996) criticized these models for focusing on limited weed species within static frameworks rather than dynamic and multi-species control settings. The earliest study reviewed here, by Maxwell and Colliver (1995), did not incorporate a bioeconomic model and focused on single weed species (*Avena fatua)* in winter wheat. Yet, a simple economic evaluation was performed, calculating *annualized net returns* over a 10-year period of SSWM application. Findings indicated a US$17.81/ha advantage for SSWM over whole-field application (WFA), although weed sampling costs were adopted from another study. Oriade *et al.* (1996) utilized a bioeconomic simulation model to compare site-specific to WFA of herbicides in maize and soybeans. Initial weed patchiness was identified as the most influential factor. Average annual benefits varied, with returns up to US$11.67/ha depending on crop and

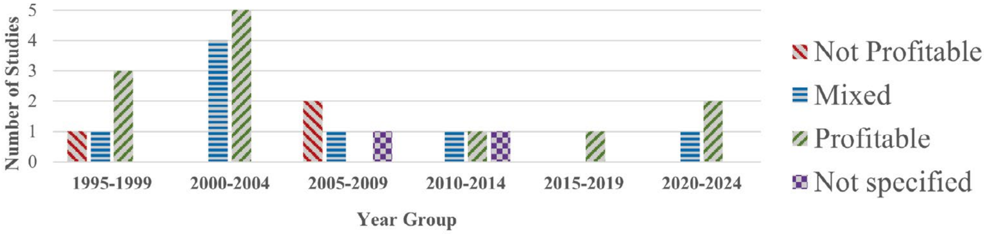

Figure 1. Distribution of study outcomes on site-specific weed management profitability.

weed distribution. However, technology costs were based on variable-rate fertilizer application. Bennett and Pannell (1998), using stochastic modelling, found that pre-emergence SSWM yielded at best US$4/ha and at worst –US$17.67/ha of net present value. Under Australian conditions, weed distributions were either too high or too low, so WFA or no treatment was often the superior strategy. Lindquist et al. (1998) modelled herbicide application in maize and soybeans under different weed density patterns – uniform, clustered (negative binomial), and spatially mapped. When spatially mapped weed density was used, it minimized yield loss and maximized economic returns, with average benefits across studied fields of US$21.71/ha and US$12.17/ha compared to uniform and clustered, respectively. However, the authors assumed management costs from variable-rate seeding technology. Paice *et al.* (1998) used stochastic modelling to investigate the effects of weed distribution, seed dispersal range, and spatial resolution of spot-spraying in continuous winter cereal cropping infested with *A. myosuroides* over a 10-year production cycle in the UK. Net present value ranged from –US$18.2/ha to US$31.1/ha, depending on spatial resolution, weed distribution, and seed dispersal range. Management costs of SSWM were not considered. Profitability was highest at 1–2 m resolutions. At lower resolutions, seed dispersal reduced effectiveness, as it allowed initially discrete patches to spread into previously uninfested areas. Conversely, Barroso *et al.* (2004) found that a spatial resolution of 12 m was more profitable in barley under Spanish conditions. The lower cost of less precise technology outweighed the higher expense of achieving 3 m resolution. Net returns for SSWM ranged between –€17.8/ha and €18.2/ha compared to WFA, depending on the number of patches, resolution, and infestation percentage. Nevertheless, considering low initial weed infestations, no herbicide application was often the most economical option. In similar conditions, Ruiz *et al.* (2006) confirmed that no herbicide application was indeed the most profitable strategy in barley fields. In the *net return* calculations, an average of 81.29€/ha was received for no application, while site-specific (half-rate and adjusted-rate) and uniform (label-rate and half-rate) applications yielded 72.34, 68.53, 59.4 and €77.15/ha, respectively. Andujar *et al.* (2013), studying maize under Spanish conditions, reported no herbicide application as the optimal strategy in the fields with *Sorghum halepense* infestations under 6%. SSWM was the most profitable for weed coverage between 6.5% and 18.7%, and full-rate uniform application was superior above 40.8%. Wiles *et al.* (2009) examined the impact of varying herbicide combinations on SSWM profitability. In irrigated maize, patch spraying with a single herbicide increased net returns by US$3.09/ha compared to WFA, rising to US$8.43/ha and US$9.69/ha when using two or a combination of herbicides that maximized net returns, respectively. Savings came mainly from a reduction in herbicide costs and improved control of the weed population. The authors emphasized that net returns would likely not cover additional management costs. Young *et al.* (2003) evaluated a computerized herbicide decision model for SSWM in winter wheat, comparing its recommendations to those from farmers, consultants, weed scientists, and label rates. The model recommended increased broadleaf herbicide rates and reduced applications of more costly grass herbicides. The model projected an average profit increase of US$130.57/ha over other approaches due to herbicide savings and reduced yield-loss. Mapping and technology costs, estimated at US$6/ha, were expected "to be easily absorbed by the model's profitability". Takács-György and Takács (2009) examined the effects of precision fertilization and differentiated herbicide spraying on production costs, yields, gross margin, and returns on technological investment under Hungarian conditions. Using net present value and Monte Carlo simulation, authors assessed the risks of returns and theoretical limits of SSWM, respectively. Greater variability in factors such as soil parameters and weed coverage increased the likelihood of benefits from precision farming, while balanced conditions made it less likely. In a follow-up study (Takács-György and Takács, 2011), the authors expanded their analysis to model the impact of weed coverage, heterogeneity, and production intensity on production costs. Precision farming was found economically unviable in scenarios with low nutrient supply and weed coverage due to high technology costs. However, in areas with high nutrient supply and weed coverage, precision technology was beneficial only in heterogeneous conditions; in homogeneous areas, undifferentiated treatment proved to be more cost-effective. Factors influencing profitability included soil nutrient levels, crop, weed competition, technology costs, and potential cost savings.

Simulation studies with genetically modified crops and broad-spectrum herbicides

Five studies from the US on SSWM considered non-selective post-emergence herbicide application such as glyphosate in genetically modified (GM) maize and soybeans or paraquat in peanuts. Medlin and Shaw (2000) used the Herbicide Application Decision Support System (HADSS) to compare estimated net gains from SSWM and WFA in non-transgenic and GM soybeans. In non-transgenic fields, SSWM increased net gains by US$104.76/ha compared to WFA, while in GM fields, the increase was US$96.24/ha. Benefits were attributed to targeted herbicide use, reduced unnecessary applications, and variable herbicide rates based on weed density and species composition. Costs of technology were not included. Wilkerson *et al.* (2004) also employed HADSS to compare SSWM and WFA in soybeans. Optimal WFA treatments projected theoretical net returns of US$79/ha and US$139/ha for conventional and GM soybeans, respectively. When optimizing net returns (most economical treatment), SSWM increased net returns by US$13/ha in non-transgenic and US$4.50/ha in GM soybeans compared to respective WFA. When aiming to minimize yield loss (most effective treatment), SSWM reduced net returns by US$18/ha in non-transgenic and US$4/ha in GM fields compared to respective WFA. The authors did not account for scouting and technology costs, stating that returns would likely be insufficient to cover additional expenses. Similarly, Lamastus-Stanford and Shaw (2004) used HADSS to compare SSWM and WFA in GM soybeans. On average, over two years, SSWM yielded higher projected net returns of US$10.42/ha and US$19.83/ha, depending on location and sampling scales. Sampling and technology costs were omitted. Rider *et al.* (2006) compared SSWM with two WFA treatments (full-label and economically optimal rates) in GM maize and sorghum. The authors developed a decision algorithm to determine the economically optimal herbicide rate and applied quadratic and Mitscherlich production functions to model yield responses to those rates. The quadratic model projected net returns of US$61.30/ha and US$43.76/ha, while the Mitscherlich model yielded US$20.08/ha and US$1.10/ha for SSWM over WFA full label and economically optimal rates, respectively. Notably, the Mitscherlich model better captured yield responses to herbicide rates and weed competition but failed to cover technology costs estimated at US$20.38/ha. Finally, Jordan *et al.* (2003) found SSWM in peanuts increased theoretical net returns by average of US$21/ha compared to full-sample approaches, regardless of market price, weed size, or soil moisture. Sampling and technology costs were not included. According to the authors, the cost of current technology for SSWM would likely exceed US$21/ha.

From simulations to field trials

Luschei *et al.* (2001) conducted one of the first field trials focusing on *Avena fatua* in winter wheat, manually mapping weed patches using GNSS to create prescription maps. Among the four fields studied, only two yielded profitable results for SSWM, with net returns of US$14.21/ha and US$20/ha compared to WFA. Weed coverage in these fields ranged from 40 to 46%, and profitability decreased as infestation levels increased. The study included the costs of weed mapping and application equipment. Gerhards and Sökefeld (2003) assessed the economic benefits of SSWM in winter cereals, sugar beets, and maize on commercial farms in Germany. This study was perhaps the first to employ bi-spectral cameras for real-time weed detection and direct injection systems for varied herbicide mixtures. SSWM with the direct-injection system was the most profitable strategy in winter cereals and sugar beets, with increases of €22.54/ha and €65.54/ha over WFA, respectively. The single-mixture site-specific herbicide application was only profitable for winter cereals, with a €11.14/ha advantage over WFA, while uniform treatment remained the most profitable in maize. Costs of technology were assumed from prototypes used in the study. In related research, Timmermann *et al.* (2003) evaluated the economics of SSWM as part of the same experimental setup by Gerhards and Sökefeld. Different weed control strategies (SSWM, WFA, and band spraying with hoeing) were used depending on the growing crop. Average herbicide savings of €42/ha in maize, €32/ha in winter wheat, €25/ha in winter barley, and €20/ha in sugar beets were reported, with savings varying by crop and year. Schroers *et al.* (2010) compared the performance of online and map-based approaches for SSWM in field trials with winter wheat, maize, and sugar beets using cost-benefit analysis. Compared to WFA, the map-based approach resulted in savings of €12.81/ha for wheat, €17.72/ha for maize and €22.48/ha for sugar beets. The online approach yielded higher savings: €28.14/ha for wheat, €33.04/ha for maize, and €53.13/ha for sugar beets. In both scenarios, savings primarily resulted from reduced herbicide use. Although technology and application costs were included in the calculations, they were estimated based on prototypes used.

Considering recent advances in site-specific weeding technologies
Esau *et al.* (2016) analysed site-specific pesticide application in simulated North American blueberry fields, comparing a smart sprayer, swath control sprayer, and basic sprayer. Over a 2-year production cycle, total application costs were US$2052/ha for the basic sprayer, US$1799/ha for the swath control sprayer, and US$1138/ha for the smart sprayer. Savings stemmed from reduced chemical use and minimized overspray. Payback periods varied by farm size, from 2 years (60 ha) to 9.8 years (20 ha) for the swath control sprayer and from 11 months to 3.5 years for the smart sprayer. Rajmis *et al.* (2022) conducted a scenario analysis based on field trials data comparing offline and online SSWM technologies with WFA in winter cereal production in Germany. SSWM reduced herbicide costs by 66%, from €169/ha to €58/ha. The extended gross margin resulted in an economic advantage of 156€/ha compared to WFA. Savings primarily came from the assumption that conventional treatment required two applications per year, while SSWM required only one. The break-even point for SSWM varied with herbicide savings, ranging from 314 to 597 ha/year with 70% savings and 1593 to 3024 ha/year with 30% savings, while a model farm of 1000 ha became profitable with 50% herbicide savings. Fishkis *et al.* (2024) were the first to assess in-depth the economic and ecological impact of different combinations of weed control methods in sugar beets, comparing mechanical, mechanical-chemical (including spot-spraying), and chemical treatments. Mechanical control costs, given the use of manual weeding, were significantly higher (€1206/ha–2403€/ha) compared to WFA (€357/ha). In contrast, a hybrid approach using a solar-powered robot and spot spraying was only slightly more expensive (€450/ha), yet offered substantial environmental benefits, including 5% lower greenhouse gas emissions and an 87% reduction in toxicological risk. Sponagel *et al.* (2024) compared the costs of various crop protection methods, including broadcast sprayer, inter-row hoeing with band spraying, smart sprayer, and solar-powered robot, in sugar beet fields in Germany. Profitability depended on herbicide savings achieved. As the costs of the smart sprayer were unknown, two scenarios were modelled, assuming a 100% or 50% higher price than a conventional sprayer. In the first scenario, the smart sprayer became profitable at 67 ha with 50% herbicide savings, at 85 ha with 40% savings and over 100 ha with 30% savings. In the second scenario, profitability was already achieved at 59 ha with 30% savings. Inter-row hoeing with band spraying became cost-effective at 75 ha with 60% savings, while the solar-powered robot was most economical for fields smaller than 18 ha.

Discussion

Profitability results in early studies varied widely, influenced by factors such as crop, initial weed distribution, technology and management costs. Sugar beets are considered to have the highest savings potential owing to the need for multiple herbicide applications per season, as confirmed in field trials by Gerhards and Sökefeld (2003) with a direct injection system and Schroers *et al.* (2010). Barroso *et al.* (2004) emphasized technology and management costs as critical factors affecting profitability. However, ten studies omitted or underestimated these costs, reporting positive or mixed results. Among those which included costs, three reported negative, five mixed and one positive

outcomes. Bennett and Pannell (1998) underscored the importance of initial weed distribution on the profitability of SSWM. Studies on GM crops in the US showed marginally higher returns but are less relevant to EU conditions. Considering recent technological advancements, studies such as those by Esau *et al.* (2016) and Rajmis *et al.* (2022) showed improved returns, although Esau's study on blueberries may not translate directly to conventional crops. As proposed by Oriade *et al.* (1996), considerable environmental benefits from site-specific herbicide application were confirmed in the study by Fishkis *et al.* (2024).
Profitability is indeed a key factor influencing the adoption of precision technology among farmers, as suggested by Lowenberg-DeBoer *et al.* (2019). Unlike other precision agriculture technologies such as GNSS guidance or variable-rate technologies, SSWM lacked a clearly established concept and distinct advantages over conventional methods, largely due to the high costs of manual field scouting. However, with recent advancements, particularly in computer vision technology for real-time weed recognition and direct injection systems, SSWM is now a more defined and practical solution. Despite promising developments, when all costs are considered, the economic advantages of SSWM still remain modest particularly among small farms. More studies are needed to validate the economic and, more importantly, environmental benefits which, although still largely hypothetical, could in fact become a primary driver for wider adoption.

Conclusion

The results of the reviewed studies indicate that the economic viability of SSWM, even with new technologies, remains limited when all costs are considered, mainly due to long payback periods for small farms. Consequently, the environmental benefits of SSWM may take precedence. To enhance economic competitiveness and to contribute to the goal of more sustainable agriculture practices in Europe, supportive policy frameworks could be considered that considerably reduce avoidance costs for SSWM compared to WFA.

References

Andújar, D., Ribeiro, A., Fernández-Quintanilla, C., & Dorado, J. (2013). Herbicide savings and economic benefits of several strategies to control *Sorghum halepense* in maize crops. Crop Protection, 50, 17–23.

Barroso, J., Fernandez-Quintanilla, C., Maxwell, B.D., & Rew, L.J. (2004). Simulating the effects of weed spatial pattern and resolution of mapping and spraying on economics of site-specific management. Weed Research, 44, 460–468.

Bennett, A.L., & Pannell, D.J. (1998). Economic evaluation of a weed-activated sprayer for herbicide application to patchy weed populations. Australian Journal of Agricultural and Resource Economics, 42, 389–408.

Cussans, G.W. (1992). Identifying ways of optimizing herbicide use in crops. In J.H. Combellack, K.J. Levick, J. Parsons, & R.G. Richardson (eds): Proceedings of the First International Weed Control Congress. Weed Science Society of Victoria, Melbourne, VIC, pp. 208–214.

Esau, T., Zaman, Q., Groulx, D., Corscadden, K., Chang, Y., Schumann, A., & Havard, P. (2016). Economic analysis for smart sprayer application in wild blueberry fields. Precision Agriculture, 17, 753–765.

Fishkis, O., Weller, J., Lehmhus, J., Poellinger, F., Strassemeyer, J., & Koch, H.-J. (2024). Ecological and economic evaluation of conventional and new weed control techniques in row crops. Agriculture, Ecosystems & Environment, 360, 108786.

Gerhards, R., & Sökefeld, M. (2003). Precision farming in weed control - system components and economic benefits. In J.V. Stafford, & A. Werner (eds), Precision Agriculture '03: Proceedings of the 4th European Conference on Precision Agriculture. Wageningen Academic Publishers, Wageningen, pp. 229–-234.

Jordan, D.L., Wilkerson, G.G., & Krueger, D.W. (2003). Evaluation of scouting methods in peanut (*Arachis hypogaea*) using theoretical net returns from HADSS. Weed Technology, 17, 358–365.

Lamastus-Stanford, F.E., & Shaw, D.R. (2004). Evaluation of site-specific weed management implementing the herbicide application decision support system (HADSS). Precision Agriculture, 5, 411–426.
Lindquist, J.L., Dieleman, J.A., Mortensen, D.A., Johnson, G.A., & Wyse-Pester, D.Y., (1998). Economic importance of managing spatially heterogeneous weed populations. Weed Technology, 12, 7–13.
Lowenberg-DeBoer, J., Huang, I.Y., Grigoriadis, V., & Blackmore, S. (2019). Economics of robots and automation in field crop production. Precision Agriculture, 21, 278–299.
Luschei, E.C., Wychen, L.R.V., Maxwell, B.D., Bussan, A.J., Buschena, D., & Goodman, D. (2001). Implementing and conducting on-farm weed research with the use of GPS. Weed Science, 49, 536–542.
Maxwell, B.D., & Colliver, C.T. (1995). Expanding economic thresholds by including spatial and temporal weed dynamics. In Proceedings of the Brighton Crop Protection Conference, Weeds. British Crop Protection Council, Farnham, pp. 1069–1076.
Medlin, C.R., & Shaw, D.R. (2000). Economic comparison of broadcast and site-specific herbicide applications in non-transgenic and glyphosate-tolerant *Glycine max*. Weed Science, 48, 653–661.
Oriade, C.A., King, R.P., Forcella, F., & Gunsolus, J.L. (1996). A bioeconomic analysis of site-specific management for weed control. Review of Agricultural Economics, 18, 523–535.
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.
Rajmis, S., Karpinski, I., Pohl, J.-P., Herrmann, M., & Kehlenbeck, H. (2022). Economic potential of site-specific pesticide application scenarios with direct injection and automatic application assistant in northern Germany. Precision Agriculture, 23, 2063–2088.
Rider, T.W., Vogel, J.W., Dille, J.A., Dhuyvetter, K.C., & Kastens, T.L. (2006). An economic evaluation of site-specific herbicide application. Precision Agriculture, 7, 379–392.
Ruiz, D., Escribano, C., & Fernández-Quintanilla, C. (2006). Assessing the opportunity for site-specific management of *Avena sterilis* in winter barley fields in Spain. Weed Research, 46, 379–387.
Schroers, J.O., Gerhards, R., & Kunisch, M. (2010). Economic evaluation of precision crop protection measures. In E.C. Oerke, R. Gerhards, G. Menz, & R.A. Sikora (eds), Precision crop protection—the challenge and use of heterogeneity. Springer, Berlin, pp. 417–426.
Sponagel, C., Witte, F., & Bahrs, E. (2024). Ökonomische bewertung und vergleich von pflanzenschutzverfahren mit fokus auf herbizidreduktion durch digitalisierung am beispiel des zuckerrübenanbaus (Economic evaluation and comparison of crop protection methods with a focus on herbicide reduction through digitalisation using the example of sugar beet cultivation). In C. Hoffmann, A. Stein, E. Gallmann, J. Dörr, C. Krupitzer, & H. Floto (eds): 44. GIL-Jahrestagung: Informatik in der Land-, Forst- und Ernährungswirtschaft. Bonn, pp. 413–418.
Swinton, S.M. (2005). Economics of site-specific weed management. Weed Science, 53, 259–263.
Takács-György, K., & Takács, I. (2009). Economic analysis of precision weed management. Cereal Research Communications, 37, 585–593.
Takács-György, K., & Takács, I. (2011). Risk assessment and examination of economic aspects of precision weed management. Sustainability, 3, 1114–1135.
Timmermann, C., Gerhards, R., & Kühbauch, W. (2003). The economic impact of site-specific weed control. Precision Agriculture, 4, 249–260.
Wiles, L.J. (2009). Beyond patch spraying: site-specific weed management with several herbicides. Precision Agriculture, 10, 277–290.
Wilkerson, G.G., Price, A.J., Bennett, A.C., Krueger, D.W., Roberson, G.T., & Robinson, B.L. (2004). Evaluating the potential for site-specific herbicide application in soybean. Weed Technology, 18, 1101–1110.
Young, D.L., Kwon, T.J., Smith, E.G., & Young, F.L. (2003). Site-specific herbicide decision model to maximize profit in winter wheat. Precision Agriculture, 4, 227–238.